Heart rate variability and heart rate recovery in relation to match results in elite African male badminton players

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DECLARATION

The co-authors of the three articles, which form part of this thesis, Prof Ben Coetzee (Promoter) and Prof Michael Esco (Co-promoter) hereby give permission to the candidate, Mr. Christo Bisschoff to include three articles as part of the PhD thesis. The contribution (advisory and supportive) of the co-authors was kept within reasonable limits, thereby enabling the candidate to submit this thesis for examination purposes. This thesis, therefore, serves as of the fulfillment of the requiremnets for the degree Doctor of Philosophy within PhASRec (Physical Activity, Sport and Recreation Focus Area) in the Faculty of Health Sciences at the North-West University (Potchefstroom Campus)

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SUMMARY

Since the emergence of heart rate variability (HRV) and heart rate recovery (HRR) as indicators of autonomic nervous system (ANS) activity in sport and exercise, these markers have been received with a great deal of interest and have stimulated ever-increasing research in this area. However, the use of HRV and HRR in the badminton environment, and more importantly, the possible relationships of HRV and HRR to badminton performance, have not yet been investigated. Additionally, in view of the fact that HRV and HRR are influenced by various external factors (such as muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states), it is crucial to correct for or control these factors when evaluating these variables for use in a competitive sport setting. However, no HRV and HRR related studies have thus far considered all of these variables in their testing protocols. Lastly, HRV-related variables may also be significantly influenced by external match loads (as determined through GPS-related variables) during a badminton match.

It is in the light of this background that the main objectives of this study were: firstly, to determine if pre-match, in-match, resting and post-match HRV as well as post-match and in-match (as measured during breaks between sets) HRR can serve as significant predictors of male, elite, African, singles badminton players' performance levels. Secondly, to determine if HRV and HRR are related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players. Thirdly, to investigate the relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players.

In order to fulfil abovemetioned objectives twenty-two, male, elite, African, singles badminton players (age: 23.3 ± 3.9 years; height: 177.1 ± 3.0 cm; mass: 83.4 ± 14.5 kg) were recruited. In total 46 national and international matches were recorded and analysed. Every day before the start of each match, players completed a recovery and hydration status questionnaire. Five to ten minutes before the start of each match, players also completed the Stellenbosch Mood Scale (STEMS). Prior to each match warm-up players were fitted with a Fix Polar Heart Rate Transmitter Belt and a MinimaxX GPS unit to record HR and court movements during matches. Before the start of each match a video camera was stationed on a tri-pod stand behind each of the

courts that matches were played so that researchers were able to determine the correct duration of the matches to ensure accurate heart rate and GPS (integrated with a tri-axial accelerometer, tri-axial gyroscope and tri-axial magnetometer) analyses.

For the first objective of the study binary, forward, stepwise logistic regression analyses' results showed that only spectral HRV indices, namely log transformed low frequency to high frequency ratio (Ln-LFnu/Ln-HFnu ratio) and peak very low frequency power (VLF power (Hz), were significantly related to group allocation of successful and less successful badminton players. Overall model fit was good and 75% of players could be classified into their original groups. Furthermore, all models had a large effect in predicting classification of players, although only the pre- and in-match models emerged as being useful.

For the second objective of the study canonical correlations for relationships between HRV-, HRR-related variables and several recovery indicators for each of the match time periods, were as follow: $Rc = 0.98$ ($p = 0.626$) for the pre-match period; $Rc = 0.96$ ($p = 0.014$) for the in-match period; $Rc = 0.69$ ($p = 0.258$) for the in-match rest periods and $Rc = 0.98$ ($p = 0.085$) for the post-match period. Canonical functions accounted for between 47.89% and 96.43% of the total variation between the two canonical variants. A strong, significant relationship was found between HRV, HRR and recovery indicators for the in-match period, but only strong, non-significant relationships were observed for pre-match and post-match periods and a low non-significant relationship for the in-match rest period. Results further revealed that log transformed normalised high frequency power (Ln-HFnu), sleep quality and mood state-related variables such as the energy index, confusion and vigour were the primary variables to contribute to relationships between the HRV-, HRR- and recovery-related variables.

For the third objective of the study results revealed a strong, non-significant canonical correlation of $Rc = 0.99$ ($p = 0.257$) between HR, HRV, HRR and GPS determined match characteristics. The total redundancy values showed that 38.47% of the variance in the nine GPS-related variables could be accounted for by the ten HR-related variables. Likewise 38.88% of the variance in the HR-related variables could be accounted for given these nine GPS-related variables. Furthermore, distance covered at a low exercise intensity, the amount of low intensity accelerations and player load were highlighted as the highest external match load-related contributors whereas Ln-HFnu power, peak HF (Hz) and Ln-LFnu/Ln-HFnu were identified as the highest internal match load-related contributors to the overall canonical correlation coefficient.

To the researchers' knowledge, this is the first study to thoroughly investigate the ANS (through HRV and HRR) during real badminton tournaments. Most importantly the study showed that HRV and HRR can be accurately measured over different periods of competitive badminton matches. Furthermore, frequency domain-related HRV measures, when measured over the short term, appear to be related to badminton match performances and should be considered when measuring HRV in competitive sport and exercise settings. In addition, the study proved that subjective recovery indicators influence HRV and HRR measured in a competitive badminton environment and should therefore be incorporated in protocols that evaluate the ANS through HRV and HRR. Lastly, when evaluating badminton internal match loads (through HRV-related variables) coaches and sport scientists should consider and correct for the external match loads of badminton players to prevent clouded and inaccurate conclusions of ANS behaviour.

OPSOMMING

Sedert die verskyning van harttempoveranderlikheid (HTV) en harttempoherstel (HTH) as indikatore van die outonome senuweestelsel (OS) in sport en oefening, is hierdie merkers met groot belangstelling ontvang en het dit al hoe meer navorsing in hierdie area gestimuleer. Die gebruik van HTV en HTH in die pluimbalomgewing, en meer van belang, die moontlike verband tussen HTV, HTH en pluimbalprestasie is egter nog nie nagevors nie. Daarbenewens, in die lig van die feit dat HTV en HTH beïnvloed word deur verskeie eksterne faktore (soos spierseerheid, hidrasiestatus, slaapkwaliteit en –kwantiteit, sowel as pre-kompetisie-gemoedstoestande), is dit belangrik om te korrigeer vir, of beheer uit te oefen oor hierdie faktore wanneer dit gebruik word in ŉ mededingende sportomgewing. Nietemin, geen HTV en HTH-verwante studies het tot dusvêr al hierdie veranderlikes in hul toetsprotokolle in ag geneem nie. Laastens, HTV-verwante veranderlikes mag ook betekenisvol deur eksterne wedstrydladings (soos bepaal deur Globale Posisioneringstelsel (GPS)-verwante veranderlikes) gedurende ŉ pluimbalwedstryd, beïnvloed word.

Dit is in die lig van hierdie agtergrond dat die primêre doelwitte van dié studie was om: eerstens te bepaal of pre-wedstyd, in-wedstryd, rustende en post-wedstryd HTV sowel as post-wedstryd en in-wedstryd (soos gemeet tydens breuke tussen stelle) HTH kan dien as betekenisvolle voorspellers van manlike-, elite, Afrika, enkelspel-pluimbalspelers se prestasievlakke. Tweedens, om te bepaal of HTV en HTH in verband staan met ŉ aantal subjektiewe indikatore van herstelstatus (spierseerheid, hidrasiestatus, slaapkwaliteit en –kwantiteit, sowel as pre-kompetisie-gemoedstoestande) vir verskillende wedstrydtye in manlike, elite, Afrika, enkelspel-pluimbalspelers. Derdens, om ondersoek in te stel na die verband tussen GPS-, harttempo (HT)-, HTV- en HTH-verbandhoudende veranderlikes in manlike, elite, Afrika, enkelspel-pluimbalspelers.

Ten einde die bogenoemde doelwitte te behaal, is twee-en-twintig manlike, elite, Afrika, enkelspel-pluimbalspelers (ouderdom: 23.3 ± 3.9 jare; lengte: 177.1 ± 3.0 cm; gewig: 83.4 ± 14.5 kg) gewerf. Altesaam 46 nasionale en internasionale wedstryde is opgeneem en geanaliseer. Elke dag, voor die aanvang van elke wedstryd, het spelers die Stellenbosch Mood Scale (STEMS) ingevul. Voor elke wedstryd-opwarming is spelers met ’n Fixed Polar Heart Rate Transmitter Belt en ŉ MinimaxX GPS-eenheid toegerus om HT en baanbewegings gedurende

wedstryde op te neem. Voor elke wedstryd is ŉ video-kamera op ŉ driepootstaander aan die agterkant van elke baan waarop wedstryde plaasgevind het, geposisioneer sodat navorsers in staat was om die korrekte periodes vir HT- en GPS-analises (geintegreer met ŉ tri-aksis vernsellingsmeter, ŉ tri-aksis giroskoop en ŉ tri-aksis magnetometer) te bepaal.

Met betrekking tot die eerste doelwit van die studie, het die binêre, vorentoe, stapsgewyse, logistiese regressie-analise se resultate aangetoon dat slegs spektrale HTV-indekse, naamlik log-getransformeerde, genormaliseerde lae frekwensie tot hoë frekwensie ratio (Ln-LFnu/Ln-HFnu) en piek baie-lae-frekwensie-krag (BLF) betekenisvol tot die groepverdeling van suksesvolle en minder-suksesvolle pluimbalspelers bygedra het. In geheel was die modelpassing goed en kon 75% van die spelers weer in hul oorpronklike groepe geklassifiseer word. Voorts het alle modelle ŉ groot effek gehad op die voorspelling van spelers se klassifisering, alhoewel slegs die pre- en in-wedstrydmodelle na vore getree het as bruikbare modelle.

Vir die tweede doelwit van die studie, was kanoniese korrelasies van verbande tussen HTV- en HTH-verwante veranderlikes sowel as ŉ aantal herstelindikatore vir elkeen van die wedstrydtye as volg: Rc = 0.98 (p = 0.626) vir die pre-wedstrydperiode; Rc = 0.96 (p = 0.014) vir die in-wedstrydperiode; Rc = 0.69 (p = 0.258) vir die in-wedstryd-rusperiodes en Rc = 0.98 (p = 0.085) vir die post-wedstrydperiode. Kanoniese funksies het vir tussen 47.89% en 96.43% van die totale variansie tussen die twee kanoniese variante bygedra. ’n Sterk, betekenisvolle verband is gevind tussen HRT, HTH en herstelindikatore vir die in-wedstrydperiode, maar slegs sterk nie-betekenisvolle verbande is gevind vir die pre-wedstryd- en post-wedstrydperiodes terwyl ŉ lae nie-betekenisvolle verband vir die in-wedstryd-rusperiodes gevind is. Resultate het voorts aangedui dat log-getransformeerde, genormaliseerde hoë frekwensie krag (Ln-HFnu), slaapkwaliteit en gemoedstoestand-verwante veranderlikes soos die energie-indeks, verwarring en lewenskrag die primêre veranderlikes was wat bygedra het tot die verband tussen die HTV-, HTH- en herstel-verwante veranderlikes.

Vir die derde doelwit van die studie het resultate ŉ sterk nie-betekenisvolle kanoniese korrelasie van Rc = 0.99 (p = 0.257) tussen HT-, HTV-, HTH- en GPS-bepaalde wedstrydkarakteristieke, getoon. Die totale oorbodigheids-waardes het getoon dat 38.47% van die variansie in die nege GPS-verwante veranderlikes verklaar kon word deur die tien HT-verwante veranderlikes. Eweneens, kon 38.88% van die variansie in die HT-verwante veranderlikes verklaar word deur die nege GPS-verwante veranderlikes. Voorts is afstand afgelê teen ŉ lae oefenings-intensiteit, die aantal lae-intensiteit versnellings en spelerlading uitgewys as die hoogste eksterne wedstrydlading-verwante bydraers en is Ln-HFnu, piek hoë frekwensie (HF (Hz)) en Ln-LFnu/Ln-HFnu geïdentifiseer as die hoogste interne wedstrydlading-verwante bydraers tot die algehele kanoniese korrelasiekoëffisiënt.

Sovêr navorsers se kennis strek, is hierdie die eerste studie wat ŉ deeglike ondersoek gedoen het oor die OS (deur van HTV en HTH gebruik te maak) tydens werklike pluimbaltoernooie. Belangriker nog, het die studie aangetoon dat HTV en HTH akkuraat gemeet kan word oor verskillende periodes gedurende wedstryde. Voorts, behoort frekwensie domein-verwante HTV-metings wat oor die korttermyn gemeet word, in ag geneem te word wanneer HTV gemeet word in mededingende sport- en oefeningsomgewings aangesien dit in verband staan met pluimbalwedstrydprestasies. Verder het hierdie studie bewys dat subjektiewe herstelindikatore, HTV en HTH wat gemeet word in ŉ mededingende pluimbalomgewing, beïnvloed en daarom dus ingesluit behoort te word in protokolle wat die OS evalueer deur van HTV en HTH gebruik te maak. Laastens, met evaluering van pluimbal interne wedstrydladings (deur HT-verwante veranderlikes) moet afrigters en sportwetenskaplikes die eksterne wedstrydladings van pluimbalspelers oorweeg en daarvoor korrigeer om daardeur te verhoed dat vae en onakkurate afleidings oor OS-gedrag gemaak word.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANS	Autonomic nervous system
BMI	Body mass index
BPM	Beats per minute
CSAI-2	Competitive State Anxiety Inventory-2
CV	Coefficient of variation
ECG	Electrocardiograph
FOR	Functional over reaching
GPS	Global positioning system
HF	High frequency component
HF (Hz)	High frequency power expressed in Hertz
HF%	High frequency power expressed as percentage
HFnu	High frequency component expressed in normalised units
HR	Heart rate
HRex	Exercise heart rate
HRmax	Maximal heart rate
HRR	Heart rate recovery
HRR_{60}	HRR measured after 60 seconds
HRR_T	First-order exponential curve representation of HRR
HRV	Heart rate variability
LF	Low frequency component
LF (Hz)	Low frequency power expressed in Hertz
LF%	Low frequency power expressed as percentage
LF/HF ratio	Low and high frequency components expressed as a ratio
LFnu	Low frequency component expressed in normalised units
Ln-HFnu	The natural logarithmic transformation of high frequency relative power expressed as normalised units
Ln-LFnu	The natural logarithmic transformation of low frequency power expressed as normalised units
Ln-LFnu/Ln-HFnu ratio	The ratio between Ln-LFnu and Ln-HFnu components
Ln-RMSSD	Natural logarithm applied for squared root of the mean squared differences between successive R-R intervals

Ln-RMSSDx20	The squared root of the mean squared differences between successive R-R intervals multiplied by 20
Ln-SD1	Natural logarithm applied for standard descriptor one
Ln-SD2	Natural logarithm applied for standard descriptor two
Ln-SDNN	Natural logarithm applied for the standard deviation of R-R intervals
MAS	Maximal aerobic speed
NFOR	Non-functional over reaching
PHV	Peak height velocity
pNN50	The proportion of R-R intervals that exceed 50 milliseconds
PNS	Parasympathetic nervous system
POMS	Profile of mood states
RCP	Respiratory compensation point
RER	Respiratory exchange ratio
RMSSD	Squared root of the mean squared differences between successive R-R intervals
$RMSSD_{30}$	RMSSD measured for 30 seconds
R-R intervals	Inter-beat intervals or R to R intervals
SD1	Standard descriptor one
SD2	Standard descriptor two
SD1/SD2	SD1 and SD2 expressed as a ratio
SDNN	Standard deviation of R-R intervals
$SDNN_{30}$	SDNN measured for 30 seconds
SNS	Sympathetic nervous system
STEMS	Stellenbosch mood scale
TP	Total power
VLF	Very low frequency
VLF (Hz)	Very low frequency power expressed in Hertz
VLF%	Very low frequency power expressed as percentage
VLFnu	Very low frequency component expressed in normalised units
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake

$\dot{V}O_2$	Oxygen consumption
VT1	Ventilatory threshold one
VT2	Ventilatory threshold two
Yo-Yo IR1	Yo-Yo Intermittent Recovery Test One

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Monitoring autonomic nervous system (ANS) activity through heart rate variability (HRV) and recovery (HRR) has become increasingly popular in recent years (Bellenger *et al*., 2016:20; Daanen *et al*., 2012:251,258). The popularity of these measurements has increased due to the pivotal role that the ANS plays in regulating bodily functions and the usefulness of ANS related indices to evaluate various aspects such as cardiac mortality, neurological disorders, renal failure, diabetes, fitness and sport performance (Makivic *et al*., 2013:105,108; Acharya *et al.*, 2006:1034; Aubert *et al.*, 2003:891). In this regard, HRV and HRR have been established as important indicators of ANS status (Esco *et al*., 2016:440; Plews *et al*., 2013:779; Borresen & Lambert, 2008:635,640). HRV is the result of ANS regulation of cardiac activity and is a measure of beat-to-beat variation and the time duration between each completed cardiac cycle (Tarvainen *et al*., 2014:210; Acharya *et al.*, 2006:1032; Pumprla *et al.*, 2002:3). On the other hand HRR is the rate at which heart rate (HR) decreases (or the time taken for HR to recover) after moderate to high intensity exercise (Borresen & Lambert, 2008:640). HRV and HRR are also considered to be indicators of performance in a variety of sports such as basketball, cycling and endurance running (Fronso *et al.*, 2012; Buchheit *et al.*, 2010; Lamberts *et al.*, 2010). However, the use of HRV and HRR in the badminton environment, and more importantly, the possible relationships of HRV and HRR to badminton performance, have not yet been investigated. Proof that these measurements are related to badminton match performance may provide researchers and sport practitioners with an easy measurement tool to establish badminton success, especially as it relates to the physical demands that are placed on badminton players during match play.

Research with regard to the characteristics of badminton suggests that total match duration is approximately 32.5 minutes, with individual sets lasting between 13.4 and 18.6 minutes and rallies for 8.1 seconds on average (Chen & Chen, 2008:40; Tu, 2007:139). Studies also concluded that badminton match play show a work-to-rest ratio of 1:2 for men's single matches (Phomsoupha & Laffaye, 2015:447; Chen & Chen, 2008:35; Tu, 2007:140). Because of these characteristics badminton is described as a fast-paced, vigorously intense and highly reactive sport. Elite male players obtain an average absolute HR of 169 ± 9 bpm corresponding to a relative average HR of 89% of maximum HR, as well as up to 73% of their maximal oxygen uptake during match play (Andersen *et al.*, 2007:127; Faude *et al*., 2007:484; Lees, 2003:710).

Depending on the duration and scope of the tournament, badminton players may compete in three or more matches per day during team-based tournaments or as many as four singles and doubles matches over a few days during individual events (Laffaye *et al*., 2015:585; Badminton World Federation, 2014; Garrido-Esquivel *et al*., 2011:258). Therefore, badminton is considered a physiologically demanding sport that requires a very high fitness level for players to be able to effectively and successfully play several matches in a short period of time during a tournament (Phomsoupha & Laffaye, 2015:474; Faude *et al*., 2007:482). These match play demands may lead to symptoms of neuromuscular fatigue as matches progress (Girard & Millet, 2009:163). Players will therefore need to fully recover between matches in order to maintain muscle power output and a high cognitive ability during match play (Girard & Millet, 2009:168). Accumulated neuromuscular fatigue will negatively affect players' abilities to execute shots with optimal force and accuracy and will also lead to less reactive court movements and poor tactical choices during matches (Phomsoupha & Laffaye, 2015:485). High aerobic fitness levels will enable badminton players to meet the cardiovascular and metabolic requirements of match play and prevent neuromuscular fatigue (Girard & Millet, 2009:170; Faude *et al*., 2007:485).

However, significant relationships exist between cardiac autonomic indices (such as HRV and HRR) and aerobic fitness (Esco *et al*., 2016:440; Makivic *et al*., 2013:114; Daanen *et al*., 2012:258). Consistently higher HRV values are observed in endurance trained athletes compared to untrained individuals, and research suggests that vigorous training is required to induce HRV changes (Bellenger *et al*., 2016:20; Achten & Jeukendrup, 2003:523). Well trained endurance athletes also exhibit a faster than normal HRR after maximal exhaustive exercise compared to sedentary individuals (Daanen *et al*., 2012:259; Seiler *et al.*, 2007:1372; Lucia *et al.*, 2000:1781). Also, positive changes in both HRR and HRV indices have been associated with improvements in neuromuscular-related performance parameters such as repeated sprint ability in handball players (Buchheit *et al*., 2008:368). HRV expressed as high frequency power (HF) accounted for 15% of the variance in basketball match performance in seven amateur players (Fronso *et al.*, 2012:S70). Research also showed that match play led to significant increases in low and high frequency powers expressed as a ratio (LF:HF ratio) due to a significant decrease in parasympathetic stimulation (Bricout *et al.*, 2010:115), and that highly trained athletes' ANS are more responsive and recover faster after exercise compared to less trained athletes (Seiler *et al.*, 2007:1371). Although both HRV and HRR are considered to be indicators of ANS function, various researchers found no relationship between HRV and HRR (Oliveira *et al*., 2013:147; Lee & Mendoza, 2012:2761; Bosquet *et al*., 2007:367; Javorka *et al*., 2002:996). These studies suggest that the dissociation between HRR and resting HRV is proof that these variables are independently linked to the ANS (Esco *et al*., 2011:2304; Esco *et al*., 2010:36; Bosquet *et al*., 2007: 368). Ultimately, the analyses of both HRV and HRR allow researchers to quantify and gain insight into the status of the ANS as well as the body's reaction to physical and mental stress, the level of aerobic fitness and neuromuscular fatigue (Makivic *et al.*, 2013:110; Buchheit *et al.*, 2012:712,720). Therefore, due to the fact that badminton requires a complex combination of both cardiorespiratory and neuromuscular fitness, the potential of HRR and HRV to predict changes in aerobic fitness, neuromuscular performance and most importantly match performance cannot be ignored (Buchheit, 2014:88).

However, despite the potential of HRV and HRR to serve as indicators of ANS activity, aerobic fitness, neuromuscular fatigue and sport performance, these indices seem to be influenced by various factors. For example, the square root of the mean squared differences between successive R-R intervals (RMSSD) and standard deviation of R-R intervals (SDNN) were significantly higher in a group who ingested 500 ml water after a 20-minute sub-maximal cycle test compared to a group which ingested no water, which suggests that water intake has a positive effect on post-exercise HRV (Oliveira *et al.*, 2011:102). Vaara *et al*. (2009:442) concluded that sleep quantity and quality influence HRV by observing that sleep deprivation caused a significant increase in vagal activity (HF and LF power) and a significant decrease in heart rate over a period of 60 hours in healthy physically fit adults. A psychological mood related factor, such as anxiety may also influence HRV by significantly decreasing RMSSD, LF:HF ratio and low frequency normalized power (LFnu) during competition periods when higher pre-competitive anxiety levels are experienced (Blasquez & Ortis, 2009:534). From last-mentioned research findings it would seem that sport participants' hydration status, sleep quality and quantity as well as pre-competitive anxiety levels all have a significant influence on HRV. These factors may also affect participants' HRR due to the fact that it is an independent measure of the ANS (Lee & Mendoza, 2012:2761).

Cornforth *et al*. (2015) investigated the relationship between HRV and Global Positioning System (GPS)-related variables namely distance walked and jogged during a match, player load and total distance covered during a match by Australian football players. They found that frequency-domain (very low frequency [VLF] components, low frequency [LF] components, high frequency [HF] components, and LF/HF ratio), time-domain (mean R-R intervals, and the proportion of R-R intervals that exceed 50 ms [pNN50]) and non-linear HRV indices (standard descriptor 1 [SD1] and standard descriptor 2 [SD2]) were significantly related to GPS-related variables (Cornforth *et al*., 2015:86). These results would suggest that HRV-related variables may also be significantly influenced by GPS-related variables. Therefore, it is crucial to correct for or control these factors when establishing the value of HRV and HRR for use in a sport setting. However, no HRV and HRR related studies have thus far considered all the GPS-variables in their testing protocols during actual competitions. Furthermore, although various researchers have analysed the badminton match characteristics of Asian and European players, no studies have thus far investigated the match analysis characteristics along with HRV and HRR of male, elite, African, singles badminton players.

It is in light of this background and shortcomings with regard to existing research that the following research questions are posed: **Firstly**, can pre-match, in-match, resting and post-match HRV as well as post-match and in-match (as measured during breaks between sets) HRR serve as significant predictors ($p < 0.05$) of male, elite, African, singles badminton players' performance levels? **Secondly**, are HRV and HRR specifically related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players? **Thirdly**, what is the relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players?

Answers to these questions will provide coaches and sport scientists with information regarding the usefulness of HRV and HRR as indicators of badminton performance as well as the factors that may significantly influence these variables during badminton tournament play. In addition, positive results concerning the use of HRV and HRR as indicators of badminton match performance may provide coaches and players with an incentive to integrate HRV and HRR into their training regimes. Lastly, the study will provide sports practitioners with a better understanding of the match loads of male, elite, African, singles badminton players as well as the link between variables that are used to determine the internal (HRV and HRR) and external match loads (GPS-related variables) of players, respectively.

1.2 OBJECTIVES

The main objectives of this study are to determine:

- If pre-match, in-match, resting and post-match HRV as well as post-match and in-match (as measured during breaks between sets) HRR can serve as significant predictors ($p < 0.05$) of male, elite, African, singles badminton players' performance levels.
- Whether HRV and HRR are specifically related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players.
- The relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players.

1.3 HYPOTHESES

The following hypotheses are formulated for this study:

- Pre-match, in-match, resting and post-match HRV as well as post-match and in-match rest HRR will serve as significant predictors of male, elite, African, singles badminton players' performance levels.
- Significant associations exist between HRV, HRR and subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players.
- A significant positive relationship will exist between GPS-determined indicators of external match loads and HR-determined indicators of internal match loads.

1.4 STRUCTURE OF THE THESIS

The thesis will be submitted in article format as approved by the Senate of the North-West University and will be structured as follows:

Chapter 1: Problem statement, objectives and hypotheses. A reference list is provided at the end of the chapter in accordance with the guidelines of the North-West University (NWU-Harvard style).

Chapter 2: Literature review: Heart rate variability and recovery as indicators of performance in sport and exercise. A reference list is provided at the end of the chapter in accordance with the guidelines of the North-West University (NWU-Harvard style).

Chapter 3: Article 1 – Heart rate variability and heart rate recovery as predictors of elite, African, male badminton players' performance levels. This article was submitted to the *Journal of Strength and Conditioning Research*. This chapter and the reference list at the end of the chapter were compiled in accordance with the guidelines of the last-mentioned journal (see Appendix I). Although not in accordance with guidelines of the journal, tables were included in the text to make the article easier to read and understand. Furthermore, the margins of the article were set at 2.5 cm left, 2 cm right, 2 cm top and 2 cm bottom for the rest) as to conform to the layout of the rest of the thesis.

Chapter 4: Article 2 – Relationship between autonomic markers of heart rate and subjective indicators of recovery status in male, elite badminton players. This article was accepted for publication by the *Journal of Sports Science and Medicine*. This chapter and the reference list at the end of the chapter were compiled in accordance with the guidelines of the last-mentioned journal (see Appendix L). Although not in accordance with the guidelines of the journal, tables were included in the text to make the article easier to read and understand. Furthermore, the margins of the article were set at 2.5 cm left, 2 cm right, 2 cm top and 2 cm bottom for the rest) as to conform to the layout of the rest of the thesis.

Chapter 5: Article 3 – Relationship between heart rate, heart rate variability, heart rate recovery and global positioning system determined match characteristics of male, elite, African badminton players. This article was accepted for publication by the *International Journal of Performance Analysis*. This chapter and the reference list at the end of the chapter were compiled in accordance with the guidelines of the last-mentioned journal (see Appendix O). Although not in accordance with the guidelines of the journal, the margins of the article were set at 2.5 cm left, 2 cm right, 2 cm top and 2 cm bottom for the rest) as to conform to the layout of the rest of the thesis.

Chapter 6: Summary, conclusions, limitations and recommendations of the study.

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CHAPTER 2

LITERATURE REVIEW

HEART RATE VARIABILITY AND RECOVERY AS INDICATORS OF PERFORMANCE IN SPORT AND EXERCISE

2.1 INTRODUCTION

The popularity of monitoring autonomic nervous system (ANS) function through heart rate variability (HRV) and heart rate recovery (HRR) is growing among the sport and exercise science community (Dong, 2016:1535; Plews *et al*., 2014:783). Moreover, HRV seems to be favoured as a preferred measurement and prognostic tool to assess ANS function (Makivic *et al*., 2013:105). HRV is the result of ANS regulation of cardiac activity and is a measure of beat-to-beat variation and the time duration between each completed cardiac cycle (Tarvainen *et al*., 2014:210; Armstrong *et al*., 2012:501; Karapetian e*t al*., 2008:652). HRR is a measure that researchers and practitioners mostly use to evaluate ANS reactivation after exercise and can be defined as the rate at which heart rate (HR) decreases or time taken to recover after moderate to high intensity exercise (Lee & Mendoza, 2012:2757; Borresen & Lambert, 2008:640). However, researchers recommend that HRR and HRV are used in tandem to accurately monitor and assess ANS function (Lee & Mendoza, 2012:2765), as each appear to be independently related to cardiac-autonomic modulation (Esco *et al*., 2010:36). Both HRV and HRR can therefore serve as non-invasive tools for quantifying ANS regulation before, during or after participation in sport and exercise (Makivic *et al*., 2013:110, 114; Lamberts *et al*., 2010:455).

In view that the ANS is responsible for regulating an array of bodily visceral functions (such as respiration rate, HR and thermoregulation to name a few) that contribute significantly to sport and exercise performance (McArdle *et al*., 2013:325), optimal functioning of the ANS during training is key to optimal performance (Krassioukov & West, 2014:S59, S62-S63). ANS indices (such as HRV and HRR) can be utilized as indicators of mental and physical stress caused by rigorous exercise and training as well as sport participation (Buchheit, 2014:77; Durantin *et al*., 2014:21; Makivic *et al*., 2013:124). However, despite the potential of ANS indices to serve as valid diagnostic tools in a sport and exercise setting, the value of using these indices in some sports, such as racquet sports has not been investigated yet.

In light of the lack of ANS research in some sports such as racquet sports, the aims of this literature review were to:

- **Firstly**, discuss the physiological properties of the ANS as well as the physiological mechanisms that underlie HRV and HRR as measures of ANS function.
- **Secondly**, discuss the procurement, quantification and interpretation procedures of HRV and HRR in sport and exercise settings.
- **Thirdly**, reveal relationships between HRV, HRR and sport as well as exercise performance.

- **Fourthly**, highlight possible influences of sleep quality and quantity, muscle soreness, hydration status and pre-competition anxiety on HRV and HRR as measures of ANS function.
- **Fifthly,** discuss the match characteristics of elite, male, singles badminton players as well as the possible use and application of the global position system units (GPS) in indoor sports.
- **Finally**, indicate limitations of using HRV and HRR as measures of ANS function in sport and exercise settings.

The literature review primarily targeted studies that focussed on HRV and HRR and that made use of athletes or physically fit non-athletes as study participants with no exclusion criteria set for age or population size. However, only studies conducted in sport and exercise related settings were included, with studies that investigated HRV and HRR in a clinical setting, excluded. In the majority of cases the review focussed on the most recent studies of HRV and HRR (mostly from 2005 to 2016), although older seminal studies were used to describe the methodology of HRV and HRR measurements (one pivotal study from 1996). The following search engines and databases were used to compile the literature study: Google Scholar, Medline, Science Direct and Sport Discus. These last-mentioned search engines and databases allowed the authors to consult an array of exercise and physiology textbooks, journals and websites. The named sources were used to search for the following keywords: heart rate variability (HRV), heart rate recovery (HRR), autonomic nervous system (ANS), Polar HR monitors, R-R intervals, competition, neuromuscular fatigue, aerobic fitness, mood states, hydration status, muscle soreness, sleep quality and quantity.

2.2 AUTONOMIC NERVOUS SYSTEM AND REGULATION OF HEART RATE VARIABILITY AND HEART RATE RECOVERY

As mentioned before, sport performance is influenced, among other factors, by optimal functioning of the ANS (Chalencon *et al*., 2015:595; Cipryan *et al*., 2007:17). The ANS can be described as the part of the central nervous system that regulates an array of visceral bodily functions such as sweating, body temperature, bladder emptying, blood pressure, gastrointestinal motility, pupil dilation or constriction, basal metabolism and many more (McArdle *et al*., 2013:326-327). However, the cardiovascular system which plays a significant role in the attainment of sport performance is also regulated by the ANS (Makivic *et al*., 2013:108). In order to understand the importance of the ANS in the attainment of sport performance, and the integral part that HRV and HRR play as measurement tools of ANS activity, the physiological properties of the ANS must first be explained.

2.2.1 Physiological properties of the ANS

The ANS originates from the cranial and peripheral nerves where it forms part of the peripheral nervous system (Rhoades & Bell, 2013:113, 115). The peripheral nervous system consists of the somatic and autonomic nervous systems with only the latter that will be further discussed (Hall, 2015:773). The ANS is activated by centres located in the spinal cord, brainstem and hypothalamus which transmit signals in order to influence autonomic control (McArdle *et al*., 2013:327, 328). Activation can also be induced by visceral reflexes which originate from sensory signals inside visceral organs that are relayed back to the autonomic ganglia located in the spinal cord, brainstem and hypothalamus (Rhoades & Bell, 2013:117). Efferent autonomic signals can be relayed to the target organs by means of two major subdivisions (depending on the nature of the signal) namely the sympathetic (SNS) and the parasympathetic (PNS) nervous systems (Hall, 2015:773; McArdle *et al*., 2013:328). The general organization of the ANS is denoted in Figure 2.1.

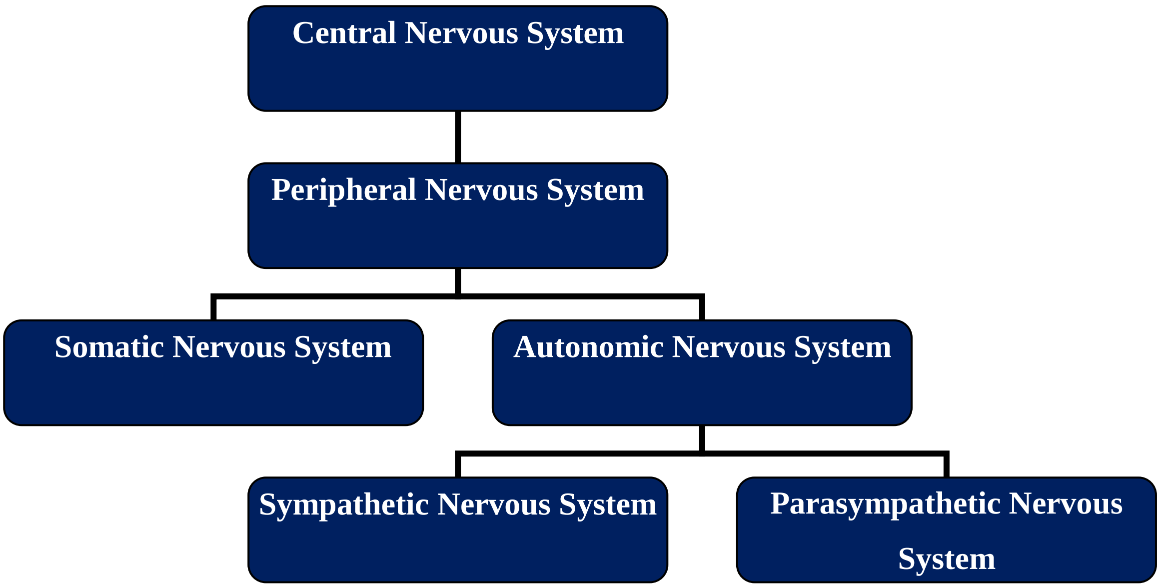

Figure 2.1: General organization of the ANS (Hall, 2015:773-775)

The SNS and PNS share an antagonistic relationship in regulating visceral bodily functions and work in tandem to ensure that homeostasis is maintained (Barrett *et al*., 2010:262; Shier *et al*., 2007:427). In this regard the PNS is often described as the "rest and digest" or "housekeeping" part of the nervous system and is predominantly active during periods of sleep and rest (Kenney *et al*., 2011:72; Barrett *et al*., 2010:261; Widmaeir *et al*., 2006:200). The SNS is seen as the "flight or fight" part of the nervous system, which is predominately active during activities that cause physiological and psychological stress such as exercise (McArdle *et al*., 2013:328; Widmaeir *et al*., 2006:200). The main differences in characteristics and functions of the PNS and SNS are summarised in Table 2.1.

From Table 2.1 it is evident that the SNS and PNS have to constantly balance and complement each other in order to regulate visceral functions throughout the day and night (Rhoades & Bell, 2013:113; Barrett *et al*., 2010:263). As mentioned before, one of the essential functions of the ANS is regulation of the cardiovascular system, which is the main focus of this study. However, before the function of the ANS in regulating the heart is discussed, the reader must understand that HR can also be regulated in the absence of the ANS. This is called intrinsic regulation and is made possible by the sinoatrial node (SA node) which is located within the posterior wall of the right atrium (McArdle *et al*., 2013:325). The SA node acts as a "pacemaker" by spontaneously polarizing and depolarizing at a rhythm of about 100 beats per minute (bpm) (McArdle *et al*., 2013:328). When the SA node is depolarized it transmits an impulse to the atria, which causes the atria to contract. The impulse then further travels through the heart and reaches the atrioventricular node (AV node), which in turn relays the same impulse to the atrioventricular bundle (AV bundle). The impulse then travels through a network of fibres called the fibres of Purkinje (which penetrates the ventricles) and ultimately results in contraction of both ventricles (Hall, 2015:781). It takes only 0.1 seconds from depolarization of the SA node to the final contraction of ventricles (McArdle *et al*., 2013:329). The path of an impulse in a normal and healthy adult is illustrated in Figure 2.2.

Figure 2.2: Path of an impulse that travels from the SA node to ventricles (McArdle *et al*., 2013:330)

Table 2.1: Main differences in characteristics and functions of the PNS and SNS (Hall, 2015:778; McArdle *et al*., 2013:332; Rhoades & Bell, 2013:115; Barrett *et al*., 2010:267; Wilmore *et al*., 2008:90; Shier *et al*., 2007:434; Widmaeir *et al*., 2006:200; Aubert *et al*., 2003:911)

Characteristics and functions	Sympathetic Nervous system	Parasympathetic Nervous System
Anatomical origin in central nervous system	Between spinal cord segments T1 and L2	At cranial nerves III, VII, IX and X as well as sacral nerves
Neurotransmitters used in pathways	Epinephrine and Norepinephrine	Acetylcholine and Nitric Oxide
Effects on target organs	**"Fight or Flight" response**	**"Rest and Digest" response**
Heart muscle	Increases the rate and the force of contractions	Decreases the rate and the force of contractions in heart muscle
Coronary blood vessels	Causes vasodilatation	Causes vasoconstriction
Lungs	Causes bronchodilation	Causes bronchoconstriction
Blood vessels	Causes vasoconstriction in the abdominal viscera and skin as well as vasodilatation in the skeletal muscles and heart during exercise	Little effect
Liver	Stimulates liver to release glucose	Has a small influence on glycogen synthesis
Skeletal muscles	Increases muscle contraction strength and increases glycogenesis	No effect
Adipose tissue	Stimulates lipolysis	No effect
Sweat glands	Increases sweating	No effect
Adrenal glands	Stimulates secretion of Epinephrine and Norepinephrine	No effect
Digestive system	Decreases activity of glands and muscles as well as constrict sphincters	Increases peristalses and glandular secretion as well as relax sphincters
Kidneys	Activates the renin-angiotension system and decreases urine production	No effect
Basal metabolism	Increases metabolism up to 100%	No effect
Eyes	Causes dilation of pupils and relaxation of ciliary muscle for far sight	Causes constriction of pupils
Mental activity	Increases mental activity	No effect

In cases where the ANS is activated, HR can be slowed to 30 bpm (from its inherent myocardial rhythm of about 100 bpm) or increased up to 200 bpm (Rhoades & Bell, 2013:114; Barrett *et al*., 2010:267). These changes in HR tempo are caused by neural influences, which originate from the cardiovascular control centre situated in the ventrolateral medulla (Makivic *et al*., 2013:106). Neural signals travel through separate SNS and PNS pathways in order to produce the desired HR (Hall, 2015:780). Stimulation of the SNS has chronotropic (increased SA node depolarization) and inotropic (increased myocardial contractility) effects on the heart through the sympathetic cardio-accelerator nerves that lead to the release of neuro-hormones (epinephrine and norepinephrine) (Kenney *et al*., 2011:74; Shier *et al.*, 2007:432). In contrast, the PNS has a decreasing effect on HR and causes bradycardia through the secretion of acetylcholine, another neurotransmitter (Hall, 2015:781; Shier *et al.*, 2007:432). At the beginning and during low to moderate intensity exercise the HR is accelerated by parasympathetic inhibition and as exercise intensity increases HR is further accelerated by sympathetic stimulation (McArdle *et al*., 2013:330).

From the above mentioned discussion it is clear that the ANS fulfils a primary role in maintaining homeostasis of the cardiovascular system. Therefore, the ANS plays a crucial role in determining cardiovascular responses of athletes to acute exercise. In addition, the ANS is responsible for increasing cardiovascular parameters such as stroke volume, HR and the arterial-mixed venous oxygen difference (of which all three plays a significant role in determining maximal oxygen uptake) so that the growing metabolic demands of exercise can be met (Fu & Levine, 2013:147). The speed and intensity with which the ANS causes cardiovascular changes during exercise, makes it a very effective control centre for regulation of the cardiovascular system (Hall, 2015:773). For example, the ANS has the ability to increase HR to double its normal rate within 3-5 seconds and increase arterial pressure to double its normal value within 10-15 seconds (Hall, 2015:774).

It is against this background that the importance of monitoring the ANS (through HRV and HRR) before, during and after exercise in order to evaluate its effectiveness cannot be ignored. Therefore, the physiological mechanisms that underlie HRV and HRR as non-invasive measures of ANS function will be discussed in the following section.

2.2.2 Non-invasive measures of ANS activity

As mentioned before, HRV and HRR are valuable, non-invasive measures employed by researchers and practitioners to examine autonomic fluctuations under different physiological conditions in sport and exercise (Makivic *et al*., 2013:107; Aubert *et al.* 2003:900). The following section discusses the physiological mechanisms that underlie HRV and HRR as quantifiable measures of ANS function.

2.2.2.1 Heart rate variability (HRV)

Changes in the balance between the SNS and PNS, cause fluctuations in the time period that elapses between heart beats (successful cardiac cycles) or two peaks of a QRS complex which is called a R-R interval (expressed in milliseconds) (see Figure 2.3) (Makivic *et al*., 2013:106). These fluctuations in time duration of R-R intervals form the basis of all HRV calculations (Plews *et al*., 2013:775). Low variations in R-R intervals or a shorter time duration of R-R intervals is usually an indication of sympathetic predominance (which occurs when parasympathetic activity is suppressed) (Dong, 2016:1532; Aubert *et al*., 2003:896). On the other hand, high variations in R-R intervals or a longer time duration of R-R intervals is usually an indication of parasympathetic predominance (which occurs when parasympathetic activity is not suppressed) (Tarvainen *et al*., 2014:210). Therefore, the conversion of whole R-R interval data sets to time-domain, frequency-domain and non-linear variables, which will be explained in the next section, allows researchers to evaluate the current status of cardiac-ANS control (Buchheit, 2014:4; Tarvainen *et al*., 2014:219). Figure 2.3 is an example of different R-R intervals between two peaks of a QRS complex.

Figure 2.3: Example of R-R intervals as it appears on an electro-cardio graph (ECG) strip (Makivic *et al.,* 2013:106)

2.2.2.2 Heart rate recovery (HRR)

Heart rate recovery is traditionally seen as the decline in an elevated HR after intense exercise within a certain timeframe and is expressed in beats per minute (bpm) or percentage metrics (Boullosa *et al*., 2013:402; Daanen *et al.*, 2012:257). At the onset of exercise, parasympathetic activity decreases after which sympathetic activity increases to meet the metabolic demands of exercise (Daanen *et al*., 2012:251). However, when exercise is terminated reactivation of the PNS is triggered which causes the HR to decrease and recover to pre-exercise levels (Oliveira *et al*., 2013:146; Javorka *et al*., 2002:998). Therefore, the tempo of HRR directly after exercise is mainly dependent on the speed of parasympathetic reactivation (Daanen *et al*., 2012:256). For this reason the last-mentioned mechanism forms the base for explaining changes in HRR values.

2.3 QUANTIFICATION AND INTERPRETATION OF HRV AND HRR IN SPORT AND EXERCISE SETTINGS

The previous section explained how HRV and HRR are physiologically tied to the ANS. In this section the quantification and interpretation of HRV and HRR will be elucidated. Different protocols and parameters that researchers use to quantify and interpret HRV and HRR in sport and exercise will also be discussed as well as the methodologies that researchers utilize to determine HRV and HRR in a sport and exercise setting. Information with regard to the last-mentioned themes will then be used to make recommendations to increase the accuracy and reproducibility of HRV and HRR measurements. The recommendations will aimed at practitioners who want to use it in a sport and exercise setting.

2.3.1 The quantification of HRV

Currently the most popular devices used for obtaining R-R intervals, in order to calculate HRV, is ambulatory ECGs, wrist HR monitors (such as Polar and Suunto) and smartphone applications (BioForce™ and Ithlete™) (Bisschoff, 2014:107; Flatt & Esco, 2013:90; Parrado *et al*., 2010:341; Porto and Junqueira, 2009:49). The advantages and disadvantages as well as the preferred use for each of these devices are presented in Table 2.2.

Table 2.2: Advantages and disadvantages as well as the preferred use of popular HRV devices (Boos *et al*., 2016:5; Flatt & Esco, 2016:783 Bisschoff, 2014:107; Flatt & Esco, 2015:998; Flatt & Esco, 2013:90; Heathers, 2013:302; Wallen *et al*., 2012:1162-1163; Jamieson, 2011; Corrado *et al*., 2010:257; Parrado *et al*., 2010:341; Porto and Junqueira, 2009:49; Vanderlei *et al*., 2008:855; Berkoff *et al*., 2007:231; Gamelin *et al*., 2007:568; Gamelin *et al*., 2006:887, 891; Achten & Jeukendrup, 2003:524; Radespiel-Troger *et al.*, 2003:102)

	Stationary ECG	**Wrist HR monitors**	**Smartphone applications**
Advantages	• Very accurate • Validity supported by scientific research	• Very accurate • Validity supported by scientific research • Can be used in almost any condition within a sport and exercise setting • Easy to operate • Quick to set up • Can be used in competitions or matches	• Affordable • Intended for non-scientific use • Easy to set-up • Easy to operate and interpret • Validity is supported by scientific research
Disadvantages	• Time consuming to setup • Takes a high level of expertise to operate • Participants cannot engage in contact sports • Participants cannot be monitored in water	• Can become separated from participants and recordings will then be lost • Most require extrapolation of HRV parameters to specialized software for analysis	• Can only be used in resting conditions
Preferred application	Used in situations where: • Participants need to be monitored consistently • In clinical evaluations of ANS conducted in standardised enviroments such as laboratories	Used in situations where participants are: • Mobile during sport and exercise or • Stationary during sport and exercise	Used in situations where participants are: • Resting or fully recovered from an activity or • In a seated or standing position

From Table 2.2 it is clear that devices have different applications and must be used according to each of these guidelines. Wrist HR monitors (like Polar and Suunto) are more versatile in sport and exercise settings as a result of their practical and non-invasive qualities (Porto and Junqueira, 2009:50). However, ECGs are still favoured by exercise physiologists for the measurement of HRV because of their accuracy, reliability and validity (Wallen *et al*., 2012:1162-1163). Smartphone applications for the measurement of HRV have become popular over the last few years due to their user-friendly interface and the immediate availability of HRV values (Bisschoff, 2014:107; Flatt & Esco, 2013:90; Jamieson, 2011). These applications show promise for use by sport practitioners who want to obtain accurate HRV values field based settings.

Processes by which most of the devices or applications obtain and use R-R intervals to determine HRV are explained in the following section.

2.3.1.1 Step 1: R-R intervals obtained by use of an apparatus

First, a HR monitor is fitted to a participant's trunk ensuring adequate contact with the skin according to the manufacturer's guidelines (Gamelin *et al*., 2006:891). During recording of R-R intervals it is crucial that the measurement protocol is standardised to ensure that every participant's recordings take place under similar conditions (Nunan *et al*., 2009:247; Sandercock *et al*., 2005:243). After the R-R intervals have been recorded, it is exported to a computer for further processing (Aubert *et al*., 2003:913). However, existing measurement protocols employ different body positions, make use of different time durations for recordings, take measurements at different times of the day and require different breathing frequencies, which cause confusion among researchers who want to standardise the HRV measurement protocol (Makivic *et al*., 2013:126; Saboul *et al*., 2013:540; Aubert *et al*., 2003:914). Despite the debate that surrounds HRV measurement protocols researchers have successfully used these protocols to obtain accurate and repeatable R-R intervals (Makivic *et al*., 2013:126-127). Nonetheless, there are certain physiological factors that diminish the accuracy and repeatability of R-R interval recordings which will be discussed later.

2.3.1.2 Step 2: Raw R-R interval data is normalised

Before exporting a series of R-R intervals to HRV analysis software, data sets are first normalised by removing artefacts which may include ectopic beats, arrhythmic events, missing data, "noise" effects induced by mobile phones and electromagnetic fields (Kaufmann *et al*., 2011:1164; Bricout *et al*., 2010:113; Aubert *et al*., 2003:893). Normalising can either be done manually by visually inspecting each individual data set for artefacts and removing it, or, it can be done automatically through HRV analysis software (Tarvainen *et al*., 2014:213; Kaufmann *et al*., 2011:1167). HRV analysis software automatically removes artefacts and normalises the data set with the aid of filtering (eliminating spurious QRS peaks) and interpolation algorithms (replacing missed beats with the mean of the preceding and following beats) (Tarvainen *et al*., 2014:213; Kaufmann *et al*., 2011:1165; Aubert *et al*., 2003:894). However, these algorithms are specific to each HRV analysis program and are frequently customized by users which complicate the repeatability and comparability of HRV measurements (Nunan *et al*., 2010:1415). Normalising of data should therefore also be standardized to ensure accuracy and repeatability of measurements (Nunan *et al*., 2010:1415; Sandercock *et al*., 2005:245).

2.3.1.3 Step 3: Export and analysis of normalised R-R interval set

After normalising the R-R interval data set it is exported to a Matlab based, HRV analysis program (such as Kubios) where HRV parameters are calculated (Tarvainen *et al*., 2014:214). HRV derived parameters can be divided into time-, frequency- and non-linear-based categories with each category portraying ANS activity from a different mathematical point of view (Archarya *et al*., 2006:1037-1038; Aubert *et al*., 2003:893-896).

a) Time-domain based HRV parameters

Time-domain based parameters are computed by making use of simple and basic statistics such as mean values, standard deviations and coefficients of variation, mitigating the need for dedicated HRV analysis software (Tarvainen *et al*., 2014:211). Well-known HRV parameters that can be extracted from these computations include:

- The mean of R-R intervals (mean R-R). Mean R-R is a reflection of the changes in R-R interval time and also represents overall cardiac variability (Makivic *et al.*, 2013:110).
- The standard deviation of R-R intervals (SDNN). SDNN represents total variability of cardiac autonomic activity and is significantly influenced by the duration of measurements. Therefore, in view of the influence of measurement duration, SDNN components that are compared should be of the same measurement duration (Makivic *et al.* 2013:105; Aubert *et al.* 2003:894). SDNN is also very sensitive to factors that influence long-term cardiac variability (such as circadian rhythms) (Sztajzel, 2004:516).
- The squared root of the mean squared differences between successive R-R intervals (RMSSD). RMSSD is representative of parasympathetic activity due to its ability to reflect

short-term alterations in autonomic tone that are predominantly vagally mediated (Sztajzel, 2004:516).

- The percentage of successive R-R intervals that differs more than 50 milliseconds from one another over an entire measurement (pNN50). pNN50 is similar to RMSSD and also represents the same autonomic changes as RMSSD, however pNN50 is often dismissed due to the better statistical properties of RMSSD (Aubert *et al*., 2003:895; Task force, 1996:357).

The abovementioned time-domain based HRV parameters are summarised in Table 2.3.

Table 2.3: Summary of the most frequently used time domain HRV parameters in sport and exercise settings (Buchheit, 2014:80; Tarvainen *et al*., 2014:212; Makivic *et al.*, 2013:108; Plews *et al*., 2013:775; Bertsch *et al*., 2012:679; Tarvainen & Niskanen 2012:20; Bosquet *et al*., 2007:365; Archarya *et al*., 2006:1036-1038; Aubert *et al.*, 2003:892)

HRV parameter	Description	Link to ANS
Mean R-R (ms)	Mean of R-R intervals	R-R changes correspond to changes in HR and represents overall cardiac variability
SDNN (ms)	Standard deviation of R-R intervals	Reflects global cardiac variability
RMSSD (ms)	Squared root of the mean squared differences between successive R-R intervals	Represents PNS activity
pNN50 (%)	Percentage of successive R-R intervals that differ more than 50 milliseconds from one another over an entire measurement	Represents PNS activity

b) *Frequency-domain based HRV parameters*

Frequency-domain based parameters are more complex and need to be computed by performing a spectral analysis on the R-R interval data set (Buchheit, 2014:81; Archarya *et al*., 2006:1037-1038). Spectral analysis converts the R-R interval data set to a sinusoidal form of itself (Aubert *et al*., 2003:893-896). In this form, the sinusoidal components of the R-R data set can be plotted as a function of its frequency by performing a fast Fourier transform (FFT) or autoregressive modelling (AR) (Tarvainen *et al*., 2014:212). Both techniques allow that the new R-R interval set can be divided into three separate widely-used frequency categories namely a very low frequency (VLF) (at frequencies below 0.04 Hz), a low frequency (LF) (at frequencies of between 0.04-0.15 Hz) and a high frequency (HF) category (at frequencies of 0.15 Hz and higher) (Tarvainen & Niskanen, 2012:20). From this the frequency components can be measured in the form of absolute powers (expressed as ms^2), relative powers (expressed as percentage) and normalised power (expressed as normalised units) (Tarvainen & Niskanen, 2012:20). From a physiological point of view, HF components of the HRV signal are mediated by the PNS, thus representing PNS activity (Makivic *et al*., 2013:107), whereas VLF and LF components are mediated by the SNS, thus representing SNS activity (Reyes del Paso *et al*., 2013:483). LF is also sometimes considered to reflect both SNS and PNS activation (Diveky *et al*., 2013:65; Martinmaki *et al.*, 2008:546; Lewis *et al.*, 2007:35; Hedelin *et al.*, 2001:1397). The ratio between HF and LF is used to quantify and provide an accurate index of sympathovagal balance (Reyes del Paso *et al*., 2013:483; Lewis *et al.*, 2007:35; Lopes & White, 2006:41). In this regard Aubert *et al.* (2003:901) and Lewis *et al.* (2007:35) reported that LF/HF ratio increased during low intensity exercises which may be an indication of parasympathetic stimuli withdrawal and a simultaneous enhancement of sympathetic stimuli. The total power of entire spectral analysis (TP) is occasionally also used to assess overall variability of R-R intervals (Cipryan *et al*., 2007:18; Task force, 1996:360). These frequency domain parameters are summarised in Table 2.4.

c) Non-linear based HRV parameters

Non-linear based parameters require more powerful computing and make use of non-linear methods such as the Poincare plot to fully capture the chaotic nature of beat-to-beat variability (Tarvainen *et al*., 2014:212). The Poincare plot indicates the non-linear dynamics of R-R intervals as well as the fluctuations in R-R intervals (Buchheit, 2014:4; Aubert *et al*., 2003:898). For this technique each R-R interval is plotted as a function of the previous R-R interval (Tarvainen *et al*., 2014:212). The plot can then be analysed quantitatively by calculating the standard deviations of correlations between consecutive R-R intervals (Tarvainen & Niskanen, 2012:14). These standard deviations are denoted as SD1 (considered to measure short-term cardiac variability) and SD2 (considered to measure long-term cardiac variability) (Makivic *et al*., 2013:107). The increase in cardiac variability represents SNS predominance with the decrease in cardiac variability representing PNS predominance (Aubert *et al*., 2003:898). It has also been suggested that SD1 and SD2 represents PNS and SNS activity respectively and this has led to the ratio between SD1 and SD2 being used (similar to the LF/HF ratio) to evaluate overall ANS status (Garrido-Esquivel *et al*., 2011:260). Although non-linear parameters are not as popular as time- and frequency-domain parameters due to the sensitivity of artefacts, SD1 and SD2 are widely used to aid in the investigation of short- and long-term cardiac variability (Archarya *et al*., 2006:1046). Tarvainen *et al*. (2014:214) also argued that the ANS can only be fully explored if non-linear methods are employed during analyses of R-R intervals. These non-linear parameters are summarised in Table 2.5.

Table 2.4: Summary of the most frequently used frequency-domain HRV parameters in sport and exercise settings (Tarvainen *et al*., 2014:212; Makivic *et al.*, 2013:107; Plews *et al*., 2013:775; Reyes del Paso *et al*., 2013:483; Bertsch *et al*., 2012:679; Tarvainen & Niskanen 2012:20; Bosquet *et al*., 2007:365; Archarya *et al*., 2006:1036-1038; Aubert *et al.*, 2003:892)

HRV parameter	Description	Link to ANS
Peak VLF (Hz)	Peak band frequency of VLF component	Reflects SNS activity
Absolute VLF power (ms^2)	Peak VLF frequency power expressed in ms^2	Reflects SNS activity
Relative VLF power (%)	Peak VLF frequency power expressed as a percentage	Reflects SNS activity
Peak LF (Hz)	Peak band frequency of LF component	Reflects SNS and PNS activity
Absolute LF power (ms^2)	Peak LF frequency power expressed in ms^2	Reflects SNS and PNS activity
Relative LF power (%)	Peak LF frequency power expressed as a percentage	Reflects SNS and PNS activity
Normalised LF power (nu)	Peak LF frequency power expressed in normalised units	Reflects SNS and PNS activity
Peak HF (Hz)	Peak band frequency of HF component	Reflects PNS activity
Absolute HF power (ms^2)	Peak HF frequency power expressed in ms^2	Reflects PNS activity
Relative HF power (%)	Peak HF frequency power expressed as a percentage	Reflects PNS activity
Normalised HF power (nu)	Peak HF frequency power expressed in normalised units	Reflects PNS activity
LF/HF ratio	Ratio and fractional distribution between LF and HF band powers	Index of sympathovagal balance
TP	Total power of entire spectral analysis	Represents overall variability of R-R intervals

Table 2.5: Summary of the most frequently used non-linear HRV parameters in sport and exercise settings (Buchheit, 2014:81; Tarvainen *et al*., 2014:214; Makivic *et al.*, 2013:107; Plews *et al*., 2013:775; Bertsch *et al*., 2012:680; Tarvainen & Niskanen 2012:20; Bosquet *et al*., 2007:365; Archarya *et al*., 2006:1036-1038; Aubert *et al.*, 2003:897)

HRV parameter	Description	Link to ANS
SD1 (ms)	Standard deviation of the correlation between consecutive R-R intervals	Considered to measure short-term, over-all cardiac variability as well as PNS activity
SD2 (ms)	Standard deviation of the correlation between consecutive R-R intervals	Considered to measure long-term, over-all cardiac variability as well as SNS activity
SD1/SD2 Ratio	Ratio of SD1 and SD2 units	Index of sympathovagal balance

All of the discussed HRV parameters are sensitive markers of autonomic balance and possess a natural high day-to-day variation due to environmental factors that cause acute changes to homeostasis (Makivic *et al.*, 2013:110). Sport and exercise settings possess a higher number of environmental factors which can increase the coefficient of variation (CV) of HRV parameters (Buchheit, 2014:83). The variation in HRV values may confuse practitioners who wish to quickly evaluate autonomic changes in more practical situations due to the pre-required knowledge of HRV quantification. To lessen the variation in these HRV parameters some researchers have employed the natural logarithm (Ln) transformations of time domain HRV parameters due to its inherent lower CV (Al Haddad *et al*., 2011:603). One of the more promising HRV parameters that emerged from this approach is the natural logarithm of RMSSD (Ln-RMSSD). Ln-RMSSD is considered to be a more stable measure of parasympathetic activity due to its innate lack of sensitivity to breathing frequency (Plews *et al.*, 2013:775). Therefore, it is recommended that Ln-RMSSD is rather used when measuring HRV over short time periods (60 seconds or less) in sport and exercise settings due to its accuracy and low CV (CV = 12.3%) (Buchheit, 2014:81; Plews *et al.*, 2013:775; Al Haddad *et al*., 2011:602). Frequency domain and non-linear parameters are also occasionally presented in their natural logarithmic forms when their distributions are skewed (Plews *et al.*, 2013:775). However, they are less popular with practitioners in sport and exercise settings due to the need for specialised HRV software to calculate these parameters as opposed to Ln-RMSSD that can be calculated in Microsoft Excel (Plews *et al.*, 2013:775; Sztajzel, 2004:516).

It should be noted that all of the mentioned HRV parameters are valid measures of the ANS that researchers use in sport and exercise settings. Researchers will often use several of these HRV parameters to investigate acute changes in ANS activity such as HRV measured throughout a single day or once-off measurements (Makivic *et al*., 2013:116). However, the use of only one HRV parameter such as Ln-RMSSD is deemed to be adequate in situations where HRV is monitored daily over a period of time to evaluate ANS status (Plews *et al*., 2013:778).

2.3.1.4 Step 4: HRV parameters are calculated and ready for statistical analysis

After HRV parameter values have been determined by HRV analysis software, relevant parameters are selected for further statistical analysis. The whole process of how HRV parameters are derived from R-R intervals is summarised in Figure 2.4.

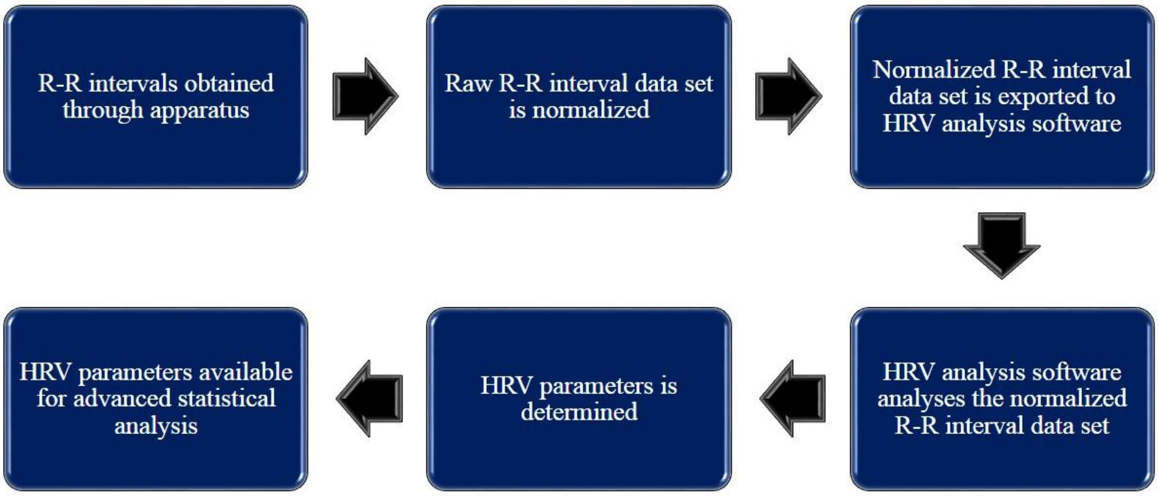

Figure 2.4: Stepwise process for determining HRV parameter values from R-R intervals (Archarya *et al*., 2006; Aubert *et al*., 2003)

2.3.2 Measuring HRV in sport and exercise settings

Although the process of obtaining HRV parameters is clear, a great deal of controversy exists with regard to the frequency at which raw R-R intervals must be measured. Two schools of thought currently exist, namely those who employ single-day HRV measurements and those who employ daily/weekly rolling, average HRV measurements (Plews *et al*., 2013:775). Single-day HRV measurements are usually taken throughout a single isolated day to investigate the acute effects of some or other intervention on the ANS or to collect data in cases where researchers only have a short space of time available for data collection (Plews *et al*., 2012:3730, 3740). On the other hand, HRV can also be measured on a daily basis over a period of one week to calculate daily/weekly rolling, average HRV measurements in order to monitor changes in ANS status (Plews *et al*., 2013:780). Summary of studies that used one of the last-mentioned methods to measure HRV in sport and exercise settings are presented in Tables 2.6 and 2.7.

Table 2.6: Summary of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Esco *et al.* (2016)	The HRV of 9 female collegiate soccer players were measured, daily, for the first and third week during their 11 week off-season conditioning program. HRV was measured to determine whether it could detect eventual changes in $\dot{V}O_{2max}$ achieved before and after conditioning program.	R-R intervals were obtained through the ithlete™ smartphone application and measurements lasted for 55 seconds. Measurements were taken in a supine position every morning after the player had woken up. Players were allowed to breathe normally. HRV values were then converted to weekly mean values (Ln-$RMSSD_{mean}$) and calculated as the coefficient of variation between these Ln-$RMSSD_{mean}$ values (Ln-$RMSSD_{CV}$).	Time domain: • Ln-RMSSDx20 • Ln-$RMSSD_{mean}$ • Ln-$RMSSD_{CV}$	Ln-$RMSSD_{CV}$ of the first week and third week showed non-significant correlations ($r = -0.13$, $p = 0.74$ and $r = 0.57$, $p = 0.11$ respectively) with the change in $\dot{V}O_{2max}$. A significant correlation ($r = 0.90$, $p = 0.002$) was found between the $\dot{V}O_{2max}$ and the difference of Ln-$RMSSD_{CV}$ from the first week to the third week. Results suggest that the initial change in weekly mean HRV during an off-season conditioning program is strongly associated with the eventual adaptation of $\dot{V}O_{2max}$.
Nakamura *et al.* (2016)	40 Elite, male rugby players' HRV was measured twice in one day (to measure intra-day variability) and then only once for the next 4 consecutive days (to measure inter-day variability) during a 1 week training camp.	R-R intervals were measured by Polar RS800CX HR monitors. Measurements were taken in the seated position for 2 minutes. Players were instructed to breathe normally.	Time domain: • Ln-RMSSD	Both intra-day (ICC = 0.96, CV = 3.99%) and inter-day (ICC = 0.90, CV = 7.65%) reported highly reliable measures. Therefore, ultra short-term HRV (specifically Ln-RMSSD) is highly consistent when measuring elite rugby players in intra- and inter-day settings. The study also shows that ultra short-term HRV can be measured in more practical field conditions where time is limited.

R-R intervals	Inter-beat intervals or R to R intervals
Ln-RMSSD	Natural logarithm applied for the squared root of the mean squared differences between successive R to R intervals
Ln-RMSSDx20	Natural logarithm applied for the squared root of the mean squared differences between successive R to R intervals and consequently multiplied by 20
Ln-RMSSDcv	Coefficient of variation values between Ln-RMSSD
Ln-RMSSDmean	Weekly mean value of Ln-RMSSD
CV	Coefficient of variation
$\dot{V}O_{2max}$	Maximal oxygen uptake

Table 2.6 (cont.): Summay of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Flatt and Esco (2014)	1 Experienced male collegiate cross-country runner was measured throughout a competitive season of 8 weeks in order to investigate the possible relationship between running performance (8 km race times) and changes in HRV.	R-R intervals were obtained through the ithlete™ smartphone application and measurements lasted for 55 seconds. Measurements were taken in a seated position every morning after the athlete had woken up. HRV values were then converted to weekly mean values (Ln-$RMSSD_{mean}$) as well as calculated as the coefficient of variation between these Ln-$RMSSD_{mean}$ values (Ln-$RMSSD_{CV}$).	Time domain: • Ln-RMSSDx20 • Ln-$RMSSD_{mean}$ • Ln-$RMSSD_{CV}$	A strong and significant relationship was found between running performance and Ln-$RMSSD_{CV}$ (r = 0.92). In addition, a moderate significant relationship was found between running performance and Ln-$RMSSD_{mean}$ (r = 0.60). Thus, the variation of weekly mean HRV values better reflect running performance compared to weekly mean HRV values. In conclusion, HRV seems to be a promising metric to measure endurance performance.
Tian *et al.* (2013)	34 Elite, female wrestlers' HRV indices were measured weekly in the training period preceding 11 major competitions in order to detect non-functional (NFOR) or functional overreaching (FOR).	R-R intervals were obtained through the Omegawave Sport Technology System. Measurements were taken in the supine position for 2.5 minutes weekly before bedtime.	Time domain: • Mean R-R • SDNN • RMSSD Frequency domain: • LF • HF • LF/HF	Researchers accurately diagnosed FOR and NFOR of wrestlers by using HRV indices (RMSSD, SDNN, LF and HF). Wrestlers that experienced NFOR showed significant decreases ($p < 0.001$) in HRV as well as wrestling performance (as determined by the coach's evaluation). HRV can therefore be used to detect overreaching in athletes.

R-R intervals	Inter-beat intervals or R to R intervals
RMSSD	Squared root of the mean squared differences between successive R to R intervals
Ln-RMSSDx20	Natural logarithm applied for the squared root of the mean squared differences between successive R to R intervals and consequently multiplied by 20
Ln-RMSSDcv	Coefficient of variation values between Ln-RMSSD
Ln-RMSSDmean	Weekly mean value of Ln-RMSSD
SDNN	Standard deviation of R to R intervals
HF	High frequency power
LF	Low frequency power
LF/HF ratio	Low and high frequency expressed as a ratio

Table 2.6 (cont.): Summary of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Boullosa *et al.* (2013)	8 Male, elite, soccer players were measured at the beginning of the pre-season and again 8 weeks later at the end of the pre-season. HRV was measured daily throughout 8 weeks (four times a week). Players were also subjected to the Yo-Yo intermittent recovery test 1 (Yo-Yo IR1) in week 1 and 8 of the pre-season period.	R-R intervals were obtained through Polar RS800 HR monitors. HRV was measured at night for 3 hours (00:00-03:00).	Time domain: • Mean R-R • SDNN • RMSSD Frequency domain: • LF • HF • LF/HF Non-linear: • SD1 • SD2	SDNN and SD2 correlated significantly with Yo-Yo IR1 performance ($r = 0.89$, $p = 0.07$ and $r = 0.92$, $p = 0.03$, respectively) for measurements of week 8. Autonomic parameters were therefore significantly related to performance parameters. Also, HRV indices improved significantly ($p < 0.05$) over the pre-season training period (all of the correlations were higher than 0.8). Results support the use of weekly HRV values (measured at night time) for the evaluation of autonomic adaptations in professional soccer players.
Sartor *et al.* (2013)	6 Male elite gymnasts took part in a 10-week observational study. R-R intervals were taken each day for weeks 1, 3, 5, 7 and 9. Individual training sessions over the 10–week period were assessed through the Borg rating of perceived exertion (RPE) scale and Fosters' index (psycho-physiological status).	R-R intervals were obtained through Polar RS800CX HR monitors. Measurements were taken in a supine position for 6 minutes during paced breathing maintained at 12 breaths per minute.	Time domain: • Mean RR • SDNN Frequency domain: • LF • HF • LF/HF Non-linear: • SD1	HF and LF/HF ratio (both expressed as percentages) correlated significantly ($p < 0.05$) with the training load of the previous training day ($r = 0.232$, $r = -0.279$). Furthermore, R-R intervals correlated significantly ($p < 0.05$) with RPE and the Fosters' index score ($r = -0.384$, $r = -0.227$) HRV could therefore be useful in monitoring training load and psycho-physiological status in elite male gymnasts.

R-R intervals	Inter-beat intervals or R to R intervals
HF	High frequency power
LF	Low frequency power
LF/HF ratio	Low and high frequency expressed as a ratio
SDNN	Standard deviation of R to R intervals
RMSSD	Squared root of the mean squared differences between successive R to R intervals
SD1	Standard descriptor 1
SD2	Standard descriptor 2

Table 2.6 (cont.): Summary of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Fronso *et al.* (2012)	7 Male, amateur basketball players were measured during the play-off phase of their competitive season. The phase lasted 7 weeks and HRV was measured on the mornings of match days. HRV was then compared with match performances.	R-R intervals were obtained through an ECG apparatus (Bioharness using an ADInstruments HRV module). HRV was measured for 10 minutes in a resting supine position.	Frequency domain: • LF • HF • LF/HF	HF accounted for 15% (R^2 = 0.15, $p < 0.05$) of the variance in match performance as statistically calculated by team staff using a procedure from the Italian Basketball Federation. In particular, higher HF values were associated with increased match performances. Thus, HRV expressed as HF was positively related to players' match performances.
Bricout *et al.* (2010)	8 Young, male, football players (age: 14.6 ± 0.2) were tested during a competitive period of 5 months. HRV was measured on training days, competitive match days and after rest days.	R-R intervals were obtained through Polar RS800 HR monitors at night after players had fallen asleep. However, only a 30-minute continuous period during the first slow sleep phase were used to determine HRV values.	Time domain: • Mean R-R • SDNN • pNN50 Frequency domain: • VLF • LF • HF • LF/HF	Mean R-R and pNN50 significantly decreased ($p < 0.05$) after competitive match days compared to rest days. Mean R-R and pNN50 also significantly correlated ($p < 0.001$) with mean HR (r = 0.988; r^2 = 0.976; r = 0.683; r^2 = 0.466). LF significantly increased ($p < 0.05$) whereas HF significantly decreased after match days compared to rest days. Furthermore, LF/HF showed significant increases ($p < 0.05$) after training and match days compared to rest days. Therefore, results suggest that HRV can be used to highlight any neuro-negatative adjustments that players experience due to changes in physical loads.

LF/HF ratio	Low and high frequency expressed as a ratio
HF	High frequency power
LF	Low frequency power
VLF	Very low frequency powers
pNN50	Number of successive R to R interval pairs that differ more than 50 milliseconds
SDNN	Standard deviation of R to R intervals
Mean R-R	Mean of the R to R intervals
HR	Heart rate

Table 2.6 (cont.): Summary of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Buchheit *et al.* (2010a)	14 Male, recreational runners were subjected to an 8 week training intervention. Resting HRV indices were measured daily. Maximal aerobic speed and 10 km running performance were assessed before and after the intervention.	R-R intervals were obtained through Polar S810i HR monitors. HRV measurements were taken in 5 minute sessions at rest while subjects breathed spontaneously.	Time domain: • Ln-RMSSD	Ln-RMSSD significantly correlated ($p < 0.05$) with maximal aerobic speed and 10 km running performance ($r > 0.60$). This study confirmed the interdependency between cardiac autonomic function and aerobic running performance. It was therefore concluded that resting and post exercise HRV may possibly serve as predictors of changes in aerobic running performance.
Buchheit *et al.* (2010b)	36 Young, male, soccer players participated in a 3 week long training camp. During this time players completed a 5 minute sub-maximal run every morning as part of their warm-up. HRV was measured during this time. 2 weeks prior to the camp players were subjected to a graded field running test to estimate maximal aerobic speed (MAS) and maximal HR.	R-R intervals were obtained through Polar S810i HR monitors. HRV measurements were taken in 3 minute intervals during passive recovery and while participants breathed spontaneously.	Time domain: • Ln-RMSSD	HRV (Ln-RMSSD) correlated significantly with MAS ($r = -0.52$, $p = 0.002$). Results showed that HRV is a valid marker of aerobic performance in young soccer players.

R-R intervals	Inter-beat intervals or R to R intervals
Ln-RMSSD	Logarithmic function for RMSSD
MAS	Maximal aerobic speed
HR	Heart rate

Table 2.6 (cont.): Summary of studies that made use of the long-term daily/weekly HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Cipryan and Stejskal (2010)	18 Male, ice hockey players were divided into two groups, namely: a junior group (average age: 18 years) and an adult group (average age: 26 years). The study took place over a 2 month conditioning period. HRV was measured twice a week during this period in order to observe autonomic adaptions to training loads.	R-R intervals were obtained through VarCor PF7 HR monitors. HRV was measured at 5 minute intervals in a supine and standing position while participants breathed spontaneously.	Frequency domain: • LF • HF • LF/HF	Regardless of age, players could be divided into 2 groups, namely players with a higher ANS activity and players with lower ANS activity (as measured by total spectral power). Players with higher all round ANS activity showed a significantly better ($p < 0.05$) "adaption capacity" to increased training as measured by changes in spectral HRV indices. The study concluded that players should be placed into groups with similar ANS profiles so that training efficiency can be increased and the risk of overtraining decreased.
Kiviniemi *et al.* (2007)	26 Male, recreational runners were subjected to a 4 week training program and divided into the following groups: a predefined training group (n = 8) which trained in accordance with a set training program (6 days a week); an HRV guided training group (n = 9) which trained according to daily HRV profiles and a control group (n = 9) who trained only 4 days per week. $\dot{V}O_{2\,peak}$ was measured before and after the 4 week training period.	R-R intervals were obtained through Polar S810i HR monitors. Measurements were taken every morning during the training period for 5 minutes while participants were sitting and 5 minutes while participants were standing. Pre- to post-HRV was also compared to baseline values. In cases where HRV showed a decrease in the HRV-guided training group, low intensity training or rest was prescribed.	Frequency domain: • HF	The training group who used HRV (HF power) to guide training intensity throughout the training period showed a significant increase ($p = 0.048$) in running velocity and $\dot{V}O_{2\,peak}$ ($p = 0.002$) compared to the non-HRV guided training group. It was therefore concluded that cardiorespiratory fitness can be improved with HRV as a training prescription tool.

HF	High frequency component	$\dot{V}O_{2\,peak}$	Peak oxygen uptake
LF	Low frequency component	R-R intervals	Inter-beat intervals or R to R intervals
LF/HF ratio	Low and high frequency expressed as a ratio	HF Power	High frequency power

Tabulated findings (Table 2.6) suggest that HRV measured on a long-term basis may allow researchers and practitioners to monitor athletes and detect early signs of overtraining in wrestlers and ice hockey players (Tian *et al*., 2013:1517; Cipryan & Stejskal, 2010:61). HRV can also be used successfully to assess training status in athletes such as elite gymnasts and young soccer players (Sartor *et al*., 2013:2788; Bricout *et al*., 2010:115; Kiviniemi *et al*., 2007:749). Furthermore, researchers have established significant relationships between HRV and Yo-Yo IR1 performance ($r > 0.89$, $p < 0.05$), 10km running performance ($r = 0.60$; $p < 0.05$) and aerobic speed ($r = -0.52$; $p = 0.002$) in elite soccer players, recreational runners and young soccer players, respectively (Boullosa *et al*., 2013:408; Buchheit *et al*., 2010a:1161; Buchheit *et al*., 2010b:875). In addition, weekly mean HRV is strongly associated ($r = 0.90$, $p = 0.002$) with the changes in $\dot{V}O_{2max}$ of collegiate soccer players (Esco *et al*., 2016:439). Finally HRV also seem to be significantly associated with race times of a collegiate cross country runner ($r = 0.92$) and significantly predicted match performances in amateur basketball players ($R^2 = 0.15$, $p < 0.05$) (Flatt & Esco, 2014:44; Fronso *et al*., 2012:S45).

Several studies only used Ln-RMSSD as the primary HRV parameter to evaluate ANS activity. A frequency domain-based HRV parameter namely HF power (a measure of parasympathetic activity) has also been used by researchers and seems to be an effective measure of ANS status in sport and exercise settings (Nakamura *et al*., 2016:8). However, other studies incorporated several HRV parameters into measuring protocols in order to establish an ANS profile.

Although abovementioned results show that HRV measured over a long-term basis allow researchers to monitor changes in training status and performance, the importance of building up a cardiac profile for each individual athlete so that subtle changes in ANS activity can be monitored, should not be understated. In practise a more developed cardiac profile must contain a repertoire of HRV measures taken in different conditions such as when an athlete was sick, over trained, at his/her peak and other instances. Such a profile will allow researchers and practitioners alike to evaluate HRV changes and the impact of different factors on the ANS-profile of an athlete. However, for researchers that do not have time to obtain a long-term HRV-profile, a minimum of three days for elite athletes and five days for recreational athletes is required to build an adequate cardiac profile for research purposes (Plews *et al*., 2014:789). Therefore, long-term based measures is the most accurate and recommended methodological approach to evaluate the chronic changes in ANS activity through HRV within sport and exercise (Plews *et al*., 2013:779).

Researchers who wish to investigate the acute effects of exercise and sport on ANS activity usually measure HRV within a single day. Table 2.7 summarise studies that investigated HRV measures during a single day.

Table 2.7: Summary of studies that made use of the single-day HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Danieli *et al*., (2014)	20 Endurance trained athletes (age: 50 ± 7 years) and 20 sedentary control participants (age: 52 ± 6 years) were subjected to a sub-maximal cycle test on a bicycle ergometer. HRV was measured before and 30 minutes after the cycle test. The aim of the study was to investigate parasympathetic modulation before and after sub-maximal exercise.	R-R intervals were obtained through a Polar RS800CX and an ECG apparatus (Cardiosoft). HRV was measured for 5 minutes in a supine position while participants were breathing spontaneously.	Time domain: • SDNN • RMSSD Frequency domain: • LF • HF • LF/HF	HF, SDNN and RMSSD were significantly higher ($p < 0.05$) in endurance trained compared to sedentary participants. Results show that endurance training is associated with an increased HRV.
Esco and Williford (2013)	54 Young, healthy, male participants were subjected to maximal exercise testing to determine their $\dot{V}O_{2max}$ Skinfold measurements were taken beforehand. HRV recovery was measured directly after completion of the $\dot{V}O_{2max}$ test and again 30 minutes later.	R-R intervals were obtained through an ECG apparatus. HRV was measured in a supine position for 5 minutes while participants were breathing spontaneously.	Frequency domain: • LF • HF • LF/HF	Sum of skinfolds was found to be the most significant predictor ($p < 0.05$) of resting HRV (HF and LF:HF ratio). $\dot{V}O_{2max}$ was not related to post-exercise HRV. Bigger sum of skinfold values were related to a delayed HRV recovery to baseline values. Findings suggest that a healthy fat percentage is related to better cardiac autonomic regulation.

HF	High frequency power
LF	Low frequency power
LF:HF ratio	Low and high frequency expressed as a ratio
R-R intervals	Inter-beat intervals or R to R intervals
ECG	Electrocardiograph
SDNN	Standard deviation of R to R intervals
RMSSD	Squared root of the mean squared differences between successive R to R intervals
$\dot{V}O_{2max}$	Maximal oxygen uptake

Table 2.7 (cont.): Summary of studies that made use of the single-day HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Di Michele *et al*. (2012)	14 High-level swimmers (6 male, 8 female) completed the 7 x 200m front crawl test to determine anaerobic threshold. HRV and blood lactate concentrations were measured continuously throughout the test. Swimmers had to attempt to swim their best times during the test.	R-R intervals were obtained through Polar S810i HR monitors. HRV measurements were divided into 90-second segments to better monitor changes in HRV.	Frequency domain: • HF	HF power correlated significantly ($r = 0.93$, $p < 0.05$) with the lactate anaerobic threshold level, demonstrating that the anaerobic threshold can be determined from HRV.
Schmitt *et al.* (2008)	11 Elite cross country skiers (6 female, 5 male) completed a high-low and low-low altitude training intervention lasting 18 days. $\dot{V}O_{2max}$ as well as HRV were measured before and after the training intervention.	R-R intervals were obtained through Polar S810i HR monitors. Measurements were taken in a supine position for 8 minutes and in a standing position for 6 minutes while skiers paced their breathing.	Frequency domain: • LF • HF • LF/HF • TP	Changes in aerobic capacities ($\dot{V}O_2$ at respiratory compensation point (RCP)) correlated significantly with HF, LF and total power (TP) ($r = 0.48$, $r = 0.68$ and $r = 0.53$; $p < 0.05$), thereby confirming the relationship between changes in aerobic capacity and HRV.

R-R intervals	Inter-beat intervals or R to R intervals
HF	High frequency power
LF	Low frequency power
TP	Total power
LF:HF ratio	Low and high frequency expressed as a ratio
RCP	Respiratory compensation point
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_2$	Oxygen uptake
HR	Heart rate

Table 2.7 (cont.): Summary of studies that made use of the single-day HRV measurement methods to determine HRV in sport and exercise settings

Author	Brief methodology of study	Details of HRV measurement	HRV parameters used for analysis	Results and conclusions related to HRV
Seiler *et al.* (2007)	9 Highly trained (HT) and 8 recreational trained male runners (T) were subjected to the following exercise intensities: below ventilatory threshold one (VT1) for 60 and 120 minutes respectively; between VT1 and VT2 intensities for 30 minutes and above the VT2 for 60 minutes during four separate training sessions. HRV was measured shortly before and after each training session to compare ANS recovery between groups.	R-R intervals were obtained through Polar S810i HR monitors. Measurements were taken for 5 minutes in a supine position while athletes breathed spontaneously. HRV was measured at 5, 15, 30, 60, 90, 120, 180 and 240 minutes after completion of the exercise sessions. Food and fluid intake was controlled for every participant during the recovery period.	Time domain: • Mean RR • RMSSD Frequency domain: • LF • HF	HRV results showed that HT athletes' ANS recovered significantly quicker ($p < 0.05$) after each training session than that of the T athletes. HT athletes took five minutes to exhibit pre-exercise HRV values (RMSSD, LF power and HF power) after the exercise session above the VT2 intensity, compared to the T athletes, who took significantly longer (60 to 90 minutes, $p < 0.05$) to exhibit pre-exercise HRV values. Therefore, authors concluded that highly trained athletes' ANS is more responsive and recover faster after exercise compared to regular athletes. Consequently, the correct utilization of HRV assessments may help HT athletes to organise day-to-day distributions in training intensity.
Cottin *et al.* (2006)	11 Male cyclists executed an incremental exhaustive test on a cycle ergometer while HRV was measured. Well-established ventilatory equivalents (minute ventilation over oxygen consumption and carbon dioxide production) as well as experimental HRV-based (HF peak spectral power) detection methods were used to determine cyclists' ventilatory thresholds.	R-R intervals were obtained through an ECG (Power Lab) device. HRV was measured during the incremental exhaustive test in 20-second intervals and in synchronisation with ventilatory data.	Frequency domain: • HF	No significant differences between the HRV-based (HF peak spectral power) and conventional ventilatory-based thresholds expressed as a percentage of $\dot{V}O_{2\,peak}$ (VT1: $r = 0.94$; $p < 0.05$ and VT2: $r = 0.97$; $p < 0.01$) were found. Therefore, HRV determined from R-R intervals can be used to estimate ventilatory thresholds during exercise in well-trained cyclists.

Mean R-R	The mean of the inter-beat intervals or R to R intervals	LF	Low frequency power
RMSSD	Squared root of the mean squared differences between successive R to R intervals	ECG	Electrocardiograph
HF	High frequency power	$\dot{V}O_{2\,peak}$	Peak oxygen uptake

Table 2.7 shows that HRV measured on a single day, is also a versatile and practical method to evaluate ANS status. Results further revealed that higher HRV values are significantly ($p < 0.05$) associated with aerobic fitness and lower body fat percentage (Danieli *et al*., 2014:56; Esco & Williford, 2013:345). HRV can also be used to determine ventilatory threshold one ($r = 0.94$), ventilatory threshold two (otherwise known as the respiratory compensation point (RCP)) ($r = 0.97$) or anaerobic threshold ($r = 0.93$) in highly trained cyclists and swimmers (Cottin *et al*., 2006:963). In addition, higher HRV values are also associated with significantly higher ($p < 0.05$) oxygen uptake values at the RCP in elite cross country skiers (Di Michele *et al*., 2012:3063; Schmitt *et al*., 2008:304; Cottin *et al*., 2006:964). A significant faster ($p < 0.05$) HRV recovery (HRV return to baseline values) is also related to a better training status in runners (Seiler *et al*., 2007:1369). Ultimately, coaches and athletes alike would benefit from the use of individual HRV values to establish fitness, training and performance levels within a specific sport. However, the possible link between HRV measures and sport performances in several sports such as racquet sports must still be established.

HF power was a prominent HRV-based sport performance indicator in most of the studies (Table 2.7). These results suggest that frequency domain-based HRV parameters such as HRV power can be effectively used as accurate measures of ANS activity during "rugged" conditions within sport and exercise settings as opposed to the more favoured time domain parameters. Tables 2.6 and 2.7 also suggest that HRV can be measured in almost any sport and exercise setting. However, results of these tables also show that HRV measuring protocols differ from one another with regard to time duration of R-R interval measurements, body position during measurements, breathing frequency and the use of different HRV indices to evaluate ANS, which are all factors that influence the repeatability of HRV measurements (Van Diest *et al*., 2014:178; Makivic *et al*., 2013:126). These differences in HRV measuring procedures have compelled researchers to search for a standardised method by which the ANS of athletes can be evaluated (Plews *et al*., 2013:775). The next section will therefore be dedicated to studies that have investigated established protocols by which HRV can be measured in a sport and exercise setting and also made recommendations according to which the accuracy, reliability and validity of HRV measurements can be improved.

2.3.2.1 Guidelines for the measurement of HRV

Nunan *et al*. (2010) investigated studies that measured short-term HRV in healthy individuals of which participants numbered more than 30. Studies that adhered to recommendations for measuring short-term HRV as set by the Task Force of the European Society of Cardiology and North-American Society of Pacing and Electrophysiology in 1996 were also included. From this literature review the following recommendations for the measurement of short-term HRV followed (Nunan *et al*., 2010:1415):

- R-R interval data editing procedures should be reported and standardised.
- As far as possible, short-term HRV analysis should be automated (through computer software) to decrease the coefficient of variations in data sets.

A review by Plews and colleagues (2013) analysed studies that focused on the measurement of resting HRV through Ln-RMSSD (five to six minutes after waking up) in endurance athletes to evaluate ANS activity. After analysing each of these studies the following recommendations with regard to monitoring and interpretation of HRV measurements were put forth by last-mentioned researchers (Plews *et al*., 2013:775, 780):

- Longitudinal monitoring of HRV is needed to better understand an athlete's optimal HRV fingerprint.
- Ln-RMSSD is the most reliable and practical HRV parameter for ANS evaluation during day-to-day monitoring.
- In order to identify meaningful changes in ANS activity seven-day/weekly rolling HRV averages should be used.

Saboul *et al*. (2013) investigated the effects of breathing frequency on longitudinal HRV parameters in athletes. Resting short-term HRV was measured for five minutes over 21 consecutive days during controlled breathing and spontaneous breathing. The study delivered the following results (Saboul *et al*., 2013:538, 540):

- No differences were observed between controlled and spontaneous breathing when RMSSD and SD1 were used as HRV parameters.
- Frequency-domain HRV parameters were influenced by breathing frequency and it was therefore recommended that these parameters should not be used when longitudinal HRV measurements are taken in situations where breathing frequency is not controlled.

Plews *et al*. (2014:789) further recommended the following after examining the minimum days per week that HRV should be measured to reflect training adaptions in elite and recreational runners:

- A minimum of three days are necessary to measure short-term resting HRV in order to reflect training adaptions in elite runners.
- A minimum of five days are necessary to measure short-term resting HRV in order to reflect training adaptions in recreational runners.
- Short-term resting HRV values taken over a week give a better indication of training adaptions than single day-to-day HRV values.

Lastly, Esco and Flatt (2014:538) investigated the level of agreement between ultra-short-term HRV measurements (10, 30 and 60 seconds in duration) and conventional longer term HRV measurements (5 minutes). HRV (Ln-RMSSD) was measured in a resting supine position before and 25-30 minutes after a maximal exercise test. The following results came to light:

- The limits of agreement decreased as the time duration decreased for the ultra-short-term Ln-RMSSD values during both pre-exercise and post-exercise segments.
- However, 60 second Ln-RMSSD values showed the highest levels of agreement and the strongest correlations with the widely accepted five-minute Ln-RMSSD values throughout the pre-exercise and post-exercise segments.
- Therefore, 60 second Ln-RMSSD can be regarded as a promising and accepted measure of HRV to monitor athletes at rest in sport and exercise settings.

Despite these recommendations, time and logistical constraints, especially during matches and competitions make it difficult to duplicate similar measuring protocols in all studies. Therefore, the above-mentioned recommendations should rather be seen as guidelines according to which HRV protocols that are aimed at determining athletes' HRV values must be designed.

2.3.3 Measuring HRR in sport and exercise settings

However, in recent years alternative and innovative methods have been used to measure and interpret HRR. The next section will discuss different applications of HRR and methods to measure HRR in sport and exercise settings. Not only does the ANS increase HR through parasympathetic inhibition and sympathetic stimulation at the onset of moderate to intense exercise, it also causes the decrease in HR after the cessation of exercise by parasympathetic reactivation and sympathetic inhibition (McArdle *et al*., 2013:327). Therefore the ANS ultimately returns the HR to its intrinsic rhythm (McArdle *et al*., 2013:327). The responsiveness of the ANS to regulate HR during and after exercise can therefore be used as a measure to evaluate its effectiveness and overall status. In this regard HRR allows researchers, sport scientists and coaches to quantify and subsequently assess ANS function between bouts of exercise, during training or competition participation and after exercise. From a methodological point of view HRR is traditionally seen as the decline in elevated HR after intense exercise within a certain timeframe and is expressed in beats per minute (bpm) or percentage metrics (Boullosa *et al*., 2013:402; Daanen *et al.*, 2012:257).

2.3.3.1 Conventional methods to measure HRR

HRR is normally measured by making use of an accurate HR monitor devices such as Polar or Suunto wrist watches (Porto and Junqueira, 2009:51). The versatility of these devices allow researchers to measure athletes' HRR in their natural, competitive and training environments, which in turn, provides a more accurate reflection of autonomic regulation during real life sport activities (Gocentas *et al*., 2011:15). However, factors such as exercise intensity, work-to-rest ratios and characteristics of each sport make it difficult to develop a standardised, HRR measuring protocol and to compare the HRR of different types of athletes. In view of these problems, researchers rather measure HRR directly after standardized exercise tests such as the maximal oxygen uptake ($\dot{V}O_{2max}$) test or after the Yo-Yo IR1 (Boullosa *et al*., 2013:402; Daanen *et al*., 2012:258). Researchers usually express HRR indices in the form of absolute (differences in HR beats between the exercise and post-exercise HR) or relative values (percentage decrease of HR from exercise to post-exercise HR) (Daanen *et al*., 2012:257). The method of measuring HRR after $\dot{V}O_{2max}$ tests or field tests is illustrated in Figure 2.5.

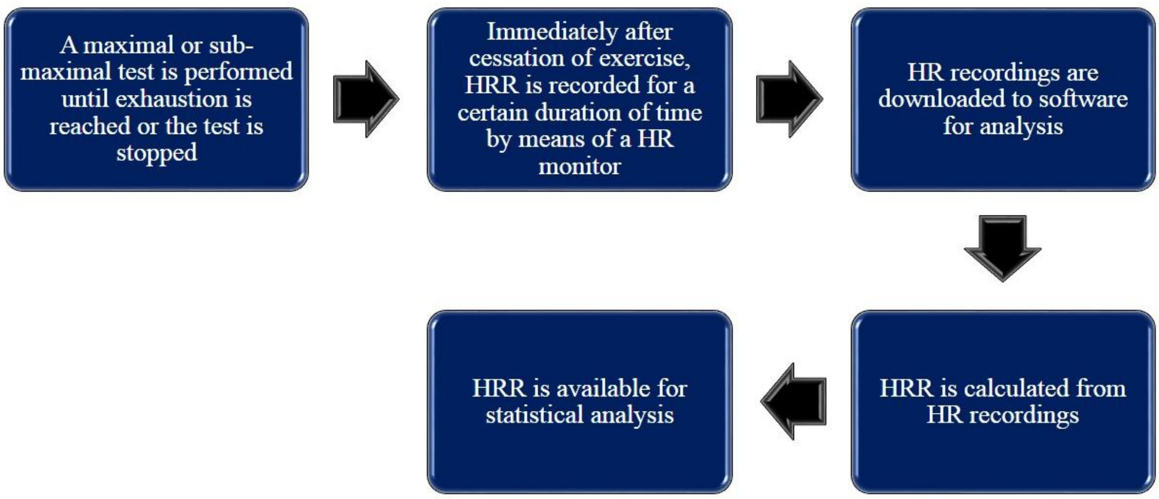

Figure 2.5: Method of obtaining an HRR measurement after a maximal exercise test (Adapted from Daanen *et al.*, 2013:257; Henriquez *et al*., 2013:113)

The measurement of HRR is not as complicated and detailed as that of HRV. Studies that have measured HRR by making use of the abovementioned method are presented in Table 2.8.

Table 2.8: Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Guerra *et al.* (2014)	18 Sedentary (SE), 15 resistance-trained (RT) and 14 aerobically trained (AT) male participants (age: 22 ± 2.8 years) were subjected to a $\dot{V}O_{2max}$ bicycle test. Participants were matched for $\dot{V}O_{2max}$ and their cardiac autonomic function investigated.	HRR was measured directly after the $\dot{V}O_{2max}$ bicycle test. HRR was measured for 60 seconds in a seated, recovery position and calculated as the absolute difference between the peak HR at the end of the test and the HR after 60 seconds of recovery. Following this, the time constant of HRR (*t*) was calculated by fitting a mono-exponential curve over the 60 second recovery period. Lastly, HRR was analysed by measuring the HR for 30 seconds (T30) (HR between the 10^{th} and 40^{th} seconds) using a semi-logarithmic regression analysis.	Both AT and RT exhibited significantly faster HRR ($p < 0.05$) than SE. HRR did not differ significantly between AT and RT. Results show that exercise type (SE vs. RT and AT) improves HRR and that there are no significant differences concerning HRR between participants who practise aerobic and resistance training exercises. Thus, strength training is equally effective in improving autonomic function and should be considered with athletes that are aerobically less inclined.
McDonald *et al.* (2014)	10 Anaerobically trained, track cyclists (age: 25.9 ± 6 years; body fat percentage: 10 ± 6.3%) and 15 aerobically trained, road cyclists (age: 39.9 ± 8.5 years; body fat percentage: 13.1 ± 4.5%) were subjected to a $\dot{V}O_{2max}$ bicycle test in order to compare HRR between the 2 groups of cyclists.	HRR was taken for 2 minutes directly after completion of the bicycle test. During the first minute (0-60 seconds) cyclists were seated and pedalled lightly where-after they sat on the bicycle without speaking or moving for the second minute (60-120 seconds). HRR was calculated as the change in HR values between the first and second minute divided by the maximum HR minus the resting HR.	Aerobically trained cyclists showed a faster HRR after both the first and second minute. However, HRR only showed a significant decrease ($p < 0.05$) after the second minute. Results suggest that training mode affects HRR and that HRR should be measured beyond a minute to determine the post-exercise autonomic shift.

$\dot{V}O_{2max}$	Maximal oxygen uptake
SE	Sedentary
AT	Aerobically trained
RT	Resistance trained
T30	Heart rate measured for 30 seconds
t	HRR measured through a mono-exponential curve
HR	Heart rate

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Vicente-Campos *et al*. (2014)	789 Healthy and physically active, male participants (age: 38.5 ± 8.64 years; BMI: 24.82 ± 3.10 kg/m^2) were subjected to a $\dot{V}O_{2max}$ treadmill test in order to investigate the HRR of a normal population.	HRR was measured for 3 minutes directly after test termination. Participants walked slowly at a pace of 4km/h for the first 2 minutes of the HRR period (0-120 seconds), after which they stood still on the treadmill while HRR was measured for the third minute (120-180 seconds). Absolute HRR was calculated as the HR at the first and third minute subtracted from the maximum HR attained during the test. HRR was also expressed as a percentage value.	The mean HRR (in beats per minute) after 1 and 3 minutes was 15.24 ± 8.36 bpm and 64.58 ± 12.17 bpm, respectively. The HRR percentage declined by 8.60 ± 4.70% and 36.35 ± 6.79% after 1 and 3 minutes, respectively. A significant correlation of r = 0.36 ($p< 0.001$) was found between HRR at 3 minutes and $\dot{V}O_2$ peak. Thus, HRR after 3 minutes is a better indicator of aerobic capacity than HRR after 1 minute in a normal population of physically active men.
Henriquez *et al.* (2013)	18 Male wrestlers (10 highly trained and 8 moderately trained) were subjected to a maximal incremental exercise test. HRR was taken and compared between highly (HT) and moderately trained (MT) wrestlers.	HRR was measured for 60 seconds directly after cessation of exercise. HRR was calculated as the absolute difference between immediate post-exercise HR and HR at 60 seconds after passive recovery.	HRR was significantly different ($p < 0.01$) between HT and MT. HT wrestlers also possessed a significantly faster ($p < 0.05$) HRR than MT wrestlers. Results suggest that HRR after 60 seconds is related to the training state of wrestlers.

$\dot{V}O_2$	Oxygen uptake
BMI	Body mass index
HT	Highly trained
MT	Moderately trained
HR	Heart rate

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Dupuy *et al.* (2012)	11 Male, endurance runners were subjected to a 2 week overloading period by increasing the training load by a 100% in order to induce an overreached state. A maximal graded exercise test and a continuous, sub-maximal running test (85% of peak treadmill speed) were completed by runners before and after the 2 week period in order to determine HRR. Runners then completed a taper period of 1 week.	HRR was taken directly after the maximal exercise test for 60 seconds while runners sat down in a seated position next to the treadmill. HRR was calculated as the absolute difference between immediate post-exercise HR and HR after 60 seconds of passive recovery.	HRR was significantly faster ($p < 0.05$) after the maximal graded exercise test following the 2 week overloading period. However, no significant changes in HRR were found after the continuous, sub-maximal running test. HRR returned to baseline values after the 1 week taper period. Results show that cardiac autonomic control is altered by a 2 week overloading period.
Lee and Mendoza (2012)	19 Endurance trained athletes (8 males, 11 females) were subjected to a $\dot{V}O_{2max}$ treadmill test. HRR was taken and relationships between this measurement and aerobic fitness as well as physical activity (as assessed *via* a structured questionnaire) were determined.	HRR was taken for 60 seconds directly after cessation of the $\dot{V}O_{2max}$ test. HRR was calculated as the absolute difference between the immediate post-exercise HR and HR after 60 seconds of an active, low intensity cool-down on the treadmill.	HRR was significantly correlated ($r = 0.51$; $p = 0.039$) with physical activity and $\dot{V}O_{2max}$ ($r = 0.67$; $p = 0.003$), respectively. Results suggest that HRR may be a valid marker of fitness as well as a marker of autonomic recovery.
Buchheit *et al.* (2011a)	15 High-level, male soccer players completed a 5-minute submaximal run (9 km/h) in the heat (34.6 ± 1.9˚C) every day during a training week. Players also completed the Yo-Yo IR1 test in standardised conditions (22°C) before and after the training week. HRR was measured after every run as well as after the Yo-Yo IR1 test.	Absolute HRR was calculated by taking the difference between the final HR at exercise termination and the HR recorded after 60 seconds of recovery.	Yo-Yo IR1 test performance increased significantly ($p = 0.009$) by 7 ± 9% after a week of training in the heat. However, HRR remained stable throughout the study. This led to the conclusion that HRR on its own should not be used to measure maximal running performance but along with other proven measures of running performance.

$\dot{V}O_{2max}$	Maximal oxygen uptake
Yo-Yo IR1	Yo-Yo Intermittent Recovery Test One

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Buchheit *et al.* (2011b)	46 Young, male soccer players (age: 15.1 ± 1.5 years) were subjected to the following series of performance tests on 2 separate occasions: 5 minute sub-maximal run, counter-movement jumps, 40m sprint and repeated sprint as well as the aerobic incremental running test.	The mean HR during the last 30 seconds of the sub-maximal run was termed HR exercise (HRex). Absolute HRR was then calculated as the difference between HRex and HR after 60 seconds in a seated, recovery position.	Moderate correlations were found between the change in HRR and 40m sprint performance (r = 0.39, CI 90%: 0.07-0.64) and repeated sprint performance (r = -0.38, CI 90%: -0.05 to -0.64). Results show that cardiac autonomic indices, such as HRR is associated with changes in physical performance of youth soccer players.
Ostojic *et al.* (2011)	26 Male soccer players (12 elite and 14 sub-elite) performed a $\dot{V}O_{2max}$ treadmill test in order to reach their maximal HR.	HRR was taken every 10 seconds for 60 seconds immediately after test termination. Immediately after test termination players were placed in a seated position. Absolute HRR was calculated at each 10 second time interval and was termed T10-T60sec.	A significant difference ($p < 0.05$) was found in HRR at 10 and 20 seconds between elite and sub-elite soccer players, with elite soccer players, who recovered significantly faster ($p < 0.05$) than their sub-elite counterparts. Furthermore, elite soccer players achieved an average $\dot{V}O_{2max}$ of over 60 ml/kg/min compared to sub-elite soccer players who achieved an average value of under 50 ml/kg/min. Therefore, it was concluded that ultra-short HRR indices (at 10 and 20 seconds) can be used to distinguish and identify athletes with higher aerobic and exercise capacities.

HRex — Heart rate during exercise

$\dot{V}O_{2max}$ — Maximal oxygen uptake

T10-T60 — HRR taken at 10 second intervals for the first 60 seconds

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Buchheit *et al.* (2010b)	18 u/15 and 15 u/17, male soccer players were tested during a 3 week competitive soccer training camp. Players were subjected to a 5 minute sub-maximal run (9 km/h) followed by a 5 minute seated recovery period. Players were tested 14 times throughout the camp.	The mean HR during the last 30 seconds of the sub-maximal run was termed the HR exercise. Absolute HRR was calculated as the difference between HR exercise and HR after 60 seconds in a seated recovery position.	HRR was not significantly correlated with any aerobic performance indicators. However, HRR was significantly correlated with players' years of peak height velocity (PHV) ($r = -0.52$; $p = 0.002$). In conclusion, it is possible that maturity level (as determined by PHV) may have a bigger influence on HR measures compared to daily aerobic activities.
Al Haddad *et al.* (2010)	12 Healthy, male adults were tested on 3 separate occasions. Each testing occasion consisted of an all-out 30 second Wingate test which was followed by 5 minutes of seated recovery. After this recovery period the participants completed a sub-maximal exercise test on a treadmill. Next, participants passively recovered through either cold water immersion, thermo-neutral water immersion or no water immersion.	HRR was taken for 60 seconds directly after completion of the sub-maximal treadmill exercise test whilst participants sat in a water tank. Absolute HRR was calculated as the difference between the post- exercise HR and HR after 60 seconds of seated recovery (in the water tanks).	Compared to the no water immersion recovery period, HRR was significantly higher for both cold water ($p = 0.017$) and thermo-neutral water immersion periods ($p = 0.003$). Water immersion can therefore facilitate parasympathetic stimulation which in turn can increase autonomic recovery.

PHV Peak height velocity

HR Heart rate

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Bosquet *et al.* (2008)	28 Trained, middle- and long-distance runners (24 male and 4 female) performed a $\dot{V}O_{2max}$ treadmill test to determine their $\dot{V}O_{2max}$, ventilatory threshold and peak treadmill speed. After the tests were completed, participants with similar $\dot{V}O_{2max}$ values were matched and were divided into two groups, namely a high and a low endurance group. Group classification was also based upon the treadmill speed that participants reached at the ventilatory threshold (VT).	HRR was taken directly after cessation of the maximal graded incremental exercise test for 60 seconds in a supine position. Absolute HRR was calculated as the difference between the post-exercise HR and HR after 60 seconds of passive recovery.	No significant difference ($p > 0.05$; ES ≤ 0.4) was found for HRR between the low and high endurance groups. Furthermore, no significant association was found between HRR and relative ventilatory threshold ($r < 0.23$; $p > 0.05$). Therefore, it was concluded that cardiac autonomic control as determined by HRR is not associated with aerobic endurance.
Borresen and Lambert (2007)	28 Physically active adults (12 = male, 16 = female) trained for 2 weeks on their own. At the end of this period participants were divided into 3 groups: Group 1: participants who increased their training load over the 2 week period; Group 2: participants who decreased their training load over the 2 week period; Group 3: participants whose training load remained the same over the 2 week period.	HRR was taken directly after a standardised sub-maximal shuttle run test while participants were standing upright. Absolute HRR was calculated as the difference between the post- exercise HR and HR after 60 seconds of passive recovery. HRR was also expressed as a percentage decline.	Group 1 showed a significant decrease ($p < 0.05$) in mean percentage HRR after the 2 week period compared to group 2 who showed a significant increase ($p < 0.05$) in mean percentage HRR after 2 weeks. For group 3 no significant difference in percentage HRR was observed. Overall, results suggest that HRR responds to acute changes in training load and that this ANS indicator can be used to determine the body's exercise capacity.

$\dot{V}O_{2max}$	Maximal oxygen uptake
ES	Effect sizes
VT	Ventilatory threshold
HR	Heart rate

Table 2.8 (cont.): Studies that employed standardised exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Otsuki *et al.* (2007)	12 Male, strength trained, 12 endurance trained athletes and 12 sedentary adults performed a $\dot{V}O_{2max}$ bicycle test. The following day athletes performed 8 minutes of sub-maximal exercise at 40% of $\dot{V}O_{2max}$.	HRR was taken directly after each of the $\dot{V}O_{2max}$ and sub-maximal exercise tests. HRR was taken during the first 30 seconds after each test in a standing position. Linear regression analysis was performed on the natural logarithm of the first 30 seconds of HR decline after exercise. The negative reciprocal of the slope of the regression line was defined as T30.	Both strength and endurance trained athletes showed a significant faster ($p < 0.05$) HRR than the control group. However, no significant differences were found in HRR between the strength and endurance trained athletes. It can therefore be concluded that both strength and endurance trained athletes possess more or less similar accelerated HRR values.

$\dot{V}O_{2max}$ Maximal oxygen uptake

T30 HRR measured through a negative reciprocal slope of the regression line

Tabulated results suggest that although athletes display significantly faster HRR than sedentary counterparts and that the HRR of aerobically and resistance trained athletes is more or less similar (Guerra *et al*., 2014:118; Bosquet *et al*., 2007:366; Otsuki *et al*., 2007:368). On the other hand McDonald *et al*. (2014:48) observed that aerobically trained cyclists exhibit faster ($p < 0.05$) HRR within the first and second minute of recovery compared to anaerobically trained cyclists. HRR after 10 and 20 seconds was also identified as the distinguishing factor between elite and sub-elite soccer players with elite soccer players displaying a significantly ($p < 0.05$) faster HRR than their sub-elite counterparts (Ostojic *et al*., 2011:107). Similarly, highly trained wrestlers also showed faster ($p < 0.05$) HRR than moderately trained wrestlers (Henriquez *et al.*, 2013:114). Superior HRR is also associated with increased physical activity in endurance trained athletes as well as with peak height velocity and 40 m sprint performance in young soccer players (Lee & Mendoza, 2012:2765; Buchheit *et al*., 2011b:484). In contrast, other studies found no associations between HRR and aerobic endurance in soccer players or distance runners (Buchheit *et al*., 2010a:1158; Buchheit *et al*., 2011a:720; Bosquet *et al*., 2007:366). However, researchers must realise that various factors may influence HRR rate. In this regard, Dupuy *et al.* (2012:205) and Al Haddad *et al*. (2010:115), for example, showed that cold water immersion and a two week overloading period led to a significant ($p < 0.05$) increase in the HRR of endurance runners and physically active adults.

From Table 2.8 it is clear that standardised $\dot{V}O_{2max}$ or other standardised field exercise tests can be used to successfully determine HRR and associations between HRR and athletes' exercise capacity as well as athletes' ability to adapt to training (Guerra *et al*., 2014:119; McDonald *et al*., 2014:48; Vicente-Campos *et al.*, 2014:1127; Henriquez *et al.*, 2013:114; Dupuy *et al.*, 2012:204; Lee & Mendoza, 2012:2765; Ostojic *et al.*, 2011:109). Furthermore, this method allows researchers to reproduce and compare HRR results of athletes from different sporting codes (Guerra *et al*., 2014:115; McDonald *et al*., 2014:44; Henriquez *et al.*, 2013:112; Dupuy *et al.*, 2012:203; Lee & Mendoza, 2012:2758).

2.3.3.2 Sport-specific procedures of measuring HRR

Although the abovementioned method seems to be accepted in the sport and exercise fraternity others have opted for other tests and protocols to measure HRR in order to make measurements more specific to the conditions that athletes experience during sport participation. Table 2.9 summarises studies that measured HRR through the use of more sport-specific exercise tests.

Table 2.9: Studies that employed sport-specific exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Boullosa *et al.* (2013)	8 Male, elite soccer players were measured at the beginning of the pre-season and again 8 weeks later at the end of the pre-season. During these measurements players were subjected to small-sided sport specific soccer games (SSG) during which HR data was collected. Players were also subjected to the Yo-Yo IR1 during week 1 and 8 of the pre-season period.	Ultra short HRR was taken during execution of the SSG. HRR was only measured when players exceeded 85% of maximal Yo-Yo IR1 obtained HR and experienced an active recovery period of at least 20 seconds in duration and did not exceed a walking pace of 4 km/h. HRR was calculated as the absolute HR recovery and expressed as a percentage of HR peak during SSG.	HRR during the SSG improved significantly ($p < 0.05$) from the start to the end of the pre-season. Therefore, players experienced better parasympathetic reactivation during the active recovery periods at the end of the pre-season. These results support the use of ultra-short-term HRR for the evaluation of autonomic adaptations in professional soccer players.
Gocentas *et al.* (2011)	8 Male, high-level basketball players completed a 3.5 minute intensive sport specific exercise drill at the end of team practice. This procedure was repeated during four consecutive practices over the course of the competitive season. Players were ranked according to sport-specific efficiency as determined by sport specific drill execution and game time exposure.	HRR over 60 seconds was taken each time directly after execution of the drill. HRR was calculated by subtracting the HR after 60 seconds from the peak HR achieved during the sport-specific exercise drill.	Players that were more efficient during the sport-specific drill and had the most competition time also showed a significant ($p < 0.05$) decrease in HRR over the competitive season. Players that were less efficient during the sport-specific drill and had the least competition time showed a significant ($p < 0.05$) increase in HRR. In conclusion, results suggest that HRR is useful to determine functional status in basketball players throughout a competitive season.

Yo-Yo IR1	Yo-Yo intermittent recovery test one
SSG	Sport specific games
HR	Heart rate

Table 2.9 (cont.): Studies that employed sport-specific exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Buchheit *et al.* (2010a)	14 Recreational, male runners were subjected to an 8 week training intervention. Runners completed a modified 10 km field test on an athletics track. Maximal aerobic speed and 10 km running performance were assessed before and after the intervention.	HRR indices were measured every two weeks. HR peak was determined by measuring HR during the last 5 minutes of the field test. HRR was calculated *via* the time constant (60 seconds) of the HR decay by a first-order exponential decay curve.	HRR showed a significant negative relationship ($r = 0.54$; $p < 0.05$) with 10 km running performance. Therefore, results suggest that post-exercise HR indices have the potential to serve as indicators of aerobic endurance performance.
Lamberts *et al.* (2010)	14 Well-trained, male cyclists completed a 4 week high intensity (HIT) program before the study. Cyclists were divided into 2 groups according to either their increases or decreases in HRR throughout the HIT program. HRR and its relation to cycling performance were subsequently analysed.	HRR was taken for 60 seconds directly after a bicycle exercise. Once cyclists completed a time trial they were instructed to bend over in a standing position whilst resting their arms on the handlebars of their bicycles. Absolute HRR was calculated by taking the difference between the final HR at the end of exercise completion and HR recorded after 60 seconds. HRR was also expressed as a percentage.	Cyclists who displayed an increase in HRR during the HIT program exhibited a significantly higher average power output during the 40 km time trial ($p = 0.01$) as well as a faster non-significant 40 km time-trial ($p = 0.059$) compared to participants who displayed a decrease in HRR during the HIT program. Therefore, HRR has the potential to serve as a measurement to monitor changes in endurance cycling performance.

HIT High intensity training

HR Heart rate

Table 2.9 (cont.): Studies that employed sport-specific exercise tests to measure HRR

Author	Brief methodology of study	Details of HRR measurement	Results and conclusions related to HRR
Lamberts *et al.* (2009a)	14 Well-trained, male cyclists completed a high intensity training (HIT) program consisting of eight sessions in four weeks. Before and after the HIT program cyclists completed a peak power output test, a sub-maximal cycle test and a 40 km time-trial (all performed on a bicycle ergometer). HRR was only measured after every HIT session as well as after the 40 km time-trials. HRR was investigated in this manner to determine if it would improve during as well as after the HIT program.	HRR was taken for 60 seconds directly after a 40 km time-trial and HIT sessions on a bicycle. Once cyclists completed time trials and HIT sessions they were instructed to bend over in a standing position whilst resting their arms on the handlebars of their bicycles. Absolute HRR was calculated by taking the difference between the final HR at the end of exercise completion and HR recorded after 60 seconds of recovery.	HRR significantly improved (7 ± 6 beats; $p = 0.001$) after HIT training sessions throughout the eight-week period. HRR after the 40 km time-trial also improved significantly (6 ± 3 beats; $p = 0.02$) due to the HIT program. Good relationships were also found between HRR improvement and peak power output ($r = 0.73$; $p = 0.0001$) as well as 40 km time ($r = 0.96$; $p = 0.0001$). In conclusion, HRR is a sensitive marker for changes in training status in already well-trained cyclists.
Lamberts *et al.* (2009b)	17 Well-trained, male cyclists completed a peak power output test, a sub-maximal cycle test and 40 km time-trial (all performed on a bicycle ergometer) on four separate occasions. HRR was only measured during the sub-maximal cycle test. HRR and its ability to predict cycling performance was investigated.	HRR was taken for 60 seconds directly after the sub-maximal cycle test (which peaked at 90% of HRmax). Once cyclists reached 90% of their HRmax during the sub-maximal cycle test they were instructed to stop immediately and bend over in a standing position whilst resting their arms on the handlebars of their bicycles. Absolute HRR was calculated by taking the difference between the final HR at the end of exercise completion and HR recorded after 60 seconds of recovery. HRR was also expressed as a percentage.	HRR showed significant relationships with duration of 40 km time-trial and peak power output ($r = 0.68$ and $r = 0.55$; $p < 0.05$ respectively). HRR and $\dot{V}O_{2max}$ as determined from the peak power bicycle test also showed a significant correlation ($r = 0.62$; $p < 0.05$). Researchers concluded that HRR along with other performance indicators could be useful in monitoring and predicting cycling performance in trained cyclists.

$\dot{V}O_{2max}$ Maximal oxygen uptake

HRmax Maximal heart rate

HIT High intensity training

HR Heart rate

Results (Table 2.9) show that HRR can be successfully determined by making use of more sport-specific exercise tests. In this regard, HRR improved significantly in elite soccer players when HRR was measured during soccer-specific games as the season progressed (Boullosa *et al*., 2013:407). Similarly, basketball players that were more effective in sport-specific basketball drills displayed significant lower HRR after drills compared to their less proficient teammates (Gocentas *et al*., 2011:15). Results also suggest that HRR can be successfully measured during competition and training in order to predict sports-specific on-field performance in soccer and basketball players (Boullosa *et al.*, 2013:408; Gocentas *et al.*, 2011:15). Regarding individual sports, a faster HRR was associated with 10 km race performance ($r = 0.54$; $p < 0.05$) in recreational runners (Buchheit *et al*., 2010a:1165). Well-trained cyclists who displayed faster HRR after a high intensity training program also exhibited a significantly higher average power output ($p = 0.01$) and faster time ($p = 0.059$) during a 40 km cycle time trial (Lamberts *et al*., 2010:453). Lastly, HRR is a sensitive marker to detect changes in training status in all ready well-trained cyclists and can also be used as a predictor of elite cycling performance (Lamberts *et al*., 2009a:711; Lamberts *et al*., 2009b:802).

Thus, the measurement of HRR through sport-specific exercise tests also yielded positive results and highlighted HRR as a sport performance indicator. Although this approach is not as well-known as the use of standardised exercise tests to determine HRR, positive results obtained by using this method suggest that future research should test this methodology on a wider range of sports. However, it should be noted that sport-specific tests are only used within the confines of a specific sport and HRR results of one sport should not be generalised to another sport. Nonetheless the standardisation of HRR measuring protocols will increase the repeatability and accuracy of HRR measurements in sport and exercise settings.

2.3.3.3 Guidelines for the measurement of HRR

Despite the value of using HRR as a tool to determine athletes' training and functional status, autonomic adaptations as well as performances, some methodological issues that are related to HRR measurements in sport and exercise settings must be considered. For example, Barak *et al*. (2011:370) investigated the possible influence of body position on the measurement of HRR after a sub-maximal, cycle exercise test in 21 trained, male athletes and 19 sedentary, healthy males. HRR was measured for five minutes directly after cessation of the test on four occasions. Furthermore, on each occasion HRR was measured in the following recovery positions: an inactive upright seated position, an active recovery upright seated position on a bicycle, a supine position and a supine position with elevated legs (knees bent 90° and resting on pillows). In addition, HRR was calculated in the following two ways: firstly, the absolute difference in HRR (value in bpm) between the maximal HR, attained after the sub-maximal cycle exercise test and 60 seconds of recovery (HRR_{60}); secondly, the HR decay over a period of five minutes through a linear-exponential model (calculated by fitting the five-minute post-exercise HRR into a first-order exponential curve) and presented as HRR_T. The following results were found:

- Athletes' HRR_{60} were significantly faster ($p < 0.001$) than sedentary counterparts in all recovery positions.
- Athletes' HRR_T were significantly faster ($p < 0.05$) than sedentary counterparts in the active recovery period as well as in the supine position with legs elevated.
- Supine recovery positions led to a significant increased acceleration in HRR_T and HRR_{60} ($p < 0.05$) compared to seated recovery positions in both athlete and sedentary groups.
- Active recovery positions caused HRR_T and HRR_{60} to be significantly slower ($p < 0.05$) compared to all other recovery positions in both athlete and sedentary groups.
- No significant difference was found between the HRR_T in the inactive supine recovery position in both athletes and sedentary groups.

From the abovementioned results it is clear that the body position in which HRR is measured as well as the training status of participants should be considered when measuring HRR as it may have a significant effect on the comparability of HRR values.

Bosquet *et al*. (2008:239) investigated the reliability of passive post-exercise HRR measurements after exercise as well as the most accurate means of quantifying HRR. Healthy participants (22 males and 8 females) completed two maximal, graded, continuous treadmill tests as well as two sub-maximal, continuous treadmill tests at 80% of peak treadmill speed over a duration of ten minutes within 72 hours of each other. Participants completed both tests at the same time of day followed by a five-minute passive recovery period that consisted of one minute of standing and four minutes of sitting. HRR was calculated by making use of the raw HR (in bpm) at cessation of the exercise test as well as one, two, three and five minutes after the exercise test (HRR_{raw}). Changes in absolute HRR were calculated as the difference (in bpm) between HR directly after the exercise test and HR at 1 one, two, three and five minutes after the test (HRR_{diff}). Lastly, HRR kinetics were calculated by following a mono-exponential curve (using the least squares procedure) to quantify the decay of HR throughout five minutes of HRR (HRR_{curve}). Relative and absolute reliability of HRR data was analysed by using interclass correlation coefficients (ICC) and the standard error of measurement (SEM), respectively. Results of this study revealed the following:

- Relative reliability for the HRR_{diff} was lower compared to HRR_{raw} throughout the recovery periods ($0.43 < ICC < 0.71$ vs. $0.68 < ICC < 0.83$, respectively).
- Absolute reliability was relatively constant for HRR_{raw} throughout the recovery period (SEM = 8%) while HRR_{diff} exponentially decreased (improved) from the first to the fifth minute of the recovery period (SEM = 20% to 8%).
- The reliability of the mono-exponential curve was less consistent with both ICC (0.43 to 0.88) and SEM (5.7% to 21.4%) differing from one parameter to another throughout the recovery period.

As a result of these findings, Bosquet *et al*. (2008:242) concluded that the reliability of passive post-exercise HRR is heterogeneous and that their methods for determining HRR should be duplicated in a study where active recovery is rather used. They also pointed out that HRR_{raw} is the most reliable measure of passive, post-exercise HRR.

A simple, yet very important, aspect of HRR measurements that must be considered is circadian or biological rhythms or more specifically the influence that the time of day over which measurements is taken, has on HRR values (Cruz *et al*., 2014:21). Cruz *et al*. (2014:22) subjected eight male, mountain bike cyclists to a progressive bicycle ergometer test in order to obtain their maximal HR followed by a five-minute recovery period over which HRR was measured. Tests were conducted between 06:00 and 08:00 in the mornings and 18:00 and 20:00 in the evenings interspersed by a 24-hour period. Findings showed no significant differences ($p > 0.05$) in minute-for-minute HRR over the five-minute recovery period between the morning and evening periods. Cruz *et al*. (2014:24) therefore concluded that time of day does not have an influence on HRR values of male, mountain bicycle cyclists.

In a systematic review by Daanen and colleagues (2012), the methodological flaws of various studies that measured HRR in a sport and exercise setting were identified. The following findings and recommendations were highlighted (Daanen *et al*., 2012:257):

- Participants' training status (athletes exhibit faster HRR than untrained counterparts), age (maximum HR and HRR tend to decline with age) and gender (whether male athletes possess a faster HRR than female athletes is still a controversial topic) should be considered when determining an appropriate protocol to measure HRR and when comparing HRR values between different participant groups.

- As far as possible researchers should try and standardise as well as thoroughly document exercise intensity, duration and type when employing maximal and sub-maximal exercise tests to measure HRR. Higher exercise intensities also result in higher HR which in turn slows HRR due to a larger decrease in HR that needs to take place. HRR from maximal exercise also produces slower HRR due to sympathetic activity that is still present during early recovery stages. Regarding the type and duration of exercise, intermittent *versus* continuous endurance *versus* resistance type of training may influence HRR. Athletes that are engaged in intermittent sports usually exhibit slower HRR after maximal exercise than endurance trained athletes. In addition running athletes have faster HRR values than cyclists which are probably related to the higher aerobic demands of running. Thus, all of the mentioned factors may influence parasympathetic reactivation, which directly influence HRR values.
- When using sub-maximal exercise tests it is advisable to fix the sub-maximal HR from which HRR is measured (for example 85-90% of each participants maximal HR), thereby ensuring that HRR is measured every time from the same HR in order to detect meaningful changes in HRR measured from sub-maximal exercise.
- HRR is generally measured over periods of between 30 seconds and 2 minutes, however, HRR after 60 seconds of recovery tends to be more effective for detecting meaningful changes over time. In addition, HRR measured over different recovery periods should not be compared. Lastly, HRR should be expressed in absolute values (bpm) due to the fact that in this form it can be evaluated immediately making it more practical for sport and exercise settings.
- Maximum and resting HR should only be compared when the same participants are being evaluated. In addition, when dealing with small sample sizes it is recommended that normal day-to-day variations in HRR (which can vary by 6 ± 2 beats per day for values of 85-95% of maximal HR) should be known in order to correct for any inconsistencies and improve statistical significance.

In conclusion, Daanen *et al*. (2012:258) found that studies that were not successful in measuring HRR contained methodological flaws and inconsistencies. One example of methodological related aspects which may cause HRR results to be questioned is the presence of co-founding factors. In this regard environmental factors such as hot and humid conditions may lead to slower HRR due to an increase in vasodilation of blood vessels near the skin which will result in a lower venous return (Daanen *et al*., 2012:259).

2.4 SIMULTANEOUS MEASUREMENT OF HRV AND HRR

Despite above mentioned findings with regard to the value of separately measuring the HRV and HRR of athletes, researchers recommend that these variables should be used in tandem to analyse autonomic function in sport and exercise settings (Lamberts *et al.*, 2009:706). This approach was followed by Oliveira *et al*. (2013:147), who investigated parasympathetic reactivation after maximal exercise through HRV and HRR. Fifteen Healthy male participants (age: 21 ± 3.7 years; BMI: 24 ± 2.2 kg^{-2}) were subjected to a $\dot{V}O_{2max}$ test on a cycle ergometer. HRV and HRR were measured upon voluntary failure for a period of five minutes.

- The variables selected to represent HRV were RMSSD ($RMSSD_{30}$) and SDNN ($SDNN_{30}$) measured during non-overlapping segments for 30 seconds over the course of a five minute recovery period. $RMSSD_{30}$ is considered to reflect parasympathetic activity and $SDNN_{30}$ can be used in tandem with $RMSSD_{30}$ to measure sympathetic withdrawal.
- The variables selected to represent HRR were the absolute difference (in bpm) between the peak HR at end of the $\dot{V}O_{2max}$ test and the HR after the first (HRR_{1min}) and the fifth minute (HRR_{5min}) of test completion. Both of these variables are considered to be indexes of parasympathetic reactivation after maximal exercise.

The HRR results showed a percentage decline of 17.8 ± 3 % and 38.2 ± 3.1 % for the first and fifth minute respectively. Compared to resting levels (measured before the onset of the $\dot{V}O_{2max}$ test) $RMSSD_{30}$ did not increase significantly ($p > 0.05$) during the entire five minute recovery period. However, $SDNN_{30}$ showed a significant increase ($p < 0.05$) throughout the five minute recovery period when compared to resting levels. According to Oliveira *et al*. (2013:146) these results are odd due to the fact that $RMSSD_{30}$ is supposed to represent parasympathetic reactivation and yet remained suppressed after five minutes of recovery. In addition, the HRR after the test (which also represents parasympathetic reactivation) was within normal ranges for the specific population (Oliveira *et al*., 2013:145). The increase in $SDNN_{30}$, suggested that this variable represented sympathetic withdrawal rather than parasympathetic reactivation (Oliveira *et al*., 2013:147). In conclusion, the decline in HR after maximal exercise in the absence of parasympathetic stimulation is contrary to what most researchers believe and was possibly caused by the withdrawal of sympathetic stimulation (Oliveira *et al*., 2013:147).

Although both HRV and HRR are considered to be indicators of ANS function, various researchers found no relationship between HRV and HRR (Oliveira *et al*., 2013:147; Lee & Mendoza, 2012:2761). For example, Esco *et al*. (2010) indicated no relationship between any of the HRV (SDNN, HFnu and LFnu/HFnu ratio) and HRR variables (HRR after one and two minutes of the maximal treadmill exercise test) in 66 male college students. Therefore, researchers suggest that the dissociation between HRR and resting HRV is proof that these variables are independently linked to the ANS (Esco *et al*., 2010:36; Bosquet *et* al., 2007:368). Consequently, protocols that are designed in such a way that both HRV and HRR are measured simultaneously should be given preference above those that only measure one of these variables. The measurement of both HRV and HRR will allow researchers to fully interpret cardiac autonomic regulation in sport and exercise settings. However, co-founding factors which may influence HRV and HRR measurements should be considered when compiling protocols to determine last-mentioned variables.

2.5 FACTORS THAT INFLUENCE HRV AND HRR MEASUREMENTS WITHIN SPORT AND EXERCISE SETTINGS

In the previous section the measurement of HRV and HRR in sport and exercise settings as well as certain methodological factors that may influence HRV and HRR results, were discussed. However, a number of factors that were not discussed in previous sections and that may influence the ANS should also be highlighted as it may influence the outcome of HRV- and HRR-related results. These factors are sleep quality and quantity, muscle soreness, hydration status, pre-competition or exercise anxiety and training/competition intensity. Results of studies that have investigated the possible influence of last-mentioned factors on HRV and HRR measurements are presented in Table 2.10.

Table 2.10: Factors that influence HRV and HRR measurements in sport and exercise settings

Author	Influencing factor	Brief aims and methodology	Results and conclusions
Pecanha *et al*. (2014)	Water intake	12 Male, recreational, active participants (age: 22 ± 1 years) were subjected to a 30-minute high intensity workout on a cycle ergometer on 2 occasions. On the first occasion participants were not allowed to drink water after exercise, whereas participants drank 500ml of water on the second occasion after exercise. This allowed researchers to investigate the effects of hydration on HRR and HRV.	Both HRV (RMSSD, RMSSD30, SD1 and HF peak frequency) and HRR (60 second recovery in bpm) showed significant increases ($p < 0.05$) after water intake followed cessation of a high intensity workout. Therefore, results suggest that hydration improves parasympathetic reactivation as seen by the improvement in HRV and HRR values directly after high intensity exercise.
Plews *et al*. (2014)	Training intensity	9 Elite rowers (4 men and 5 women) were monitored during their preparation period (26 weeks) for the 2012 London Olympics. HRV was measured daily throughout this period in order to investigate the effects of training intensity distribution on post-exercise autonomic activity.	HRV (weekly averaged Ln-RMSSD) was significantly decreased (CI of 90%; $p < 0.05$) after high intensity training sessions (most time spent above lactate threshold intensity) compared to lower intensity training sessions (most time spent under lactate threshold intensity). This led to the conclusion that training at high intensities suppresses parasympathetic activity with subsequent decreases in HRV values.
Mikulski *et al*. (2013)	Sleep deprivation	11 Male, amateur, endurance trained athletes (age: 31 ± 2 years) were subjected to a 30-hour adventure race during which participants had no sleep. The study investigated the effects of prolonged endurance racing along with sleep deprivation on cardiac autonomic regulation. HRV was measured before and after prolonged exercise and sleep deprivation.	RMSSD, SDNN, pNN50 and LF/HF ratio all showed a significant decrease ($p < 0.05$) after prolonged exercise and sleep deprivation. This led to the conclusion that prolonged exercise and sleep deprivation decrease resting HRV in endurance trained athletes.

RMSSD	Squared root of the mean squared differences between successive R to R intervals
RMSSD30	Squared root of the mean squared differences between successive R to R intervals measured for 30 seconds
Ln-RMSSD	Natural logarithm function for the squared root of the mean squared differences between successive R to R intervals
HF	High frequency power
SD1	Standard descriptor 1
SDNN	Standard deviation of R to R intervals
pNN50	Number of successive R to R interval pairs that differ less than 50 milliseconds expressed as a percentage
LF/HF ratio	Low and high frequency expressed as a ratio

Table 2.10 (cont.): Factors that influence HRV and HRR measurements in sport and exercise settings

Author	Influencing Factor	Brief aims and methodology	Results and conclusions
Buchheit *et al.* (2013)	Muscle soreness and training intensity	18 Professional, male, Australian Rules football players (age: 21.9 ± 2 years) completed a 2 week training camp during which HRV along with muscle soreness (subjective questionnaire) and training load (GPS tracking) were evaluated daily in order to investigate the possible relationship between HRV, training load and muscle soreness.	HRV (Ln-SD1) correlated highly with muscle soreness ($r = -0.53$; $p < 0.001$) throughout the training camp. Training load was significantly related to day-to-day changes in HRV ($p < 0.001$). In conclusion, HRV is negatively influenced by an increase in muscle soreness and training load, all factors that should be considered when evaluating changes in autonomic activity.
Mateo *et al.* (2012)	Pre-competitive anxiety	11 Male, national BMX cyclists (age: 19.3 ± 2.1 years) completed the CSAI-2 questionnaire twice before competition days and once on the previous training day to determine pre-competition anxiety during a national championship. HRV was also measured in the morning of each of the last-mentioned days. The study investigated the effects of pre-competitive anxiety on cyclists' resting HRV.	Both somatic and cognitive anxiety significantly increased ($p < 0.001$) on the competition days compared to the training days. HRV indices (SDNN, RMSSD, Ln-LF peak frequency, Ln-HF peak frequency and LF/HF) also showed a significant decrease ($p < 0.05$) during competition days compared to training days. Thus, HRV is negatively influenced by anxiety and may serve as a useful tool in the measurement of competition pressure.
Oliveira *et al.* (2011)	Water intake	10 Healthy adults (7 men and 3 women; age: 23 ± 4 years) were subjected to a 20-minute high intensity cycle ergometer workout on two occasions. On the first occasion participants were not allowed to drink water after exercise, whereas participants drank 500ml of water on the second occasion after exercise. This allowed researchers to investigate the effect of hydration on HRV.	HRV indices (RMSSD, SDNN, pNN50 and HF peak frequency) increased significantly ($p < 0.05$) after water intake compared to no water intake following cessation of a high intensity workout. In conclusion, water intake after high intensity exercise was beneficial to post-exercise autonomic regulation as seen through significant increases in HRV-related measurements.

CSAI-2	Competitive State Anxiety Inventory-2
GPS	Geographic position system
BMX	Bicycle motocross
SDNN	Standard deviation of R to R intervals
RMSSD	Squared root of the mean squared differences between successive R to R intervals
pNN50	Number of successive R to R interval pairs that differ less than 50 milliseconds expressed as a percentage
LF/HF	Low and High frequency expressed as a ratio
Ln-HF	Natural logarithm function of high frequency power
Ln-LF	Natural logarithm function of low frequency power
Ln-SD1	Natural logarithm function of standard descriptor 1

Table 2.10 (cont.): Factors that influence HRV and HRR measurements in sport and exercise settings

Author	Influencing Factor	Brief aims and methodology	Results and conclusions
Blasquez and Ortis (2009)	Pre-competitive anxiety	The pre-competitive anxiety of 10 master swimmers (6 women and 4 men; age: 47 ± 8 years) was evaluated (through the use of the CSAI-2 questionnaire) before training and competition, respectively. HRV was also measured during these occasions in order to examine the relationship between pre-competitive anxiety and autonomic regulation.	HRV indices (RMSSD, HFnu, $HFms^2$ and SD1) all showed significant decreases ($p < 0.05$) before competition compared to training. Pre-competitive anxiety was also found to be significantly ($p = 0.009$) higher before competitions compared to training. Thus, increased pre-competitive anxiety levels may decrease overall HRV.
Vaara *et al.* (2009)	Sleep deprivation	Cardiac autonomic regulation of 20 military cadets (17 men and 3 women; age: 26 ± 3 years) was monitored during a 60-hour sleep deprivation period in order to investigate the effects of sleep deprivation on HRV. Participants were subjected to a 60-hour sleep deprivation period during which HRV was measured twice a day for three days.	Overall, a significant increase ($p < 0.05$) in sympathetic activity during the sleep deprivation period was found. HF (ms^2) and LF (ms^2) absolute powers significantly increased ($p < 0.05$) during and after the sleep deprivation period. HR also showed a significant decrease ($p < 0.001$) over the sleep deprivation period. In conclusion, sleep deprivation can negatively influence cardiac autonomic regulation with subsequent decreases in HRV and HR values.

CSAI-2	Competitive State Anxiety Inventory-2
RMSSD	Squared root of the mean squared differences between successive R-R intervals
HFnu	High frequency power expressed in normalised units
$HFms^2$	High frequency power expressed in ms^2
$LFms^2$	Low frequency power expressed in ms^2
HF	High frequency component
LF	Low frequency component
SD1	Standard descriptor 1
HR	Heart rate

Table 2.10 highlights the potential of external factors such as sleep deprivation, muscle soreness, dehydration, heightened levels of pre-competition anxiety, and high training/match intensities to negatively influence ANS regulation. Results also show that no particular HRV parameter is more affected by last-mentioned factors than others but rather that overall HRV is affected.

Therefore, above-mentioned factors will most likely play a role when HRV and HRR values are measured during training and competition periods, and should be considered when planning HRV and HRR measuring protocols and interpreting results. The use of subjective questionnaires is one way to evaluate athletes' sleep quality and quantity, muscle soreness, hydration status and pre-competition anxiety in sport and exercise settings (Stanley *et al*., 2013:381; Al Haddad *et al*., 2012:34). Subjective questionnaires are quick, non-invasive and effective evaluation tools for use in competitive environments due to the small amount of time and effort that is required from athletes to complete it (Flatt & Esco, 2014:40; Plews *et al*., 2012:3732). However, some researchers do caution against the use of subjective questionnaires due to their dependency on "honest self-assessment" from participants (Plews *et al*., 2012:3737). Then again several researchers have successfully used subjective questionnaires to evaluate external factors such as sleep quality and quantity, muscle soreness, hydration status and pre-competition anxiety in sport and exercise settings (Stanley *et al*., 2013:382; Al Haddad *et al*., 2012:34). Thus, the use of subjective questionnaires (based on the Likert scale) for the evaluation and quantification of external factors that may possibly influence athletes' HRV and HRR values is an established method in sport and exercise settings.

2.6 THE POSSIBLE USE AND APPLICATION OF GPS UNITS IN INDOOR SPORTS

The following section investigates the possible use and application of GPS units in indoor sports as well as the reliability and validity of these devices to determine the match characteristics of indoor sports. Due to the fact that GPS units are among other things used to determine the external (physical) demands of different sports, the match characteristics of badminton singles match play will also be discussed. Heart rate monitoring also forms part of a GPS unit match analysis, which is why this heart rate data of singles badminton players will also be under scrutiny.

2.6.1 The use and application of GPS units in indoor sports

The emergence of GPS units enabled researchers to analyse the external demands of indoor sports in a detailed, time-efficient manner, and to circumvent or minimise the shortcomings of notational analyses (Townshend *et al.*, 2008:130). Monitoring with GPS units in competitive settings are simple, accurate and non-invasive which make them suitable for use by players and researchers alike (Catapult-Sports, 2016; Halson, 2014:145). GPS units are able to determine the external demands of indoor match play through the combined use of a tri-axial accelerometer, magnetometer and gyroscope located within each device (Hurst *et al.*, 2014:3). Tri-axial accelerometers are instruments that simultaneously measure the acceleration forces in three perpendicular axes (X - medio-lateral, Y - anterior/posterior and Z - vertical planes) (Cormack *et* al., 2014:288; Catapult-Sports, 2012b:12). A gyroscope aids the tri-axial accelerometer in determining an athlete's orientation by measuring acceleration forces while taking gravitational forces into account that (Norris *et al.*, 2014:4). The magnetometer then acts a "digital compass" which determines the direction of an athlete's movements (Raffin *et al.*, 2012:15). Therefore, these three instruments can be used to determine the external demands of an activity.

However, the use of tri-axial accelerometers, magnetometers and gyroscopes to analyse the external demands of match play, is still a new phenomenon in the sporting fraternity. The following studies explored the validity, reliability and use of these instruments in sport, exercise and clinical settings:

- Raffin *et al.* (2012:19) showed satisfactory to excellent concurrent validity ($r > 0.83$, $p = 0.001$) when comparing a magnetometer to two pre-existing validated ambulatory devices for measuring gait activity in physically active adults.
- Seifert *et al*. (2014:199) compared and validated small, wireless, light and wearable inertial measurement units (that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer) to an ubiquitous optic system for joint angle assessment during breaststroke swimming and 10m indoor rock climbing. Data revealed a mean error of 5° that were among other things attributed to the drift relating to the inertial measurement units' set up. When the angle was normalised for the drifting interval, the level of similarity increased greatly.
- Beanland *et al.* (2014:237) investigated the criterion validity of wearable integrated tri-axial accelerometers (a Catapult-Sports unit that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer) to assess stroke count in sub-elite swimmers. Stroke count as determined by the accelerometer and actual stroke count (determined by video footage) showed a strong significant correlation ($r = 0.98$, $p < 0.05$). Researchers suggested that the wearable accelerometer devices show acceptable validity to determine stroke count

in the breast stroke and butterfly style as well as a time effective alternative to conventional methods.

- Gastin *et al*. (2013:590) quantified the frequency, velocity and impact acceleration during tackling of Australian Football players through wearable integrated tri-axial accelerometers (a Catapult-Sports unit that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer). Tackles could be classified into three catogories (low, moderate and high) with 61% of the tackles classified as medium intensity tackles. Also, that high intensity tackles are the least frequent tackles (only 6% of total tackles) during a match. They found these instruments to be ecologically valid devices to differentiate and quantify tackles of contact sports such as Australian Football.
- Holleczek *et al*. (2010:7) measured the angle, turn rate and direction of a snowboarding action while participants were coming down a slope and compared data between a GPS receiver and a gyroscope attached to the centre of the snowboard. GPS action detection algorithm slightly outperformed (90.5%) the gyroscope data (88.2%). Researchers concluded that the combined GPS receiver and gyroscope system is capable of recognizing turns and distinguishing between nine different snowboarding activities.
- Bergamini *et al*. (2012:1124) validated stride and stance durations derived from an inertial measurement unit (Freesense-sensorize IMU unit) that included a 3D accelerometer and a 3D gyroscope, using force platforms and a high-speed video camera in amateur and elite athletes during maximal sprint runs outdoors and indoors. Absolute differences in both stride (<2%) and stance duration (<8%) between the inertial measurement unit and reference measurements was of the same order as the temporal resolution of the criterion measure as well as of the unit estimates (0.005 s). Therefore, researchers suggested that the mentioned inertial measurement unit may have potential to provide reliable estimates of temporal parameters during in field training sessions.
- Accelerometers together with magnetometers have also been used to monitor and measure the range of motion, position in space, track ambulatory position, orientation and angular velocities in clinical settings (Johnson *et al*., 2015:4; Raffin *et al*., 2012:20).
- Similairly, Arai *et al*. (2012:178) used a gyroscope to measure the angular velocity of the knee joint during knee extension in older adults in a clinical setting. Researchers suggested that gyroscopes are reliable to measure the angular velocity of joints in the lower extremities in geriatric settings.

- Chandler *et al*. (2014:2735) investigated the match demands of different positions in collegiate female netball players through wearable integrated tri-axial accelerometers (a Catapult-Sports unit that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer). The data obtained through the integrated tri-axial accelerometer showed that match demands do in fact differ significantly ($p < 0.05$) between team positions with center position having the highest match demand. They also found that the metabolic demands of specific skills training and actual match play do not differ significantly ($p > 0.05$). They therefore concluded that a wearable integrated tri-axial accelerometer is a useful and practical measure of the metabolic demands in collegiate netball.
- Boyd *et al*. (2011:319) tested the between-device reliability of a wearable integrated tri-axial accelerometers (a Catapult-Sports unit that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer) for determining the physical activity levels of semi-profesional Australian football players during a three-hour indoor exercise session (playing volley ball). They found that CV was acceptable (below 1.5% at the 90% CI) between the devices. Between-device reliability was also determined over nine AFL games and showed to be acceptable (CV was below 2% at the 90% CI) for monitoring physical activity during Australian football games.
- Cormack *et al*. (2013:288) used wearable integrated tri-axial accelerometers (a Catapult-Sports unit that included a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer) to differentiate between match demands of lower and higher levels of netball match play. Higher level players showed significantly higher ($p < 0.05$) match loads than lower level players. Furthermore, players of a higher level performed significantly more movements in the vertical plane. Consequently, researchers concluded that a wearable integrated tri-axial accelerometer can be used to accurately determine the match loads of netball.

Although in some cases, above-mentioned studies used either a tri-axial accelerometer, magnetometer and gyroscope or a combination of these instruments, the combined use of these instruments should provide better and more accurate results with regard to movement data, and the external demands of sport activities. Furthermore, the “indoor mode” of GPS units allows to function without depending on satellite signals for data collection, which means that data are not affected by signal interferences (Catapult-Sports, 2012c:101). Raw data obtained from tri-axial accelerometers, magnetometers and gyroscopes are analysed by the Catapult Sprint 5.0.9.2

software (Catapult Sports, Victoria, Australia) through advanced Kalman filtering techniques (Catapult-Sports, 2016; Catapult-Sports, 2012b:13).

Few studies have up until now successfully employed GPS units that include a tri-axial accelerometer, magnetometer and gyroscope to determine the match characteristics of indoor sports. Information with regard to the available studies is presented in Table 2.11.

Table 2.11: Studies that have employed GPS units to analyse indoor sports

Author	Sport	Brief aims and methodology	Results and conclusions
Abian *et al.* (2015)	Badminton	16 Male elite badminton players (age: 25.4 ± 7.3 years) took part in a study to determine whether caffeine ingestion was beneficial to match performance. Players were subjected to two separate sessions during which they either received a caffeine drink or a placebo. After 60 minutes players' match data (number of high intensity accelerations/decelerations) were recorded during a simulated badminton match through GPS units (SPI Pro GPS units with integrated accelerometers).	Results showed that the number of high intensity accelerations/decelerations significantly increased after ingesting the caffeinated drink (7395 ± 1594 vs. 7707 ± 2033; $p < 0.05$). Results suggest that caffeine ingestion can be beneficial to actual badminton match performance.
Hurst *et al.* (2014)	Mixed martial arts	8 Male, mixed martial arts (MMA) fighters (age: 25.5 ± 4.5 years) were subjected to a MMA routine in which they were required to perform a series of standing strike, ground strike and take-down techniques. Fighters were fitted with GPS units (Catapult GPS units with integrated accelerometers) which they wore while performing the routine in order to determine the effectiveness of these devices for use in a MMA setting. Fighters wore different GPS units between techniques to test the intra-unit reliability of units for indoor use.	Player load between different techniques showed satisfactory intra-unit reliability (ICC = 0.70-0.97). Accumulated player load also attained satisfactory intra-unit reliability (ICC = 0.79-0.98). It was concluded that GPS units are reliable and effective for determining the physical demands of MMA fighters in indoor settings.
Leite *et al.* (2013)	Basketball	10 Male basketball players (age: 17.5 ± 0.3 years) participated in the study to determine the effect of time-outs on the spatial organisation of basketball teams. Players were subjected to two separate sessions: one session involved a continuous game of 20 minutes and the other session consisted of a 20 minute game interrupted by a one-minute time-out every five minutes. Players were fitted with GPS units (SPI Pro GPS units with integrated accelerometers) to record match data.	During the time-out games players covered significantly more ($p < 0.05$) distance at lower running speeds and less distance at higher running speeds. Researchers concluded that this contributed to better spatial organisation during the time-out games. Researchers also recommended that GPS units be used to further explore the time-motion analysis of basketball.

GPS	Global positioning system
HR	Heart rate

Table 2.11 (cont.): Studies that have employed GPS to analyse indoor sports

Author	Sport	Brief aims and methodology	Results and conclusions
Hoffman *et al*. (2012)	Basketball	10 Female basketball players (age: 21.2 ± 1.6 years) were subjected to two trial games which lasted 40 minutes each. The purpose of the study was to determine the effect of L-alanyl-L-glutamine (AG) on basketball performance. During the first trial game players ingested water (500ml) and during the second trial game water with AG (2g/500ml). Players were fitted with GPS units (Catapult GPS units with integrated accelerometers) in order to measure player load.	Player load was significantly greater ($p < 0.05$) after ingesting AG compared to only water. Researchers concluded that the increased player load associated with AG intake prolonged players' ability to maintain a higher level of play. Therefore, AG intake could possibly benefit overall basketball performance.
Boyd *et al*. (2011)	Volleyball	10 Male Australian Football players (age: 23.2 ± 2.3 years) were recruited to complete a three-hour indoor exercise session (playing volleyball). During this session between-device reliability of GPS units (Catapult GPS unit with integrated accelerometers) was tested.	Researchers found that coefficient of variation was acceptable (below 1.5% at the 90% CI) among the devices and therefore concluded that GPS unit with integrated accelerometers could be used interchangeably among players during a simulated volleyball match.
Montgomery *et al*. (2010)	Basketball	11 Male basketball players (age: 19.1 ± 2.1 years) were recruited to characterize physical and physiological responses to basketball specific drills and practice games. Each player was fitted with a $\dot{V}O_{2max}$ unit, HR monitor and GPS unit (Catapult GPS unit with integrated accelerometers), which they wore during the basketball specific drills and practice games on an indoor court.	No significant differences ($p < 0.05$) in player load, mean HR and the oxygen cost ($\dot{V}O_2$) were observed, between offensive and defensive basketball drills. However, there were significant differences ($p < 0.05$) in player load, mean HR and the oxygen cost ($\dot{V}O_2$) between the practise games and basketball specific drills. Researchers therefore concluded that live play seems to be more demanding than basketball drills. Lastly, the combined use of a GPS unit and HR monitor can be recommended to determine basketball practise and live play demands.

$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
GPS	Global positioning system
HR	Heart rate

Table 2.11 shows that GPS units have previously been used to monitor and determine the demands of various indoor sports. The use of GPS units in these settings aided researchers to explore the effects of caffeine and L-alanyl-L-glutamine ingestion on match performance in sports such as badminton and basketball, respectively (Abian *et al*., 2015:1048; Hoffman *et al*., 2012:7). Furthermore, GPS units allowed coaches to determine how certain training structures affect the responses of high-level basketball players (Leite *et al*., 2013:217; Montgomery *et al*., 2010:84). Lastly, Hurst *et al*. (2014:5) and Boyd *et al*. (2011:319) validated the interchangeable use of GPS units for MMA and volleyball. Therefore, results suggest that GPS units can be used to monitor the demands of indoor sports such as badminton.

2.6.2 Charactertistics of singles badminton match play

It is in light of the last-mentioned statement that studies that have investigated the charactertistics of singles badminton match play by making use of conventional methods will be discussed in order to provide the reader with information regarding badminton match demands. Badminton is described as a fast-paced, vigorously intense and highly reactive sport (Garrido-Esquivel *et al*., 2011:256). Badminton players can be involved in more than one version of the game as it is not uncommon for an elite singles player to be part of a doubles or mixed doubles team during the same tournament (Badminton World Federation, 2014; Carson, 2014). Thus, depending on the duration and scope of the tournament, badminton players may compete in three or more matches per day during team-based tournaments or as many as four singles and doubles matches over a few days during individual events (Laffaye *et al*., 2015:585; Badminton World Federation, 2014; Garrido-Esquivel *et al*., 2011:258). The match characteristics of male, singles badminton are summarised in Figure 2.6.

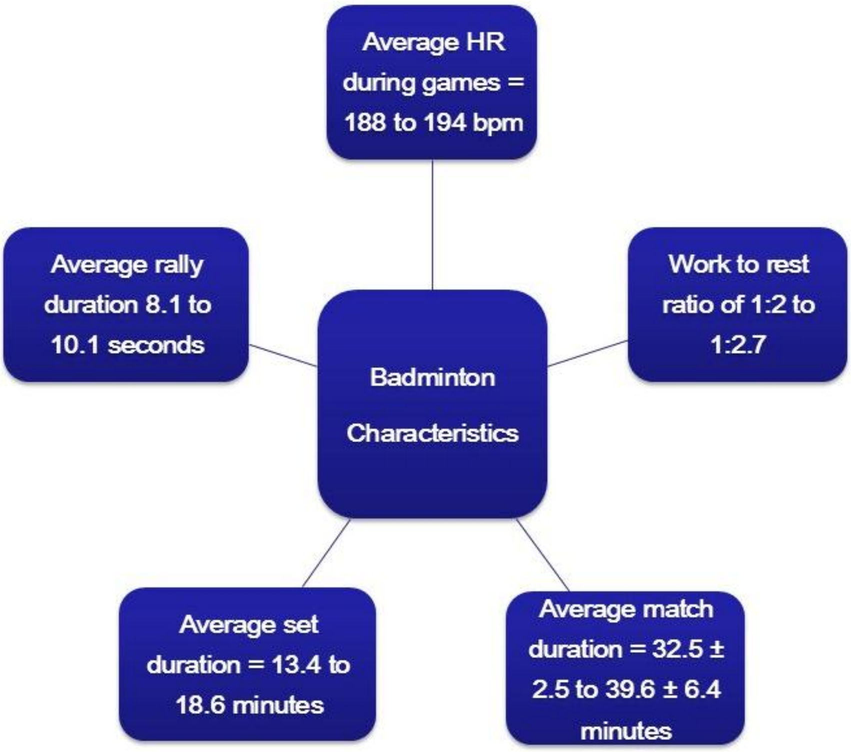

Figure 2.6: Match characteristics of male, singles badminton (Phomsoupha & Laffaye, 2015:447; Laffaye *et al*., 2015:586; Abian-Vincen *et al*., 2013:317; Chen & Chen, 2008:40; Tu, 2007:139; Andersen *et al.*, 2007:127; Faude *et al*., 2007:484; Lees, 2003:710)

Figure 2.6 shows that total match duration varies between 32.5 and 39.6 minutes, with individual sets lasting between 13.4 and 18.6 minutes and rallies for 8.1 to 10.1 seconds on average (Laffaye *et al*., 2015:586; Abian-Vincen *et al*., 2013:317; Chen & Chen, 2008:40; Tu, 2007:139). Furthermore, badminton match play delivers work-to-rest ratios of between 1:2 and 1:2.7 for men's single matches (Phomsoupha & Laffaye, 2015:474; Chen & Chen, 2008:35; Tu, 2007:140). Lastly, average absolute heart rates of between 188 and 194 beats per minute are reported for male, singles badminton players during match play (Phomsoupha & Laffaye, 2015:481; Andersen *et al.*, 2007:127; Faude *et al*., 2007:484; Lees, 2003:710). Elite players can easily reach HR of over 200 bpm during match play, although average maximal heart rates for elite and sub-elite players range between 90 to 94% of their true maximal HR (Laffaye *et al*., 2015:586). Therefore, badminton is considered to be a physiologically demanding sport that requires very high fitness levels for players to be able to effectively and successfully play several matches in a short period of time during a tournament (Phomsoupha & Laffaye, 2015:474; Faude *et al*., 2007:482).

2.7 CONCLUSIONS

Despite the potential of HRV and HRR to act as indicators of athletes' fitness levels and performances, studies that have investigated these aspects in competitive environments are scarce. It is against this background that the primary aims of this chapter were, *firstly,* to discuss the physiological properties of the ANS as well as the physiological mechanisms that underlie HRV and HRR as measures of ANS function; *secondly,* to discuss the procurement, quantification and interpretation procedures of HRV and HRR in sport and exercise settings; *thirdly*, to reveal relationships between HRV, HRR and sport as well as exercise performance; *fourthly*, to highlight the possible influences of sleep quality and quantity, muscle soreness, hydration status and pre-competition anxiety on HRV and HRR as measures of ANS function; *fifthly*, to discuss the match characteristics of elite, male, singles badminton players as well as the possible use and application of GPS units in indoor sports and *finally,* to indicate the limitations of using HRV and HRR as measures of ANS function in sport and exercise settings.

The chapter began by illustrating that the ANS entirely or partially control arterial pressure, sweating, body temperature, gastrointestinal motility, gastrointestinal secretion, bladder emptying and many other physiological functions. Literature also indicates that the ANS is divided into the SNS and the PNS which have antagonistic characteristics but function synergistically. Functions of these branches of the ANS differ with the SNS that prepares and sustains the body to face a crisis, danger or stress whereas the PNS is more active when a person is calm and relaxed, and little physical demand is put on the body. The collaborative nature of the SNS and PNS leads to effective and responsive regulation of the cardiovascular system. Thus, information with regard to the response of the ANS during exercise, and more importantly, during competition participation is invaluable to exercise scientists who want to better understand how the demands of sport and exercise affect the nervous system. In this regard both HRV and HRR are regarded to be established measures of cardiac ANS function and are used in sport and exercise settings due to their time-efficient and non-invasive qualities.

HRV is usually measured by determining the time that elapses between two R-R cycles and by quantifying these values through HRV analysis software in order to obtain different HRV measures for interpretation. HRV derived variables can be divided into time-, frequency- and non-linear-based categories with each category portraying different branches of ANS status (SNS and PNS activity). Currently, the two ways in which researchers measure HRV are single-day HRV measurements and daily/weekly rolling average HRV measurements. HRV measured on a more longitudinal basis (daily, weekly or during competition) is a widely accepted approach to monitor the ANS over time. With this approach meaningful negative or positive changes in HRV can be detected. Research that has used this approach show that HRV can be effectively used as a training prescription tool to detect early signs of fatigue and prevent over-training, thereby ensuring that training days are used optimally. Additionally, HRV can also serve as a predictor of on-field performances in team sports as well as of individual performances in aerobic related sports.

Literature also indicates that Ln-RMSSD is the preferred HRV-related parameter when daily/weekly rolling average HRV measurements are used in sport and exercise settings in order to evaluate ANS activity. However, the success of the daily/weekly rolling average HRV measurement approach lies in the creation of a unique cardiac autonomic profile (using a repertoire of HRV measurements) for each individual athlete. This profile is required because of the unique response of each athlete's ANS during training and competition participation. In addition, HRV has to be measured in the same manner and conditions every time to ensure that external factors do not influence measurements.

On the other hand, researchers who wish to investigate the acute effects of exercise and sport on ANS activity usually measure HRV within a single day. Research that made use of this approach show that significant relationships do exist between established performance indicators such as aerobic fitness, anaerobic capacity and match/game results and HRV-measures. Therefore, HRV can be employed in a range of sport and exercise settings as well as in a competitive environment. However, the single day measurement approach limits researchers to only a few opportunities to capture HRV. In view of this, researchers need to use a large number of HRV-measures to quantify HRV. Different HRV-measures capture different branches of ANS activity and enable researchers to fully investigate ANS status.

Overall, the review identified several practical uses for HRV and presented different methodological approaches through which HRV can be measured in training or competition settings. Guidelines and recommendations on how to measure HRV in sport and exercise settings were also discussed in order to highlight the advances made by researchers and practitioners in this regard. These guidelines and recommendations focused on the following aspects that must be considered when HRV measuring protocols are applied in sport and exercise settings: time duration and frequency of measurements, raw data analysis and type of HRV-related parameters used. Additionally, beforehand researchers must determine the HRV measurements which will be the most effective for a specific protocol or research design, the external factors that should be considered and the possible effects of breathing frequency on HRV results.

HRR is widely accepted as an index of parasympathetic reactivation and overall ANS health. HRR values are usually obtained by measuring HR with a HR monitor at cessation of a maximal or sub-maximal exercise and again post-exercise at a certain time point. HRR is then calculated as the decrease in HR (in bpm) or as a percentage decrease of exercise to post-exercise HR. HRR after one minute is the most widely used parameter due to the practicality of exploiting this HRR variable in sport and exercise settings as it is almost immediately available. Generally HRR is measured after standardised $\dot{V}O_{2max}$ tests or field tests in order to standardise exercise intensities and durations so that intra- en inter-group HRR values can be compared. HRR which is measured in this way can be used as an indicator of aerobic fitness, training status and a measure of exercise capacity. However, more recently several researchers and practitioners started to use HRR measures that were obtained during sport participation. These studies revealed that HRR can be used as a predictor of on-field performance and may act as a discriminator between different levels of athletes (elite over sub-elite). Despite the value of HRR measures, researchers must realise that HRR values can only be compared if athletes are from the same sport and were measured by making use of the same methodological approach. Furthermore, the type of body position during recovery, reliability and practicality of different HRR indices, time frame from which HRR is measured and effects of circadian rhythms on HRR should not be ignored. In addition, researchers should standardise the percentage of an individual's maximal- and sub-maximal HR from which HRR is taken and consider co-founding factors such as atmospheric conditions, the training modality and the possible effects of exercise intensity on HRR.

In the penultimate part of the review it was acknowledged that external factors such as a decrease in sleep quality and quantity, high levels of muscle soreness, dehydration, heightened levels of pre-competition anxiety, and high training/match intensities have the potential to negatively influence HRV, HRR and ANS regulation. These external factors are all present during competition participation and should therefore be considered when interpreting HRV and HRR measurements as well as evaluating the ANS. The use of subjective questionnaires (based on a Likert scale) seems to be the most practical approach to measure and evaluate last-mentioned factors in competitive settings where time is limited.

Lastly, the review discussed the use and application of GPS units in indoor sports as well as the badminton match characteristics of elite, male, singles players. GPS units are able to determine the external demands of match play through the combined use of tri-axial accelerometers, magnetometers and gyroscopes. Several studies have validated the use of tri-axial accelerometers, magnetometers and gyroscopes in sports such as Australian football, netball, sprinting, snowboarding, and swimming to determine external match loads as well as to define match charateristics of a specific sport. These instruments are regarded to be invaluable tools to replace time-consuming notational analyses and to serve as training aids to coaches and sport scientists. However, several indoor sports have also taken note of the advantages of using last-mentioned instruments. In this regard GPS units (with integrated tri-axial accelerometers, magnetometers and gyroscopes) have been successfully employed to determine the effects of supplements (caffeine and L-alanyl-L-glutamine) on match performance in badminton and basketball; to determine differences in physical and physiological responses between sport specific drills and actual match play in basketball as well as to determine the physical demands of MMA. The interchangeable use of these GPS units have also been proven in sports such as MMA and volleyball. Therefore despite a scarcity in research that have thus far used GPS units to monitor and determine the demands of competitive badminton match play, results suggest that GPS units can be used to monitor the demands of indoor sports such as badminton.

Studies that investigated thet match characteristics of elite, male, singles badminton players revealed that average match durations vary between 32.5 and 39.6 minutes, individual sets between 13.4 and 18.6 minutes and rallies for 8.1 to 10.1 seconds on average at work-to-rest ratios of between 1:2 and 1:2.7. Players reach absolute heart rates of between 188 and 194 beats per minute during matches which fall between 90 to 94% of maximal HR. Therefore, badminton is considered to be a physiologically demanding sport that requires very high fitness levels for players to be able to effectively and successfully play several matches in a short period of time during a tournament.

In summary, this literature study accentuated the importance and value of HRV and HRR as indicators of ANS activity for sport participants and practitioners in the field of sport science. However, the possible link between HRV, HRR measures and sport performances in various sports such as racquet sports must still be established. Results also suggest that HRV and HRR are more of value if measured during competition participation compared to laboratory-based or competition simulation scenarios. The main reason for this is that athletes' ANS reacts differently under these conditions compared to laboratory-based or competition simulation scenarios. Baseline HRV measurements are usually measured in resting conditions when an athlete is calm and has just woken up. However, baseline measurements are not always possible in competitive settings due to time and logistical constraints. Research should therefore focus more on the measurement and analyses of HRV and HRR values that are obtained during real competitions or matches. Key to these types of investigations is a practical and validated methodological approach that is relevant for situations during which athletes are participating. External factors such as sleep quantity and quality, muscle soreness, hydration levels, pre-competition anxiety levels as well as competition intensities that are also related to competition participation, should however be considered when doing studies of this nature.

Even though current literature does highlight the value of using HRV and HRR in sport and exercise settings, several limitations and recommendations to address these limitations should be taken into account when using HRV and HRR as possible measures of sport and exercise performance, physiological fatigue or overtraining. HRV and HRR measurers alone are not always sufficient to predict performance, monitor fatigue or determine overtraining. Therefore HRV and HRR must be used in conjunction with other widely accepted performance, fatigue and overtraining indicators such as aerobic fitness, competition demands or characteristics, match performance outcomes, grip strength, explosive power as well as overall perception of wellness and fatigue (Buchheit, 2014:85). Another limitation of using HRV is that daily/weekly rolling average HRV measurements is the preferred method for obtaining measurements. However this methodological approach is not always practical or possible in training and competition settings, which places the focus on the use and value of short-term HRV measurements (less than five minutes).

Researchers are also confronted with more or less a similar problem when it comes to the use of HRR. A practical and valid method for obtaining HRR measures during competition participation must still be determined. Furthermore, post-match or post-game HRR measures often vary considerably from one match or game to the next probably due to, among other factors, differences in match or game intensities. One way to limit the possible influence of game or match intensities is to account for this variable when establishing HRR values. Furthermore, methods to establish in-match HRR values can probably control for variability between values by setting a fixed criteria such as a certain percentage of maximum HR attained during the match from which HRR is determined. In addition it will also be of value to standardize recovery conditions when determining HRR. Standardising the period over which HRR is taken during or after matches or games, can also assist in curbing a high variability in HRR measures. The value of using ultra short-term (less than 60 seconds) HRR measures should be further investigated as very few researchers have thus far focussed on the use of this type of methodological approach in their research protocols.

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CHAPTER 3

ARTICLE 1:

HEART RATE VARIABILITY AND HEART RATE RECOVERY AS PREDICTORS OF ELITE, AFRICAN, MALE BADMINTON PLAYERS' PERFORMANCE LEVELS

This article was submitted to the *Journal of Strength and Conditioning Research* and is currently under review.

TITLE: HEART RATE VARIABILITY AND HEART RATE RECOVERY AS PREDICTORS OF ELITE, AFRICAN, MALE BADMINTON PLAYERS' PERFORMANCE LEVELS

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RUNNING HEAD: HEART RATE VARIABILITY AND RECOVERY IN BADMINTON PLAYERS

THIS MANUSCRIPT IS ORIGINAL AND NOT PREVIOUSLY PUBLISHED, NOR IS IT BEING CONSIDERED ELSEWHERE UNTIL A DECISION IS MADE AS TO ITS ACCEPTABILITY BY THE JSCR EDITORIAL REVIEW BOARD.

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Abstract

The primary aim of this study was to determine whether pre-match, in-match, resting and post-match heart rate variability (HRV) as well as resting and post-match heart rate recovery (HRR) can serve as significant predictors of performance levels of male, elite, African, singles badminton players'. Twenty-two male badminton players (age 23.3 ± 3.9 years) were categorised into successful and less successful player groups according to match results. A Fixed Polar Heart Rate Transmitter Belt was used to record heart rate every second before (pre-match), during (in-match) and directly after (post-match) 46 national and international matches to determine 14 HRV and two HRR indices. Binary, forward, stepwise logistic regression analyses' results showed that only spectral HRV indices, namely log transformed low frequency to high frequency ratio (Ln-LFnu/Ln-HFnu ratio) and peak very low frequency power (VLF power (Hz)), were significantly ($p < 0.05$) related to group allocation of successful and less successful badminton players. Overall model fit was good and 75% of players could be classified into their original groups by making use of the HRV-based logistic regression formulas. Furthermore, all models had a large effect in predicting classification of players, although only the pre- and in-match models emerged as being useful. Overall results suggest that HRV and HRR can be measured over different periods in real competition matches. In conclusion, short term frequency domain-related HRV variables are related to badminton match performances and should be considered when measuring HRV in sport and exercise settings.

KEY WORDS: match analysis, autonomic nervous system, parasympathetic, sympathetic

INTRODUCTION

Since the emergence of heart rate variability (HRV) and heart rate recovery (HRR) as indicators of the autonomic nervous system (ANS) activity in sport and exercise, these markers have been received with a great deal of interest and have stimulated ever-increasing research in this area (3,9). HRV describes the oscillations that occur between successive heartbeats (successful cardiac cycles or R-R intervals) (37). On the other hand, HRR is the rate at which heart rate (HR) decreases (or time taken for HR to recover) after moderate to high-intensity exercise (3). Many regard HRV and HRR as important ANS parameters that are useful for monitoring athletes' fatigue, fitness and the ability to adapt to different training intensities (3,5,9). Additionally, research suggests that HRV and HRR can serve as performance indicators for sports such as basketball, cycling and endurance running (7,24,36). However, the use of HRV and HRR in the badminton fraternity, and more importantly, the possible relationships of HRV and HRR to badminton performance, have not yet been investigated and form an integral part of this study.

In view that the ANS is responsible for regulating an array of visceral bodily functions that contribute significantly to sport and exercise performance (28), optimal functioning and the overall status of the ANS during training may be key to peak performance (11). It is therefore not surprising that researchers such as Fronso et al. (24), found that HRV (as measured through high frequency [HF] power) accounted for 15% ($p < 0.05$) of the variance in basketball match performance. Similarly, Buchheit et al. (7) observed a significant, negative correlation ($r = -0.52$, $p = 0.002$) between the natural logarithmic transformation of the squared root of the mean squared differences between successive R-R intervals (Ln-RMSSD) and maximal aerobic speed in young, male soccer players. The standard deviation of R-R intervals (SDNN) and standard descriptor two (SD2) also correlated significantly with Yo-Yo intermittent recovery: test 1 (Yo-Yo IR1) performance ($r = 0.89$, $p = 0.07$ and $r = 0.92$, $p = 0.03$, respectively) in elite, male football players (4). Consistently higher HRV values are also observed in endurance trained athletes compared to untrained individuals, and research suggests that vigorous training is required to induce HRV changes (1). On the other hand, moderate, significant correlations were found between HRR, 40m sprint (r = 0.39, p < 0.05) and repeated sprint performance (r = -0.38, p < 0.05) in young, male football players (8). Well-trained endurance athletes also exhibit a faster than normal HRR after maximal exhaustive exercise compared to sedentary individuals (14). Esco et al. (18) further suggested that HRR and HRV are independent makers of ANS activity. Therefore, positive changes in HRR and HRV indices may be differentially associated with improvements in neuromuscular-related performance parameters such as sprinting and repeated sprint ability in athletes (7,8,14,17).

Badminton is physiologically a highly demanding sport, which requires very high fitness levels to be able to effectively and successfully play several matches in a short time during a tournament (20,27). Although not badminton related, research suggests that match play may lead to a significant decrease (p < 0.05) in parasympathetic stimulation as measured through increases (p < 0.05) in HRV (low-frequency and high-frequency powers expressed as a ratio (LF/HF)) (6). Therefore, the demands of long-duration match play may lead to neuromuscular fatigue in badminton (28). Accumulated neuromuscular fatigue will negatively affect players' abilities to execute shots with optimal force and accuracy, and may also lead to less reactive court movements and poor tactical choices during matches (42). Players will, therefore, need to recover fully between matches to maintain muscle power output and a high cognitive ability during match play (28). However, high aerobic fitness levels might enable badminton players to meet the cardiovascular and metabolic requirements of match play, cause smaller decreases in HRV and higher HRR values as well as prevent neuromuscular fatigue (14,20,28,42).

It is against this background that the primary aim of this study was to determine if pre-match, in-match, resting and post-match HRV as well as post-match and in-match (as measured during breaks between sets) HRR can serve as significant predictors of male, elite, African, singles badminton players' performance levels. The hypothesis of the study is that pre-match, in-match, resting and post-match HRV as well as post-match and in-match rest HRR will serve as significant predictors of male, elite, African, singles badminton players' performance levels. Results may provide direction for the future use of HRV and HRR as predictors of badminton performance. Also, positive results concerning the use of HRV and HRR as indicators of badminton match performance may provide coaches and players with an incentive to integrate HRV and HRR into their training regimes.

METHODS

Experimental Approach to the Problem

A selected group, repeated measures, observational, descriptive and *ex post facto* design was used for the study. On the first day of each of the tournaments informed consent was obtained from participating players as well as permission from participants' coaches in cases where they were available. Participants then completed a general information questionnaire regarding their exercising habits, injury incidence and competing level. After completion of all relevant documentation participants' stature and body mass measures were determined. Before each match warm-up, participants were fitted with a Fixed Polar HR Transmitter Belt to record HR every second during each match. During the warm-up period signals of HR monitors were checked, participants were familiarised with the equipment and HR transmitter belts were adjusted according to each participants' preference. Before the start of each match, a video camera was stationed on a tri-pod stand behind each of the courts that matches were played on. This aided the reserachers to divide the raw data into different match periods. Altogether, twenty-two players were measured before, during and after 46 matches. Each player was therefore measured more less two times with several players being measured three times. All championships took place over a period of two to three days, except for the Free-State National Championships which took place over a day, which meant that players were monitored and measured on consecutive days.

Approval for the study was obtained from the Health Research Ethics Committee of the North-West University (NWU) where the research was conducted (NWU-00199-14-A1). The study was conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and the ethical guidelines of the National Health Research Ethics Council of South Africa. Permission to conduct the research was also obtained from the Badminton World Federation (BWF), the Badminton Confederation of Africa (BCA), the Botswana Badminton Association (BBA), and Badminton South Africa (BSA).

Subjects

Twenty-two elite, male, African, singles badminton players (age 23.3 ± 3.9 years; height 177.1 ± 3.0 cm; mass 83.4 ± 14.5 kg) gave written informed consent to participate in the study. Participants competed in the following championships during the 2014/2015 season: All Africa Badminton Senior Championships, South African International Championships, Free-State National Championships, u/19 South African National Championships and the University Sport South Africa (USSA) Badminton Championships. The sample represented ten African countries, namely Botswana, Cameroon, Congo, Egypt, Namibia, Nigeria, South Africa, Uganda, Zambia and Zimbabwe. Only participants who were actively involved and competed as members of their respective teams and national badminton federations in abovementioned tournaments as well as those who were injury free at the time of testing were eligible to participate in the study. Participants' competitive badminton playing experience ranged between 4 and 12 years (mean = 9.5 ± 2.7 years). The following information concerning participants' training regimen was also obtained: participants trained for 4 ± 1 day a week which consisted of on-court training for 4 ± 1 day a week and weight training for 2 ± 2 days a week.

Procedures

Demographic and general information questionnaire: Participants' demographic and personal information were collected using a questionnaire. Participants' ages, exercising habits, injury history, competing levels and highest achievement were also obtained by means of this questionnaire.

Anthropometric measurements: Body mass was recorded to the nearest 0.1 kg, using a calibrated BFW 300 Platform scale (Adam equipment Co. Ltd., U.K.) and body stature to the nearest 0.1 cm, using a Harpenden portable stadiometer (Holtain Ltd., U.K.) so as to describe the specific cohort of participants.

Video match recordings: Before the start of each match a video camera (Sony HDR-PJ790VE Handycam, Sony Corporation, Tokyo, Japan) was stationed on a tri-pod stand behind each of the courts where matches were played. Video recordings of each match were downloaded onto a laptop computer. The video footage was used to determine the time periods of each match so that researchers were able to set the correct duration for heart rate analyses.

Heart rate variability (HRV): A Fix Polar HR Transmitter Belt along with a Polar HR Monitor (Polar Team^2 Pro, Polar Electro, Kempele, Finland) were used to record variations in beat to beat (R-R) intervals before, during and after matches. Polar HR Monitors are valid devices for measuring heart rate and for obtaining R-R intervals (26). For example, time and frequency domain HRV measurements did not differ significantly ($p > 0.05$) between a Polar heart rate monitor (Polar S810i) and an ambulatory Holter ECG recorder (26). Polar Heart Rate Transmitter Belts were adjusted according to each participant's chest size and tied around the chest, at the level of the xiphoid process after electrode areas were moistened by tap water. A Polar Heart Rate Monitor was then clipped onto the Polar Heart Rate Transmitter Belt of each player before he stepped on the court to begin his pre-match warm-up routine.

R-R-intervals were obtained for the following time periods: The first set of HRV-related measurements was taken 60 seconds before the match warm-up (pre-match) which took place five minutes before the start of each match. The next set of HRV-related measurements was calculated by determining the average R-R values for each 60-second interval match playing time (in-match). The last set of R-R intervals was taken 60 seconds directly after play stopped (post-match). The first and third sets of HRV-related measurements were taken while participants stood upright and maintained a normal breathing pattern. Finally, R-R-intervals were calculated for rest periods between sets which lasted a minimum of 60 seconds (in-match rest). This was made possible by synchronising the chronological time indexes of the digital video camera, Polar Heart Rate Monitor and wrist watches used during data collection. After data collection, researchers meticulously went through the video footage to identify and divide different periods of the match.

Researchers used Kubios HRV software (Version 2.1, Biosignal Analysis and Medical Imaging Group at the Department of Applied Physics, University of Kuopio, Kuopio, Finland) for final HRV analyses from the series of R-R-intervals. This software has become popular and has been used in several studies that employed HRV analysis software (40,41,43). Results of the following 14 HRV indices were obtained by the above-mentioned software and used in subsequent statistical analyses:

Time domain-related HRV indices consisting of:

- The natural logarithmic transformation of the standard deviation of R-R intervals in milliseconds (Ln-SDNN);
- The natural logarithmic transformation of the square root of the mean squared differences between successive R-R intervals in milliseconds (Ln-RMSSD)
- The mean of R-R intervals in milliseconds (Mean R-R).

Frequency domain-related HRV indices consisting of:

- Very low band peak frequencies in hertz (Peak VLF Hz)
- Low band peak frequencies in hertz (Peak LF Hz);
- High band peak frequencies in hertz (Peak HF Hz);
- The natural logarithmic transformation of LF relative power expressed as normalised units (Ln-LFnu)
- The natural logarithmic transformation of HF relative power expressed as normalised units (Ln-HFnu)
- VLF relative power expressed as percentage (VLF%);
- LF relative power expressed as percentage (LF%);
- HF relative power expressed as percentage (HF%) and
- The ratio between Ln-LFnu and Ln-HFnu components (Ln-LFnu/Ln-HFnu ratio)

Non-linear domain related HRV indices consisting of:

- The natural logarithmic transformation of standard descriptor 1 (Ln-SD1) and

- Standard descriptor 2 (Ln-SD2)

Heart rate recovery (HRR): HRR was calculated by determining the absolute value at 60 seconds (i.e., HR at 1-min recovery subtracted immediately post HR) as well as percentage decline (i.e., HR at 1-min recovery divided by immediately post HR multiplied by 100) for 60 seconds from the post-set or -match attained HR directly after play had stopped. However, in cases where a participant's post-set or post-match HR did not obtain a value above 85% of a participant's theoretical maximal HR (208–0.7*age) the HRR measurement was discarded (3,14,29). Boullosa et al. (4) successfully measured short-term HRR (20 seconds) from sub-maximal HR during periods of active recovery in soccer players who played small-sided soccer games. However, these researchers only measured HRR in cases where players actively recovered for at least 20 seconds during which they did not exceed a walking pace of 4km per hour. HRR was also not measured if players did not reach at least 85% of their theoretical maximal HR. Previous research (14) suggests that HRR is a measure of parasympathetic reactivation.

Match performance determination: Participants were grouped according to tournament results. Participants who reached the quarter-finals, semi-finals or finals of each tournament were categorised as "successful players" whereas the rest of players were categorised as "less successful players". Additionally, participants were allocated points according to the specific round in which the match was won: first round matches = 1; second round matches = 2; third round matches = 4; quarter-final matches = 6; semi-finals matches = 8; finals matches = 10. The average points that each participant achieved over the five tournaments were then used to allocate participants to "successful player" or "less successful player" groups.

Statistical analysis

The Statistical Data Processing package (Statsoft Inc., 2015), was used to process data. Firstly, a log transformation was applied to HRV variables to improve the normality of data. Secondly, descriptive statistics (minimum and maximum values, averages, and standard deviations) of each variable were calculated. Subsequently, an independent *t*-test was performed to determine significant differences between HRV- and HRR-related variables and successful and less successful groups of players. The level of significance was set at $p \leq 0.05$. Thirdly, tree clustering, single-linkage, 1-Pearson Correlation Coefficient cluster analyses (45) of all HRV- and HRR-related indices were performed to detect clusters of measures that are related to each other. Linkage distance for detection of different clusters was set at 0.2. Fourthly, the cluster reduced variables were entered into a binary forward stepwise logistic regression. These variables were used to screen for the predictive value of different HRV and HRR related (independent) variables in predicting successful and less successful players' group classification (dependent variables). Next, the significance of individual logistic regression coefficients for each independent variable was determined by making use of the Wald statistic. The level of significance was set at $p \leq 0.05$. In the final model, the odds ratios (OR) and 95% confidence intervals (95% CI) for all individual variables were estimated. The Hosmer and Lemeshow Chi-square Goodness-of-fit test was used to test for the adequacy of HRV- and HRR-related logistic models with adequately fitted logistic models being indicated by a non-significant χ^2-value ($p > 0.05$). The predicted probabilities of being in the successful or less successful groups were computed by making use of the logistic regression formulas. Results of these analyses were reported in the form of classification tables. The usefulness of models was determined by calculating the "hit rate" and "chance hit rate" (25). Models were deemed to be good if the observed "hit rate" was 25% better than the "chance hit rate" (25). Lastly, the "better than chance" index (*I*) was calculated by comparing the actual or observed "hit rate" with the "chance hit rate”, to verify last-mentioned results and also to determine the effect size of prediction models. Guidelines of Huberty and Lowman (33) were used to categorize the *I*-values: small= $I < 0.1$, medium = $0.15 < I < 0.25$ or large = $I > 0.3$.

RESULTS

Descriptive statistics as well as the statistical significance of differences for variables between successful and less-successful player groups during different time periods are presented in Tables 1 to 5. From the entire sample, the number of participants that were placed in the successful group and less successful group was twelve and ten, respectively.

TABLE 1. Descriptive statistics and statistical significance of differences in age, body stature, weight and HR measures of the players

	Total group (n = 22)	Successful group (n = 12)	Less successful group (n = 10)	P-level
Age (years)	23.39 ± 3.92	23.37 ± 3.65	23.41 ± 4.43	0.98
Height (cm)	177.11 ± 3.06	176.88 ± 2.83	177.63 ± 3.94	0.70
Weight (kg)	83.46 ± 14.59	82.14 ± 15.91	86.43 ± 12.62	0.65
HR minimum (bpm)	115.39 ±21.41	115.58 ± 19.78	115.15 ± 24.31	0.96
HR mean (bpm)	166.76 ±13.84	165.73 ± 14.65	168.00 ± 13.47	0.71
HR maximum (bpm)	192.78 ± 11.31	190.64 ± 11.91	195.35 ± 10.58	0.34

Table 1 shows that players obtained an average exercise HR of 166.76 ± 13.84 bpm with an average maximum HR of 192.78 ± 11.31 bpm during matches. No significant differences were found between successful and less successful players with regard to the anthropometric and HR-related variables.

Pre-match HRV results

TABLE 2. Descriptive statistics and statistical significance of differences in HRV-related variables over the pre-match period between successful and less successful badminton players

	Total group (n = 22)	Successful group (n = 12)	Less successful group (n = 10)	P-level
Mean R-R	457.72 ± 54.75	451.84 ± 65.08	464.78 ± 41.45	0.59
Ln-SDNN	3.72 ± 0.80	3.89 ± 0.59	3.50 ± 1.00	0.29
Ln-RMSSD	3.32 ± 1.00	3.33 ± 0.91	3.30 ± 1.16	0.94
Peak VLF (Hz)	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.82
Peak LF (Hz)	0.10 ± 0.03	0.08 ± 0.02	0.12 ± 0.02	0.001*
Peak HF (Hz)	0.27 ± 0.05	0.26 ± 0.04	0.28 ± 0.07	0.46
VLF Power (%)	17.62 ± 14.01	25.36 ± 12.91	8.34 ± 8.88	0.001*
LF Power (%)	28.51 ± 14.25	32.09 ± 17.01	24.20 ± 9.07	0.20
HF Power (%)	53.34 ± 18.75	42.10 ± 16.49	66.84 ± 10.82	0.001*
Ln-LFnu Power	3.60 ± 0.51	3.88 ± 0.35	3.25 ± 0.46	0.001*
Ln-HFnu Power	4.01 ± 0.38	3.81 ± 0.40	4.26 ± 0.14	0.001*
Ln-LFnu/Ln-HFnu	0.92 ± 0.22	1.04 ± 0.21	0.77 ± 0.13	0.001*
Ln-SD1	3.39 ± 1.04	3.60 ± 0.83	3.15 ± 1.25	0.32
Ln-SD2	3.82 ± 0.70	3.97 ± 0.50	3.64 ± 0.87	0.27

$p < 0.05$ *

During the pre-match period the HRV parameters that were significantly higher for the successful compared to the less successful player group were: VLF power (%) ($p < 0.001$), Ln-LFnu power ($p < 0.001$) and Ln-LFnu/Ln-HFnu ratio ($p < 0.001$). In contrast, HF power (%) ($p < 0.001$), Ln-HFnu power ($p < 0.001$) and Peak LF (Hz) ($p < 0.001$) were significantly lower for the successful compared to the less successful badminton player group.

In-match HRV results

TABLE 3. Descriptive statistics and statistical significance of differences in HRV-related variables over the in-match period between successful and less successful badminton players

	Total group (n = 22)	Successful group (n = 12)	Less successful group (n = 10)	P-level
Mean R-R	354.19 ± 28.53	351.52 ± 25.46	357.40 ± 32.96	0.64
Ln-SDNN	3.12 ± 0.58	3.30 ± 0.59	2.91 ± 0.52	0.12
Ln-RMSSD	2.43 ± 0.75	2.66 ± 0.75	2.15 ± 0.69	0.11
Peak VLF (Hz)	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.12
Peak LF (Hz)	0.09 ± 0.03	0.07 ± 0.02	0.11 ± 0.04	0.02*
Peak HF (Hz)	0.24 ± 0.04	0.24 ± 0.05	0.24 ± 0.04	0.97
VLF Power (%)	24.60 ± 19.13	31.80 ± 18.13	15.96 ± 17.33	0.05*
LF Power (%)	30.08 ± 10.45	32.26 ± 13.62	27.45 ± 3.77	0.29
HF Power (%)	44.98 ± 19.20	35.64 ± 14.46	56.18 ± 18.69	0.01*
Ln-LFnu Power	3.77 ± 0.37	3.95 ± 0.28	3.56 ± 0.36	0.08
Ln-HFnu Power	3.92 ± 0.32	3.79 ± 0.28	4.10 ± 0.29	0.02*
Ln-LFnu/Ln-HFnu	0.98 ± 0.18	1.05 ± 0.15	0.88 ± 0.16	0.02*
Ln-SD1	2.66 ± 0.82	2.89 ± 0.81	2.39 ± 0.78	0.15
Ln-SD2	3.26 ± 0.54	3.42 ± 0.55	3.07 ± 0.47	0.12

$p < 0.05$ *

During the in-match period the HRV parameters that were significantly higher for the successful compared to the less successful player group were: VLF power (%) ($p < 0.05$) and the Ln-LFnu/Ln-HFnu ratio ($p < 0.02$). Dissimilarly, HF power (%) ($p < 0.01$), Ln-HFnu power ($p < 0.02$) and Peak LF (Hz) ($p < 0.02$) were significantly lower for the successful compared to the less successful badminton player group.

In-match rest HRV results

TABLE 4. Descriptive statistics and statistical significance of differences in HRR- as well as HRV-related variables over the in-match rest periods between successful and less successful badminton players

	Total group (n = 22)	Successful group (n = 12)	Less successful group (n = 10)	P-level
Mean R-R	364.07 ± 46.12	362.68 ± 31.62	365.74 ± 61.13	0.88
Ln-SDNN	3.15 ± 0.69	3.23 ± 0.69	3.07 ± 0.70	0.59
Ln-RMSSD	2.25 ± 1.01	2.36 ± 1.05	2.11 ± 1.00	0.58
Peak VLF (Hz)	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.04*
Peak LF (Hz)	0.09 ± 0.04	0.07 ± 0.03	0.10 ± 0.04	0.05*
Peak HF (Hz)	0.21 ± 0.05	0.22 ± 0.06	0.20 ± 0.05	0.32
VLF Power (%)	31.21 ± 28.28	42.01 ± 26.29	18.25 ± 26.06	0.05*
LF Power (%)	35.25 ± 15.82	33.68 ± 17.65	37.14 ± 14.00	0.62
HF Power (%)	33.33 ± 22.90	24.13 ± 17.14	44.37 ± 24.82	0.04*
Ln-LFnu Power	3.99 ± 0.44	4.14 ± 0.28	3.82 ± 0.53	0.09
Ln-HFnu Power	3.58 ± 0.55	3.46 ± 0.44	3.72 ± 0.66	0.28
Ln-LFnu/Ln-HFnu	1.16 ± 0.31	1.22 ± 0.23	1.08 ± 0.38	0.32
Ln-SD1	2.23 ± 1.02	2.49 ± 1.01	1.92 ± 0.98	0.20
Ln-SD2	3.38 ± 0.66	3.43 ± 0.67	3.33 ± 0.67	0.72
HRR (%)	12.90 ± 6.31	12.72 ± 4.13	13.13 ± 8.49	0.88

$p < 0.05$ *

During the in-match rest periods the only HRV parameter that was significantly higher for the successful compared to the less successful player group was VLF power (%) ($p < 0.05$). On the other hand, HF power (%) ($p < 0.05$) and peak LF (Hz) ($p < 0.05$) were significantly lower for successful compared to the less successful badminton player group.

Post-match HRV results

TABLE 5. Descriptive statistics and statistical significance of differences in HRR- as well as HRV-related variables over the post-match period between successful and less successful badminton players

	Total group (n = 22)	Successful group (n = 12)	Less successful group (n = 10)	P-level
Mean R-R	381.49 ± 52.15	380.47 ± 44.14	382.70 ± 62.93	0.92
Ln-SDNN	3.24 ± 0.62	3.41 ± 0.65	3.04 ± 0.55	0.17
Ln-RMSSD	2.42 ± 1.01	2.56 ± 1.13	2.24 ± 0.87	0.46
Peak VLF (Hz)	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.02*
Peak LF (Hz)	0.09 ± 0.04	0.07 ± 0.03	0.11 ± 0.04	0.02*
Peak HF (Hz)	0.24 ± 0.07	0.24 ± 0.08	0.23 ± 0.07	0.54
VLF Power (%)	33.39 ± 28.38	43.89 ± 26.85	20.80 ± 25.97	0.05*
LF Power (%)	29.86 ± 15.27	30.33 ± 19.76	29.29 ± 8.11	0.88
HF Power (%)	36.43 ± 25.29	25.46 ± 18.20	49.58 ± 27.11	0.02*
Ln-LFnu Power	3.90 ± 0.47	4.08 ± 0.36	3.68 ± 0.51	0.05*
Ln-HFnu Power	3.62 ± 0.66	3.43 ± 0.65	3.81 ± 0.62	0.13
Ln-LFnu/Ln-HFnu	1.14 ± 0.38	1.25 ± 0.37	1.01 ± 0.36	0.13
Ln-SD1	2.44 ± 1.14	2.66 ± 1.25	2.18 ± 0.99	0.34
Ln-SD2	3.45 ± 0.54	3.59 ± 0.55	3.27 ± 0.49	0.16
HRR (%)	14.30 ± 4.80	13.28 ± 4.81	15.53 ± 8.49	0.28

$p < 0.05$ *

During the post-match period only VLF power (%) ($p < 0.05$) and Ln-LFnu power ($p < 0.05$) were significantly higher for the successful compared to the less-successful player group. In contrast, HF power (%) ($p < 0.02$), peak LF (Hz) ($p < 0.02$) and peak VLF (Hz) ($p < 0.02$) were significantly lower for successful compared to the less successful badminton player group.

Regarding HRR, no significant differences were found between the successful and less successful badminton player groups for any of the time periods.

Value of different HRV and HRR related variables in predicting successful and less successful players' group classification

In an attempt to first identify variables that relate to each other and to retain only relevant variables for each stepwise logistic regression, cluster analyses were executed. Results of these analyses are as follow:

- Pre-match HRV-related variables were reduced from 14 to the following 8 variables for the last-mentioned period: Mean R-R, Ln-RMSSD, peak HF (Hz), Ln-HFnu power, peak VLF (Hz), VLF power (%), LF power (%) and Ln-LFnu/Ln-HFnu ratio.
- In-match HRV-related variables were reduced from 15 to 8, which included the following: mean R-R, Ln-RMSSD, VLF power (%), LF power (%), Ln-HFnu power, Ln-LFnu/Ln-HFnu ratio, peak VLF (Hz) and peak HF (Hz).
- Post-match related HRR and HRV variables were reduced from 15 to the following 9 variables: HRR, Ln-RMSSD, peak VLF (Hz), peak LF (Hz), peak HF (Hz), LF power (%), VLF power (%), Ln-HFnu power and Ln-LFnu/Ln-HFnu ratio.
- In-match rest related HRR and HRV variables were reduced from 15 to the following 9 variables: HRR, mean R-R, Ln-RMSSD, peak VLF (Hz), peak HF (Hz), Ln-LFnu/Ln-HFnu ratio, VLF power (%), LF power (%) and Ln-HFnu power.

These variables were inserted into forward stepwise logistic regression analyses, with the following results (Table 6).

TABLE 6. Forward stepwise logistic regression analyses' results of pre-match, in-match, post-match and in-match rest HRV

Variable	Odds ratio (95% CI)	p-level
	Pre-Match	
Ln-LFnu/Ln-HFnu	12.0 (-25.50 - -1.48)	0.03*
	In-Match	
Ln-LFnu/Ln-HFnu	12.0 (-13.50 - -0.77)	0.03*
	In-Match Rest	
Peak VLF (Hz)	7.0 (2.36 - 222.47)	0.05*
	Post-Match	
Peak VLF (Hz)	7.0 (10.61 - 286.95)	0.03*

*$p \leq 0.05$

Table 6 shows that Ln-LFnu/Ln-HFnu ratio (pre- and in-match) and peak VLF (Hz) (post- and in-match rest periods) were identified as the only HRV-related variables that significantly predicted badminton players' group allocation. The Hosmer and Lemeshow Chi-square Goodness-of-fit test revealed values of 5.79 (p = 0.67), 9.66 (p = 0.29), 3.87 (p = 0.57) and 3.07 (p = 0.69) for pre-match, in-match and post-match as well as in-match rest periods, respectively. Therefore, all values delivered results that were non-significant ($p > 0.05$) which indicate that the models' estimates fit the data at an acceptable level.

TABLE 7. Classification table of the predicted probabilities of being in the successful or less successful badminton player groups

Group	Value of the predicted probability		
	Group 1	Group 2	Percentage correct
Pre-Match			
Less successful group (Group 1)	8	2	80
Successful group (Group 2)	3	9	75
Total	11	11	77.5%
In-Match			
Less successful group (Group 1)	8	2	80
Successful group (Group 2)	3	9	75
Total	11	11	77.5%
In-Match rest			
Less successful group (Group 1)	7	3	70
Successful group (Group 2)	3	9	75
Total	10	12	72.5%
Post-Match			
Less successful group (Group 1)	7	3	70
Successful group (Group 2)	3	9	75
Total	10	12	72.5%

The classification table indicates that 75% (pre-match and in-match) and 72.5% (post-match and in-match rest periods) of players could again be classified into their original groups by making use of the HRV component-based logistic regression formulas. The "hit rates" and "chance hit rates" were calculated to be 77.27% and 50% (difference of 27.27%), 77.27% and 50% (difference of 27.27%), 72.73% and 50.41% (difference of 22.32%) as well as 72.73% and 50.41% (difference of 22.32%) for each of the last-mentioned periods, respectively. Therefore, only the two first-mentioned logistic models of identified HRV-related variables can be regarded as useful models in view that the "hit rate" is more than 25% better than the "chance hit rate" in predicting different groups. *I*-values that were calculated are 0.55, 0.55, 0.45 and 0.45 for the above-mentioned periods, respectively. Consequently, *I*-values show that each of the models had a large effect in predicting the classification of successful and less successful badminton players.

DISCUSSION

To the researchers' knowledge, this is the first study to investigate the predictive value of forward stepwise logistic regression, HRV- and HRR-related models to classify successful and less-successful badminton players into groups. Results showed that only pre-match and in-match Ln-LFnu/Ln-HFnu as well as post-match and in-match rest peak VLF power (Hz) served as significant HRV-related predictors to distinguish between successful and less successful badminton player's groups. The hypothesis that pre-match, in-match, resting and post-match HRV as well as post-match and in-match rest HRR will serve as significant predictors of the male, elite, African, singles badminton players' performance levels, can therefore only be partly accepted.

Further analyses also revealed that the models' estimates for each of the time periods fit the data at an acceptable level. Despite the identification of only one HRV-related variable as a significant predictor of group allocation for each of the named time periods, on average 75% of players could be classified back into their original groups by making use of the HRV-based logistic regression formulas. Although *I*-values showed that each of the models had a large effect in predicting the classification of successful and less successful badminton players, only the pre- and in-match models emerged as useful models.

Peak VLF (Hz) was only significantly related to badminton performance levels when measured during the post-match period. Players who achieved better match performances obtained significantly higher average VLF power (%) values (31.80% ± 18.13%) compared to players who lost most of their matches (15.96% ± 17.33%). VLF seems to be more prominent in the absence of parasympathetic stimulation and in the presence of higher sympathetic stimulation (16). D'Ascenzi et al. (15), for example, showed that elite volley players' relative VLF power increased significantly ($p < 0.05$) on the day of a decisive match compared to the previous two days before the match, and attributed this change in HRV-related values to the physiological and psychological effects of pre-competitive stress. Consequently, VLF is regarded to be an indicator of cardiac and overall stress (30). Clinical studies have also observed a direct link between the VLF components of a spectral analysis and blood circulation, thermoregulation as well as vasomotor tone (2,13). Nevertheless, researchers are still unsure about the exact role of VLF power in serving as an indicator of ANS activity and more importantly the relation between this variable and sports performance (15).

On the other hand, the Ln-LFnu/Ln-HFnu ratio surfaced as the only significant HRV-related predictor of group allocation when measured before and during matches. More successful badminton players achieved significantly higher average Ln-LFnu/Ln-HFnu ratios for pre-match (1.04 ± 0.21 versus 0.77 ± 0.13) and in-match periods (1.05 ± 0.15 versus 0.88 ± 0.16) compared to less successful players. Ln-LFnu/Ln-HFnu ratio is regarded to be an index of autonomic balance where a value of above one indicates sympathetic predominance and a value less than one, parasympathetic predominance (10).

Consequently, results suggest that more successful badminton players exhibited higher sympathetic activity together with lower parasympathetic activity before, during and after matches than their less successful counterparts. This finding is similar to a study of seven world class rowers whose autonomic balance shifted from parasympathetic towards sympathetic predominance during the period leading up to the rowing world championships (34). Iellamo et al. (34) attributed the shift in sympathetic predominance to a neurovegetative adaption that reduces the inhibiting mechanisms of the parasympathetic nervous system (PNS), while simultaneously enhancing sympathetic activity. The increase in sympathetic activity prepares the cardiovascular system for rapid, wide and anticipatory variations in HR, cardiac output, flow distribution and muscle perfusion during highly demanding competitions (34).

However, from a physiological point of view, these results are in direct contrast to what others concluded. For example, various researchers consider sympathetic predominance to be an indicator of fatigue or over-training and not favourable for peak performance (9,15). Generally, parasympathetic predominance and reactivation are more associated with an athlete’s readiness to perform (9). In this regard Fronso et al. (24) identified Ln-HF components (HF power components transformed into their natural logarithms) as significant predictors (multiple regression result: $R^2 = 0.15$; $p < 0.05$) of basketball game performance. Furthermore, Cipryan et al. (12) used total spectral power (TP), relative power in percent of low (LF%) and high frequency components (HF%), as well as the LF/HF to significantly ($p < 0.05$) predict changes in game performance of ice hockey players. In addition, a study on Australian football players found that spectral (peak VLF power (Hz), peak LF power (Hz), peak HF power (Hz), LF/HF, Ln-LF and Ln-HF), time (mean R-R, pNN50 and TINN) and non-linear HRV indices (SD1 and SD2) were significantly related to football match performance (all regression results were above 0.7 at the 95% confidence interval) (13).

Differences between the psychological states of individual players during a competitive period may cause some players to shift towards sympathetic predominance due to higher pre-competitive stress levels, which would explain why players in this study showed dissimilar HRV values than players in other studies (15,27). Furthermore, it is possible that a high variation in individual HRV responses as seen by the high standard deviations in HRV values caused some HRV-related variables to be omitted from the prediction model.

Several researchers (9,44) have also alluded to the value of Ln-RMSSD, a time domain-related HRV parameter, for the quantification of HRV in sport and exercise settings. Ln-RMSSD is regarded to be more accurate during short and ultra-short term HRV measurements (22), due to its innate lack of sensitivity to breathing frequency (44). Some researchers also argue that Ln-RMSSD is a more important recovery marker for day-to-day athletic monitoring and for tracking of long term changes in fitness, rather than for identifying "physiological strain" (17,21,23). However, despite these results and the fact that our study employed a wide range of time domain-related HRV indices, which also included Ln-RMSSD, only frequency domain-related HRV-indices (HFnu power and VLF power (Hz)) were identified as significant predictors of group allocation. Frequency domain-related HRV variables are reported to be more sensitive and reliable to reflect mood, attention and respiratory changes in participants (31). It is, therefore, possible that these attributes caused the frequency domain-related HRV variables to be identified as level performance predictors rather than the time domain-related HRV variables.

One unexpected finding of this study was that neither in-match resting nor post-match HRR was identified as significant predictors of group allocation. Furthermore, HRR values did not differ significantly between successful and less successful badminton players. This was unexpected due to results of a previous study which showed that HRR after 10 and 20 seconds served as the distinguishing factor between elite and sub-elite football players with elite football players exhibiting a significantly faster HRR than their sub-elite counterparts (40). Similarly, highly trained wrestlers exhibited faster ($p < 0.05$) HRR values than moderately trained wrestlers (32). Researchers also found superior HRR to be associated with on-field match performance in sports such as basketball and soccer (4,29). Players in this study obtained below average post-match HRR values (14.30 ± 4.80 %) when compared to the suggested HRR values that players should obtain (38%) (35). Post- and in-match resting HRR values also varied considerably between players, probably due to among other factors differences in match and game intensities. All these factors would negatively influence the forward stepwise logistic regression analysis results and prevent HRR from being identified as a player group predictor.

One way in which researchers of this study tried to curb HRR variability among players, was by setting a fixed percentage (85%) of maximum HR from which HRR was determined. In some cases players obtained much higher HR values than the fixed value, which would lead to lower HRR values. Given these findings, the use and value of ultra-short-term (less than 60 seconds) HRR measures in sports settings for the prediction of badminton performance levels should be further investigated as very few researchers have thus far focussed their attention on this variable.

Although the study is the first of its kind to show that spectral HRV indices are significantly related to badminton performance, results must be interpreted with caution since the binary forward stepwise regression logistic model was developed specifically for male, elite, African, singles badminton players. Therefore, the accuracy of this model should be tested and measured through longitudinal studies to evaluate its significance, adequacy, accurateness and usefulness among different populations of badminton players. Furthermore, the absence of true baseline measurements, normally taken in the mornings during a fasting state, is a limitation of this study. However, time and logistical constraints experienced when measuring athletes in a real competition set-up make the measurement of baseline values difficult. Consequently, the methodology of this study provide practitioners in the fields of exercise and sport science with a more practical approach to obtain and evaluate athletes' HRV and HRR values during competition participation when compared to more traditional methodological approaches. Lastly, although differences in fitness levels between players may have influenced HRV and HRR values, researchers did not measure or consider this variable in their measuring protocol. Future research should, therefore, consider players' fitness levels when analysing and interpreting HRV and HRR results.

PRACTICAL APPLICATIONS

The short-term HRV and HRR measuring protocol of this study can be used successfully to accurately measure HRV and HRR during different time periods in real competition settings. Furthermore, spectral HRV indices such as the Ln-LFnu/Ln-HFnu ratio and peak VLF (Hz) measured over the short term appear to be related to badminton match performances and should, therefore, be considered when measuring HRV in sport and exercise settings. Despite that the study referred to prediction models, practitioners would not use these HRV-related models to predict group allocation, but rather use it to determine if a player's specific HRV profile indicates that they he/she is ready to perform well during match play. Lastly, post-match and in-match resting HRR does not offer any value regarding performance level prediction. However, it would be beneficial for practitioners and sports scientists alike to measure HRV and HRR over longer periods of time to create a competition related cardiac autonomic profile of each player. Nonetheless, more research is needed to confirm current findings and to establish whether HRV and HRR can be consistently used as indicators of match performance within the confines of competitive badminton.

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CHAPTER 4

ARTICLE 2:

RELATIONSHIP BETWEEN AUTONOMIC MARKERS OF HEART RATE AND SUBJECTIVE INDICATORS OF RECOVERY STATUS IN ELITE, MALE, BADMINTON PLAYERS

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RELATIONSHIP BETWEEN AUTONOMIC MARKERS OF HEART RATE AND SUBJECTIVE INDICATORS OF RECOVERY STATUS IN MALE, ELITE BADMINTON PLAYERS

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Running Head: Autonomic Markers in Badminton Players

Abstract

The primary aim of the study was to determine if heart rate variability (HRV), and heart rate recovery (HRR) are related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players. HRV and HRR were measured in twenty-two badminton players' before (pre-match), during (in-match), after (post-match) and during rest periods (in-match rest) of 46 national and international matches. Muscle soreness, hydration status, and sleep quality and quantity were measured on a daily basis whereas mood states were measured just before each match *via* questionnaires. Prior to each match warm-up, players were fitted with a Fix Polar Heart Rate Transmitter Belt to record heart rate every second during each match and HRR during service breaks and after matches. Kubios HRV software was used for final HRV analyses from the series of R-R-intervals. A strong, significant canonical correlation (Rc = 0.96, p = 0.014) was found between HRV, HRR and subjective indicators of recovery status for the in-match period, but only strong, non-significant relationships were observed for pre-match (Rc = 0.98, p = 0.626) and post-match periods (Rc = 0.98, p = 0.085) and a low non-significant relationship (Rc = 0.69, p = 0.258) for the in-match rest period. Canonical functions accounted for between 47.89% and 96.43% of the total variation between the two canonical variants. Results further revealed that Ln-HFnu, the energy index and vigour were the most prominent variables in the relationship between the autonomic markers of heart rate and recovery-related variables. In conclusion, this study showed that subjective indicators of recovery status influence HRV and HRR measures obtained in a competitive badminton environment and should therefore be incorporated in protocols that evaluate these ANS-related parameters.

Key words: Heart rate variability, heart rate recovery, subjective recovery questionnaires, racquet sports.

Introduction

The emergence of heart rate variability (HRV) and heart rate recovery (HRR) as indicators of autonomic nervous system (ANS) activity has stimulated research in sport science (Buchheit, 2014). However, HRV and HRR measuring protocols should adhere to certain guidelines in order to ensure the accuracy, validity and reliability of HRV and HRR measures in sport and exercise settings (Plews et al., 2014). Although existing guidelines do provide some direction with regard to the measurement of autonomic markers of heart rate, various factors that are related to competition participation and could negatively influence HRV and HRR measures, are often not considered. In this regard valid and widely used subjective indicators of recovery status such as muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states may influence HRV and HRR measures in such a way that the accuracy, validity and reliability of these cardiac autonomic measures are questioned (Buchheit et al., 2013; Stanley et al., 2013; Plews et al., 2012). Nevertheless, available studies that have explored these potential associations have several shortcomings such as, only focusing on one of the aforementioned indicators at a time, the use of a small number of HRV-related measures, the exclusion of the HRR measure and the use of non-athletes as study participants.

Oliveira et al. (2011) established that the root mean square of differences between successive R-R intervals (RMSSD), as well as the standard deviation of R-R intervals (SDNN) were significantly higher in a group who ingested 500 ml of water after a 20-minute, sub-maximal, cycle test compared to a group who ingested no water. They therefore concluded that water intake had a positive effect on post-exercise HRV (Oliveira et al., 2011). Researchers also showed that sleep deprivation caused a significant increase in vagal activity [i.e., high frequency power (HF) and low frequency power (LF)] and a significant decrease in heart rate over a period of 60 hours in physically fit adults (Vaara et al., 2009). Furthermore, a psychological mood related factor, namely anxiety, produced significant decreases in RMSSD, LF:HF ratio and normalised LF power (LFnu) in high level swimmers during competition periods when higher pre-competitive anxiety levels were experienced (Blasquez and Ortis, 2009). In addition, Buchheit et al. (2013) found that increased daily muscle soreness was significantly, negatively correlated (r = 0.53) with the natural logarithmic transformation of standard descriptor one of a Poincare plot (ln-SD1) in professional Australian football players throughout a training camp. Last-mentioned findings suggest that athletes' hydration status, muscle soreness, sleep quality and quantity as well as pre-competition mood state levels will significantly influence HRV-related measures.

The presumed parasympathetic origin of both HRR and vagal-related HRV indices as well the establishment of moderate relationships between vagally mediated measures of HRV and HRR immediately after exercise (Nunan et al., 2010; Buchheit et al., 2007), would suggest that the above-mentioned recovery indicators would have a similar effect on HRR. However, several researchers reported no relationships between absolute and relative HRR at the 1st minute post-exercise with HRV parameters (Molina et al., 2016; Javorka et al., 2002). In contrast, significant positive correlations were observed between relative HRR and all assessed time and frequency domain HRV parameters measured from the 5th and 10th minute of recovery post-exercise (Javorka et al., 2002). Last-mentioned findings would suggest that parasympathetic outflow differentially affect HR level (HRR) and HR modulation (HRV), although proof for this contention must still be found (Buchheit et al., 2007). Thus, the extent to which above-mentioned recovery indicators affect HRV and HRR is still unknown since both markers appear to be independently linked to ANS control (Esco et al., 2010).

Up until now, researchers made use of subjective questionnaires to measure muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states of participants. For example, Gastin et al. (2013) reported significant pre- versus post-differences in muscle fatigue, sleep quality, stress and general well-being following training in elite rugby league players when subjective questionnaire ratings were used. Other researchers also suggested that self-reported player ratings are useful tools to monitor different aspects of recovery (mood states, quality of sleep, over-all fatigue, muscle soreness and hydration levels) during training and competition participation (Saw et al., 2015; Buchheit et al., 2013; Leti and Bricout, 2013; Lew et al., 2010).

Consequently, it is necessary to determine if HRV and HRR are specifically related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players. Therefore the hypothesis of this study is that significant relationships exist between HRV, HRR and last-mentioned subjective indicators of recovery status for different match periods in male, elite, African, singles badminton players. The study may establish whether a relationship exists as well as determine the size and direction of this relationship between last-mentioned variables. This is also the first study of which the outcome may provide HRV and HRR protocol guidelines to researchers, sport scientists and coaches who want to measure HRV and HRR in competitive badminton and other sport settings.

Method

Participants

Twenty-two male, elite, African, singles badminton players (age 23.3 ± 3.9 years; height 177.1 ± 3.0 cm; mass 83.4 ± 14.5 kg) who participated in the following championships during the

2014/2015 season gave written informed consent to participate in the study: All Africa Badminton Senior Championships, South African International Championships, Free-State National Championships, u/19 South African National Championships and the University Sport South Africa (USSA) Badminton Championships. Players represented ten African countries, namely Botswana, Cameroon, Congo, Egypt, Namibia, Nigeria, South Africa, Uganda, Zambia and Zimbabwe. According to definitions of Swann et al. (2015) players could be categorised into three categories, namely: competitive-elite players who regularly compete at the highest level but did not have any success at that level; successful-elite players who have experienced some (infrequent) success at the highest level and world-class elite players who sustained success at the highest level, with repeated wins over a prolonged period of time.

Only players who were actively involved and competing as members of their respective teams and national badminton federations in above-mentioned tournaments as well as those who were injury free at the time of testing were eligible to participate in the study. Players' competitive badminton playing experience ranged between 4 and 12 years (mean = 9.5 ± 2.7 years). The following information with regard to the training regimen of the badminton players was also obtained: players trained for 4 ± 1 days a week which consisted of on-court training for 4 ± 1 days a week and weight training for 2 ± 2 days a week.

Approval for the study was obtained from the Health Research Ethics Committee of the North-West University (NWU) where the research was conducted (NWU-00199-14-A1). The study was conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and the ethical guidelines of the National Health Research Ethics Council of South Africa. Furthermore, permission to conduct the research was obtained from the Badminton

World Federation (BWF), the Badminton Confederation of Africa (BCA), the Botswana Badminton Association (BBA), and Badminton South Africa (BSA).

Test procedure

Twenty-two players were measured before, during and after 46 matches. Each player was therefore measured more less two times with several players being measured three times. All championships took place over a period of two to three days, except for the Free-State National Championships which took place over a day, which meant that players were monitored and measured on consecutive days. Every day before the start of each match, participants completed a recovery and hydration status as well as muscle soreness questionnaire during which researchers were present to assist players who had questions regarding the questionnaire. Participants also completed a general information questionnaire regarding their exercising habits, injury incidence and competing level. After completion of all relevant documentation, participants' stature and body mass measures were taken. Ten minutes before the start of each match, players also completed the Stellenbosch Mood Scale (STEMS) (Terry et al., 2003) under the supervision and guidance of the research team. Prior to each match warm-up participants were fitted with a Fix Polar Heart Rate Transmitter Belt to record heart rate every second during each match. The warm-up period was also used to check the signals of the heart rate monitors before each match began, to make participants accustomed to the equipment and to adjust the heart rate transmitter belts according to each participant's preference. Before the start of each match a video camera was stationed on a tri-pod stand behind each of the courts that matches were played on in order to make recordings. This aided the reserachers to divide the raw data into different match periods. The test procedure is illustrated in Table 1.

Table 1. Summary of test procedure

Test procedure				
30-60 minutes before match	**10 minutes before match**	**1 minute before match**	**During match**	**Directly after match**
• Consent form • General information questionnaire • Recovery questionnaire • Hydration status questionnaire • Muscle soreness questionnaire	• Profile of mood states questionnaire	• Pre-match HRV	• In-match HRV • In-match rest HRV (between service breaks) • In-match rest HRR (between service breaks)	• Post-match HRV • Post-match HRR

Test components

Demographic and general information questionnaire

Participants' demographic and personal information was collected by means of the above-mentioned questionnaire. Participants' ages, exercising habits, injury history, competing levels and highest achievement were also obtained by means of this questionnaire. Participants also had to indicate whether they were taking any medication or supplements during their participation in the tournament.

Anthropometric measurements

The following anthropometric components were determined according to the protocols of the International Society for the Advancement of Kinanthropometry (ISAK) (Stewart et al., 2011) to describe the specific cohort of participants: Body mass to the nearest 0.1 kg, using a calibrated BFW 300 Platform scale (Adam equipment Co. Ltd., U.K.) and body stature to the nearest 0.1 cm, using a Harpeden portable stadiometer (Holtain Ltd., U.K.). Measurements were performed twice by a Level 2 ISAK certified Anthropometrist.

Heart rate variability (HRV)

A Fix Polar Heart Rate Transmitter Belt along with a Polar Heart Rate Monitor (Polar Team^2 Pro, Polar Electro, Kempele, Finland) were used to record variations in beat to beat intervals (R-R intervals) before, during and after matches. Polar Heart Rate Monitors have been shown to provide valid measures of heart rate and HRV when compared to ambulatory Holter ECG devices (Gamelin et al., 2006). The Polar Heart Rate Transmitter Belt was adjusted according to each participant's chest size and tied around the chest, just below the chest muscles after the electrodes were moistened by tap water. A Polar Heart Rate Monitor was then clipped onto the Polar Heart rate Transmitter Belt of each participant before he stepped onto the court to begin his pre-match warm-up routine.

R-R-intervals were obtained for the following time periods:

The first set of HRV-related measurements were taken 60 seconds before the match warm-up (pre-match) which took place 5 minutes before the start of each match. The next set of HRV-related measurements were calculated by determining the average R-R values for each 60-second interval playing time during the entire match (in-match). The last set of R-R intervals was taken 60 seconds directly after play stopped (post-match). The first and third sets of HRV-related measurements were taken while participants stood upright and maintained a normal breathing pattern. Finally, R-R-intervals were also calculated for rest periods between sets which lasted a minimum of 60 seconds (in-match rest). This was made possible by synchronising the chronological time indexes of the digital video camera, Polar heart rate monitor, and wrist watches being used during data collection. After data collection researchers meticulously went through the video footage to identify and divide different periods of the match.

Kubios HRV software (Version 2.1, Biosignal Analysis and Medical Imaging Group at the Department of Applied Physics, University of Kuopio, Kuopio, Finland) was used for final HRV analyses from the series of R-R-intervals obtained from Polar devices. This software has become popular and has been used in several studies that employed HRV analysis software (Plews et al., 2014; Nakamura et al., 2009; Perandini et al., 2009). Frequency domain-related indices were obtained by making use of the fast Fourier transform algorithm. Results of the following 14 HRV indices were obtained by making use of the above-mentioned software and used in subsequent statistical analyses:

Time domain-related HRV indices consisting of:

- The natural logarithmic transformation of the standard deviation of R-R intervals in milliseconds (Ln-SDNN);
- The natural logarithmic transformation of the square root of the mean squared differences between successive R-R intervals in milliseconds (Ln-RMSSD) and
- The mean of R-R intervals in milliseconds (Mean R-R).

Frequency domain-related HRV indices consisting of:

- The very low band peak frequencies in hertz (Peak VLF Hz)
- The low band peak frequencies in hertz (Peak LF Hz);
- The high band peak frequencies in hertz (Peak HF Hz);

- The natural logarithmic transformation of LF relative power expressed as normalised units (Ln-LFnu)
- the natural logarithmic transformation of HF relative power expressed as normalised units (Ln-HFnu)
- VLF relative power expressed as percentage (VLF %);
- LF relative power expressed as percentage (LF %);
- HF relative power expressed as percentage (HF %) and
- The ratio between Ln-LFnu and Ln-HFnu components (Ln-LFnu/HF Ln-HFnu)

Non-linear domain related HRV indices consisting of:

- The natural logarithmic transformation of Standard descriptor 1 (Ln-SD1) and
- Standard descriptor 2 (Ln-SD2)

Heart rate recovery (HRR)

HRR was calculated by determining the absolute value at 60 seconds (i.e., heart rate, (HR) at 1-min recovery subtracted from immediate post-HR) as well as percentage decline (i.e., HR at 1-min recovery divided by immediate post-HR multiplied by 100) for 60 seconds from the post-set or -match attained heart rate directly after play had stopped. However, in cases where a participant's post-set or -match HR did not obtain a value above 85% of a participant's theoretical maximal HR (208–0.7*age) (Roy and McCrory, 2015), the HRR measurement was discarded (Boullosa et al., 2013). Boullosa et al. (2013) successfully measured short-term HRR (20 seconds) from sub-maximal HR during periods of active recovery in soccer players who played small-sided soccer games. However, researchers only measured HRR in cases where players actively recovered for at least 20 seconds during which they did not exceed a walking pace of 4 km per hour. HRR was also not measured if players did not reach at least 85% of their theoretical maximal HR. HRR was considered a measure of parasympathetic reactivation (Daanen et al., 2012).

Recovery and hydration status as well as muscle soreness questionnaire

Every day before the start of each match, participants completed a general recovery and hydration status questionnaire that provided researchers with information regarding sleep quantity and quality of the previous night, current hydration status, as well as the degree of muscle soreness that a participant experienced at that moment in time. In order to determine sleep quantity and quality, players needed to indicate the number of hours that they slept the previous night (2-10 hours) as well as the quality of sleep by means of a 5-point Likert scale: “very poor”, “poor”, “average”, “good”, “very good”. Various studies have also used this method to report sleep quantity and quality successfully for a range of participants (Tavernier and Willoughby, 2014; Spira et al., 2012). Participants also indicated what the colour of their urine was when they last urinated. A 5-point Likert scale with the following categories was used for urine colour identification: “transparent”, “a shade of yellow”, “light yellow”, “dark yellow”, “very dark yellow”. Urine colour scale determination is a valid and practical means of determining hydration status in athletes due to the significant correlation that exists between the specific gravity of urine (which is a quantitative indicator of hydration status) and urine colour (Lew et al., 2010). In view that Trost et al. (2012) reported that muscle soreness can be determined by means of a 3-point Likert scale with the categories of “none”, “some”, or “a lot”, this method was also used in this study. Results of the first-mentioned questionnaire therefore aided in evaluating the overall recovery status of participants.

The Stellenbosch Mood Scale (STEMS)

The STEMS was used to determine the pre-match mood states of each participant. The STEMS of Terry and co-workers (2003) is a dual language (English and Afrikaans) questionnaire which is a derivative of the Profile of Mood States (POMS) of McNair et al. (1971). The STEMS measures six subscales, i.e. Tension, Depression, Anger, Vigour, Fatigue and Confusion, with four items contributing to each subscale. Participants were requested to indicate "How are you feeling right now" in terms of 24 mood descriptors on a six-point Likert scale, anchored by descriptors ranging from "Not at all" [0], to "Extremely" [5]. Energy index (EI) was also determined by calculating the ratio of vigour to fatigue scores for each participant (Kenttä et al., 2006). Terry et al. (2003) showed that all six mood scale items of the STEMS provided acceptable internal consistency for all groups with alpha coefficient values that met or exceeded the 0.7 threshold of acceptability. A study in which the STEMS was used to measure the mood states of rugby union players (mean age: 22.26 ± 1.39 years) also reported acceptable internal consistencies for the data of these players, with Cronbach alpha values ranging between 0.65 and 0.87 (Grobbelaar et al. 2011). The criterion validity of the POMS-A (on which the STEMS is based) is supported due to relationships ($r = 0.67$-0.90, $p < 0.05$) with previously validated inventories such as the Positive and Negative Affect Schedule (PANAS), the State-Trait Anger-expression Inventory (STAXI) and the original Profile of Mood States inventory (POMS) (Terry et al., 2003). Previously researchers also found that the fatigue subscale of the POMS was significantly correlated ($r = 0.72$, $p < 0.05$) with frequency domain-related HRV indices (LFnu and HFnu, both $r = 0.66$, $p < 0.05$) over a 12 week training period in athletes (Leti and Bricout, 2013). A comprehensive review of Saw et al (2015) also concluded that various studies observed significant relationships between various subscales of the POMS and HRV. Participants completed the STEMS ten minutes before each match under the supervision of a research team member who was available at all times to answer questions or to eradicate any uncertainties.

All abovementioned questionnaires were completed while participants were seated in an area that was secluded under the supervision of researchers.

Video match recordings

A digital video camera (Sony HDR-PJ790VE handycam, Sony Corporation, Tokyo, Japan) with a high frame rate, good resolution, wide angle lens and an ability to deal with lower light levels of indoor sport facilities was stationed behind the court on a tripod stand to cover the entire court. Video footage was used to determine the time periods of each match so that researchers were able to set the correct duration for each of the HRV and HRR variables.

Statistical analysis

The Statistical Data Processing package (Statsoft Inc., 2015) was used to process data. Firstly, recovery indicators that obtained negative values were changed to positive values in order to ensure that all data showed the same trend i.e. all recovery indicator values showed ascending values as strength increased. This change is recommended in order to increase the accuracy and effectiveness of canonical correlation analyses (Statsoft, 2015). Next a log transformation was applied to HRV variables to improve the normality of data. Thirdly, each variable's descriptive statistics (minimum and maximum values, averages, and standard deviation) were calculated. In the next step tree clustering, single-linkage, 1-Pearson Correlation Coefficient cluster analyses (Wilkinson et al., 2012) of all HRV-, HRR-, recovery- and mood state related variables were performed to detect clusters of measures that are related to each other. Linkage distance for detection of different clusters was set at 0.2. The cluster analysis reduced variables were then entered into a Canonical Correlation Analysis, which is a technique for analysing the relationships between different sets of variables (Razavi et al., 2005). Results of several recovery indicators were correlated to pre-match, in-match, resting and post-match HRV as well as HRR values by doing separate analyses. Therefore, hydration status, muscle soreness, sleep quality and quantity as well as pre-match mood states were categorised under one category (named the recovery related variables) whereas pre-match, in-match, resting and post-match HRV as well as HRR results were categorised under a separate category. Finally, the level of significance was set at $p \leq 0.05$.

Results

The descriptive statistics of badminton players' HR-, HRR- and HRV-related variables over different time periods are displayed in Table 2.

Table 2. Descriptive statistics of badminton players' HR, HRR- and HRV-related variables over different time periods

HRV- and HRR-related variables	Pre-match	In-match	In-match rest	Post-match
HRV-related variables				
Mean R-R	457.72 ± 54.75	354.19 ± 28.53	364.07 ± 46.12	381.49 ± 52.15
Ln-SDNN	3.72 ± 0.80	3.12 ± 0.58	3.15 ± 0.69	3.24 ± 0.62
Ln-RMSSD	3.32 ± 1.00	2.43 ± 0.75	2.25 ± 1.01	2.42 ± 1.01
Peak VLF (Hz)	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
Peak LF (Hz)	0.10 ± 0.03	0.09 ± 0.03	0.09 ± 0.04	0.09 ± 0.04
Peak HF (Hz)	0.27 ± 0.05	0.24 ± 0.04	0.21 ± 0.05	0.24 ± 0.07
Peak VLF Power (%)	17.62 ± 14.01	24.60 ± 19.13	31.21 ± 28.28	33.39 ± 28.38
Peak LF Power (%)	28.51 ± 14.25	30.08 ± 10.45	35.25 ± 15.82	29.86 ± 15.27
Peak HF Power (%)	53.34 ± 18.75	44.98 ± 19.20	33.33 ± 22.90	36.43 ± 25.29
Ln-LFnu Power	3.60 ± 0.51	3.77 ± 0.37	3.99 ± 0.44	3.90 ± 0.47
Ln-HFnu Power	4.01 ± 0.38	3.92 ± 0.32	3.58 ± 0.55	3.62 ± 0.66
Ln-LFnu/Ln-HFnu Ratio	0.92 ± 0.22	0.98 ± 0.18	1.16 ± 0.31	1.14 ± 0.38
Ln-SD1	3.39 ± 1.04	2.66 ± 0.82	2.23 ± 1.02	2.44 ± 1.14
Ln-SD2	3.82 ± 0.70	3.26 ± 0.54	3.38 ± 0.66	3.45 ± 0.54
HRR-related variable				
HRR (%)			12.90 ± 6.31	14.30 ± 4.80
HR-related variables				
HR Minimum (bpm)		115.38 ± 21.40		
HR Mean (bpm)		166.76 ± 13.84		
HR Maximum (bpm)		192.78 ± 11.31		

From Table 2 it is evident that Mean R-R values declined from the pre- to the in-match period. Although Mean R-R recovered during the in-match rest and post-match periods, values did not recover back to pre-match values. Ln-SDNN, Ln-SD1 and Ln-SD2 also followed the same trend while the LF/HF ratio increased as the match progressed with the post-match period obtaining the highest values. HRR was higher for the post- compared to in-match rest periods. Average HR exhibited by all participants was 166.76 ± 13.84 bpm and the average maximum HR attained during matches, 192.78 ± 11.31 bpm.

Table 3 presents descriptive statistics of recovery indicators that are related to competition participation.

Table 3. Descriptive statistics of recovery indicators that are related to competition participation in badminton players

Recovery indicators	**Mean ± Standard deviation**
Sleep duration (hours)	6.64 ± 1.38
Sleep quality (scale of 1 to 5)	3.57 ± 1.03
Muscle soreness (scale of 1 to 3)	1.74 ± 0.68
Shade of urine (scale of 1 to 5)	2.76 ± 1.08
Mood state STEMS scores (scale of 0 to 5)	**Mean ± Standard deviation**
Anger	0.93 ± 1.65
Confusion	1.43 ± 1.82
Depression	0.83 ± 1.03
Fatigue	2.68 ± 2.62
Tension	4.80 ± 3.50
Vigour	11.08 ± 2.96
Energy index	7.30 ± 4.64

Table 3 shows that participants slept on average 6.64 ± 1.38 hours per night and indicated that their sleeping quality was quite high (3.57 ± 1.03). Urine shade scale results were moderate (2.76 ± 1.08) and muscle soreness tended to move to the higher side (1.74 ± 0.68). Regarding STEMS scores, vigour was the most prominent mood state among players with an average score of 11.08 ± 2.96. This result also contributed to a high average energy index scores (7.30 ± 4.64).

In an attempt to first identify the recovery-related variables that relate to each other and to retain only relevant variables for canonical correlation analyses, a cluster analysis was executed. The recovery-related variables were reduced from 11 to the following 9 variables: Sleep duration, sleep quality, shade of urine, muscle soreness, STEMS tension, vigour, energy index, anger and confusion. These recovery indicators were used for further analyses.

Pre-match

In the first canonical correlation analysis, the relationship between recovery indicators and the cluster analysis' reduced HRV-related variables for the pre-match period was determined. A cluster analysis reduced the HRV-related variables from 14 to the following 8 variables for this period: Mean R-R, Ln-RMSSD, peak HF (Hz), Ln-HFnu power, peak VLF (Hz), VLF power (%), LF power (%) and Ln-LFnu/Ln-HFnu ratio. Results of this analysis are displayed in Table 4.

Table 4. Canonical correlation analysis summary of the relationship between recovery indicators and pre-match HRV-related variables of badminton players

Canonical correlation (*Rc*): 0.975; $Chi^2(72) = 91.25$; $p = 0.063$		
	Left set	Right set
Number of variables	9	8
Variance extracted	85.23%	100.00%
Total redundancy	32.53%	51.12%
Variables:		
1	Sleep Duration	Mean RR
2	Sleep Quality	Ln-RMSSD
3	Shade of Urine	Ln-HFnu Power
4	STEMS Anger	Peak VLF (Hz)
5	STEMS Confusion	Peak HF (Hz)
6	STEMS Energy index	VLF Power (%)
7	STEMS Tension	LF Power (%)
8	STEMS Vigour	Ln-LFnu/Ln-HFnu
9	Muscle Soreness	

A strong non-significant canonical correlation of 0.98 ($p = 0.063$) was found between the recovery indicators and pre-match HRV-related variables of participants. The canonical function, therefore, accounted for about 90.06% (r^2 x 100) of the total variation between the two canonical variants. The variance extracted values were also calculated which indicates the average amount of variance extracted from the variables in the respective set by all canonical roots. Therefore, 100% of the variance was extracted from the right set of variables and 85.23% of the variance of the left set. Lastly, the total redundancy values showed that 32.53% of the variance in the nine recovery indicators could be accounted for given the eight pre-match HRV-related variables. Likewise, 51.12% of the variance in the pre-match HRV-related variables could be accounted for given the recovery indicators.

In-match

In the second canonical correlation analysis, the relationship between recovery indicators and the cluster analysis' reduced HRV-related variables for the in-match period was determined. The number of HRV-related variables was reduced from 14 to 8 by means of the cluster analysis, which included the following: mean R-R, Ln-RMSSD, VLF power (%), LF power (%), Ln-HFnu power, Ln-LFnu/Ln-HFnu ratio, peak VLF (Hz) and peak HF (Hz). Results are displayed in Table 5

Table 5. Canonical correlation analysis summary of the relationship between the recovery indicators and the in-match HRV-related variables of badminton players

Canonical correlation (*Rc*): 0.957; $Chi^2(72) = 100.84$; $p = 0.014$		
	Left set	Right set
Number of variables	9	8
Variance extracted	82.24%	100.00%
Total redundancy	44.96%	58.37%
Variables:		
1	Sleep Duration	Mean RR
2	Sleep Quality	Ln-RMSSD
3	Shade of Urine	Peak HF (Hz)
4	STEMS Anger	VLF Power (%)
5	STEMS Confusion	Ln-LFnu/Ln-HFnu
6	STEMS Energy index	LF Power (%)
7	STEMS Tension	Peak VLF (Hz)
8	STEMS Vigour	Ln-HFnu Power
9	Muscle Soreness	

A strong significant canonical correlation of 0.96 ($p = 0.014$) was found for the relationship between the above-mentioned sets of variables. The canonical function, therefore, accounted for about 91.58% (r^2 x 100) of the total variation between the two canonical variants. The variance extracted values showed that 82.24% and 100% could be extracted for the left and right set respectively. Lastly, the total redundancy values showed that, on average, 44.96% of the variance in the nine recovery indicators could be accounted for by the eight in-match HRV-related variables. Likewise, 58.37% of the variance in the eight in-match HRV-related variables could be accounted for, given the nine recovery indicators.

In-match rest periods

In the third canonical correlation analysis, the relationship between recovery indicators and the cluster analysis' reduced HRV- and HRR-related variables for the in-match rest periods was determined. The cluster analysis reduced the number of HRV and HRR from 15 to the following 9 variables: HRR, Ln-RMSSD, peak VLF (Hz), peak LF (Hz), peak HF (Hz), LF power (%), VLF power (%), Ln-HFnu power and Ln-LFnu/Ln-HFnu ratio. The results are displayed in Table 6.

Table 6. Canonical correlation analysis summary of the relationship between recovery indicators and the in-match rest HRV- and HRR-related variables of badminton players

Canonical correlation (*Rc*): 0.692; Chi²(81) = 88.85; *p* = 0.258		
	Left set	Right set
Number of variables	9	9
Variance extracted	100%	100.00%
Total redundancy	26.91%	47.27%
Variables:		
1	Sleep Duration	HRR Rest
2	Sleep Quality	Ln-RMSSD
3	Shade of Urine	Peak VLF (Hz)
4	STEMS Anger	LF Power (%)
5	STEMS Confusion	Peak LF (Hz)
6	STEMS Energy index	Ln-HFnu Power
7	STEMS Tension	Peak LF (Hz)
8	STEMS Vigour	VLF Power (%)
9	Muscle Soreness	Ln-LFnu/Ln-HFnu

The canonical correlation between the recovery indicators and in-match rest HRV-as well as HRR-related variables of the group of players revealed a non-significant canonical correlation of 0.69 ($p = 0.258$). The canonical function, therefore, accounted for about 47.89% (r^2 x 100) of the total variation between the two canonical variants. The variance extracted values showed that

100% could be extracted for both sets. Lastly, the total redundancy values revealed that 26.91% of the variance in the nine recovery indicators could be accounted for by the nine in-match rest HRV-and HRR-related variables. Likewise, 47.27% of the variance in the nine in-match rest HRV- as well as HRR-related variables could be accounted for, given the nine recovery indicators.

Post-match

In the fourth and final canonical correlation analysis, the relationship between recovery indicators and the cluster analysis' reduced HRV- and HRR-related variables for the post-match period was determined. The number of HRV- and HRR-related variables was reduced from 15 to 9 by means of the cluster analysis, which included the following: HRR post-game, mean R-R, Ln-RMSSD, peak VLF (Hz), peak HF (Hz), Ln-LFnu/Ln-HFnu ratio, VLF power (%), LF power (%) and Ln-HFnu power. The results are displayed in Table 7.

Table 7. Canonical correlation analysis summary of the relationship between recovery indicators and the post-match HRV- and HRR-related variables of badminton players

Canonical correlation (*Rc*): 0.982; Chi²(81) = 98.94; *p* = 0.085		
	Left set	Right set
Number of variables	8	8
Variance extracted	100.00%	100.00%
Total redundancy	47.64%	52.71%
Variables:		
1	Sleep Duration	Mean RR
2	Sleep Quality	VLF Power (%)
3	Shade of Urine	Ln-LFnu/Ln-HFnu
4	STEMS Anger	Ln-RMSSD
5	STEMS Confusion	HRR Post-Game
6	STEMS Energy index	Peak HF (Hz)
7	STEMS Tension	Peak VLF (Hz)
8	STEMS Vigour	Ln-HFnu Power
9	Muscle Soreness	LF Power (%)

The canonical correlation between the recovery indicators and post-match HRV- as well as HRR-related variables of players revealed a strong non-significant canonical correlation of 0.98 ($p = 0.085$). The canonical function, therefore, accounted for about 96.43% (r^2 x 100) of the total variation between the two canonical variants. The variance extracted values showed that 100%

could be extracted for both sets. The total redundancy values revealed that 47.64% of the variance in the nine recovery indicators could be accounted for, given the nine post-match HRV- and HRR-related variables. Likewise, 52.71% of the variance in the nine post-match HRV- as well as HRR-related variables could be accounted for, given the nine recovery indicators.

Discussion

The primary aim of this study was to determine if HRV and HRR are related to several subjective indicators of recovery status for different match periods in male, elite, African, singles badminton players. Canonical correlations for relationships between recovery indicators that are related to competition participation and HRV- as well as HRR-related variables for each time period, were as follows: $Rc = 0.98$ ($p = 0.626$) for the pre-match period; $Rc = 0.96$ ($p = 0.014$) for the in-match period; $Rc = 0.69$ ($p = 0.258$) for the in-match rest periods and $Rc = 0.98$ ($p = 0.085$) for the post-match period. Therefore, three time periods delivered strong non-significant canonical correlations of between 0.69 and 0.98 for relationships between above-mentioned variables whereas a significant canonical correlation of 0.98 was found for the in-match period. Consequently, canonical functions accounted for between 47.89% and 96.43% of the total variation between the two canonical roots.

The novelty of this study lies in the fact that there are no available studies investigating the relationship of HRV and HRR with several subjective indicators of recovery status in male, elite, African, singles badminton players. Additionally, this is also the first study to investigate relationships between muscle soreness, hydration status, sleep quality and quantity, as well as pre-competition mood states and the ANS (through HRV and HRR) during different periods of badminton matches (pre-match, in-match and post-match). Although researchers expected recovery indicators to be significantly related to HRV- and HRR-related measures, only the in-match period delivered significant results.

HRV and HRR are tools with which ANS status can be evaluated i.e. whether an athlete's ANS is currently in a state of parasympathetic or sympathetic predominance (Plews et al., 2014). Several studies have recommended the use of psychometric and recovery related measures in conjunction with HRV and HRR to more effectively gauge the ANS in sport and exercise settings (Buchheit, 2014; Mclean et al., 2010). In this regard, Buchheit et al. (2013), who investigated the relationship between recovery indicators and HRV in Australian football players during a pre-season training camp, showed that a significant relationship (r = 0.53) existed between muscle soreness and HRV (ln-SD1). However, none of the other components of the questionnaire that determined recovery indicators (e.g., perceived fatigue, sleep quality, and overall stress level) obtained significant results (Buchheit et al., 2013). Similarly, a study on competitive long-distance runners who were monitored over a competition period of 12 weeks, found a significant overall relationship (r = 0.65) between HF components of HRV, and sleep quality and quantity (Leti and Bricout, 2013). On the other hand, fatigue (as determined through the state of fatigue and muscle soreness (SFMS) questionnaire) and mood states (as determined through the POMS questionnaire) were not significantly related to HRV (Leti and Bricout, 2013).

We also did not find significant relationships between several recovery indicators and HRV-related measures in badminton players for most of the match periods. A possible reason for the lack of significance in relationships is the fact that the recovery indicators showed conflicting trends. For example, players reported below average sleeping hours (6.64 ± 1.38 hours per night), above-average levels of muscle soreness (1.74 ± 0.68 on a scale of 1 to 3) and scored higher on the “tension” (4.80 ± 3.50) mood state of the STEMS which are all indicators of psychological and/or physiological stress (Tavernier and Willoughby, 2014; Mateo et al. 2012; Spira et al., 2012; Grobbelaar et al., 2011; Blasquez and Ortis, 2009). We would expect higher tension and muscle soreness as well as less sleeping hours to have shifted players’ ANS towards sympathetic dominance as increased muscle soreness, inadequate sleeping hours and negative or stress related mood states can induce a state of sympathetic predominance (Buchheit et al., 2013; Oliveira et al., 2011; Vaara et al., 2009; Blasquez and Ortis, 2009). However, players were not dehydrated (2.76 ± 1.08 on a scale of 1 to 5) which suggests that some factors did not influence players’ ANS status (Buchheit et al., 2013; Trost et al., 2012; Oliveira et al., 2011; Lew et al., 2010).

On the other hand, HRV-related variables showed values that are commonly associated with competition participation (Buchheit, 2014; Garrido-Esquivel et al., 2011). The time (Ln-SDNN and Ln-RMSSD) and non-linear (Ln-SD1 and Ln-SD2) HRV variables exhibited a decrease (compared to pre-match values) during matches and slight increases during in-match rest and post-match periods. Frequency domain HRV variables also showed normal trends as Ln-HFnu decreased as matches progressed along with the Ln-LFnu/Ln-HFnu ratio. Mentioned changes in HRV-related values over match duration would indicate that players experienced parasympathetic withdrawal together with sympathetic activation which were probably caused by an increase in metabolic demands as matches progressed (Buchheit, 2014; Reyes del Paso et al., 2013). However, most of the HRV and HRR parameters that were included in the Canonical Correlation Analysis for the in-match period are representative of parasympathetic activity (HRR rest, Ln-RMSSD, Ln-HFnu Power and an average Ln-LFnu/Ln-HFnu ratio of under 1) (Burr, 2007; Hottenrott et al., 2006). Therefore, the significant positive canonical correlation would imply that increases in the values of the recovery indicators would give rise to increases in the values of the parasympathetic activity-related HRV. High match loads combined with an insufficient recovery will provoke higher sympathetic activity whereas sufficient recovery (as indicated by the higher recovery indicator scores), would lead to higher parasympathetic activity (Morales et al., 2014). This change in ANS functioning due to recovery will probably be the most pronounced during the match period as this is the period during which sympathovagal balance is challenged the most compared to other periods (pre-match, in-match rest and post-match).

Despite the above-mentioned assumption, players exhibited below average in-match rest (12.90% ± 6.31) and post-match HRR values (14.30% ± 4.80), when categorised according to the average value of 38% that researchers propose for trained athletes (Javorka et al., 2002). Low HRR may be an indication that parasympathetic reactivation was delayed during rest periods (Boullosa et al. 2013; Daanen et al., 2012). This is surprising as parasympathetic reactivation is the accepted physiological response of the ANS after exercise or competition participation (Leti and Bricout, 2013; Oliveira et al., 2013). Differences between the stress levels of individual players during a competitive period may cause some players to shift towards sympathetic predominance due to the high pressure of match play and outcomes, which would explain why players in this study showed a delayed HRR response (D'Ascenzi et al., 2014; Garrido-Esquivel et al., 2011). This anomaly combined with the opposite trends in recovery related data most likely contributed to the lack of significant relationships for the majority of time periods.

It is interesting to note that only the in-match time period delivered a significant canonical correlation coefficient for the two categories of variables. This is a promising and unanticipated finding on the grounds that HRV measured during exercise is inherently complicated to analyse due to its exercise-intensity dependency (Buchheit, 2014). Every competitive badminton match will show a distinctive intensity level due to differences in player tactics, opponents' playing level and over-all match characteristics, all factors that will directly influence players' HRV (Laffaye et al., 2015; Mcnarry and Lewis, 2012). This finding is also in direct contrast to what others have found. For example, Pinna et al. (2007) observed that players' mood, alertness and mental activity are minimised during exercise and as such will have less influence on a player's over-all HRV profile. However statistically, the majority of HRV-related variables obtained much smaller standard deviation values for this time period compared to resting values, which would indicate that data distribution was narrower. A narrow data distribution would benefit the strength of the correlation coefficient and provide an explanation for the significant result. None the less, our results substantiate the significant influence that recovery-related variables have on HRV measures in a competitive badminton environment. As such, coaches and sport scientists should consider and correct for these recovery-related variables when measuring HRV during competition participation.

Additionally, for 3 out of 4 periods, the canonical functions accounted for more than 90% of the total variation between the two canonical variants, which is considered to be a very high value (Statsoft, 2015). However, for in-match rest periods, the canonical function accounted for only 48% of the total variation between the two canonical variants, which is considered to be a moderately low value (Statsoft, 2015). Furthermore, average total redundancy scores, which is useful for assessing the practical significance of canonical roots (Statsoft, 2015), were much higher for the pre-, in- and post-match periods (between 32.53 and 58.37%) compared to the in-match rest periods (26.91% and 47.27%). Therefore, HRV-related measures seem to be more influenced by recovery indicators before, during and after matches that during in-match rest periods. These results are unexpected as two sets of HRV measurements were taken during rest periods (in- and post-match) after the completion of badminton-related actions and activities at the exact same time interval (60 sec post-match or set). The possible explanation for the discrepancy between results for last-mentioned periods may lie in the fact that parasympathetic activity was more suppressed during the in-match rest compared to the post-match periods. Proof for this contention is provided by the lower mean R-R values (Table 2) that were obtained during the in-match rest periods (364.07 ± 46.12) compared to the post-match periods (381.49 ± 52.15). Low variations in R-R intervals or a shorter time duration of R-R intervals is an indication of sympathetic predominance, which occurs when parasympathetic activity is more suppressed (Dong, 2016; Aubert et al., 2003). On the other hand, high variations in R-R intervals or a longer time duration of R-R intervals is usually an indication of parasympathetic predominance which occurs when parasympathetic activity is not suppressed) (Tarvainen et al., 2014). Consequently, players' ANS may have been under more pressure during in-match rest periods due to among other things, the superseding sets and match play activities compared to the post-match period during which players can rest.

A further analysis, in which canonical weights were examined revealed that Ln-HFnu was the primary HRV-related variable to contribute to relationships during the in-match (canonical weight = 8.28), in-match rest (canonical weight = -2.34) and post-match periods (canonical weight = 3.33). The recovery related variables that were identified as the primary variables in the relationships for different time periods were: STEMS confusion (pre-match, value = 1.38), STEMS energy index (in-match, value = 0.92), STEMS vigour (in-match rest, value = 1.55), and sleep quality (post-match, value = -0.75). This finding was not surprising due the fact that positive psychological mood states (such as vigour and energy index) are known to directly influence athletes' ANS status (Shiota et al., 2011), which would explain last-mentioned results. On the other hand, confusion represents disorganized thought and is catogorised as a negative mood state (Grobbelaar et al., 2011). It is not uncommon for players to experience confusion before participating in competitions and therefore not a suprising finding since negative emotions can also negatively influence the ANS response (Kreibig, 2010). Sleep quality of the previsous night can positively influence ANS responses that are experienced the following day (Mikulski et al., 2013). What last mentioned findings suggest is that coaches and sport scientists should primarily correct for mood state related variables and sleep quality when interpreting HRV results. This would increase the validity and accuracy of HRV measures in a competitive setting such as a badminton tournament.

Conclusion

The primary aim of this study was to determine if HRV and HRR are related to several subjective indicators of recovery status for different match periods in male, elite, African, singles badminton players. The novel finding of the study was that strong, non-significant relationships existed between HRV, HRR and several subjective indicators of recovery status for the majority of match periods. These results compelled researchers to reject the hypothesis that significant relationships exist between HRV, HRR and above-mentioned subjective indicators of recovery status for different match periods in badminton players. Only in-match HRV values were significantly influenced by recovery indicators, although very strong non-significant relationships existed for pre- and post-match time periods. On the other hand, the canonical correlation coefficient for rest periods during matches (service breaks) obtained a non-significant, low value. Results further revealed that log transformed normalised high frequency power (Ln-HFnu), sleep quality and mood state-related variables such as the energy index, confusion and vigour were the primary variables to contribute to relationships between the HRV-, HRR- and recovery-related variables.

Strong canonical correlation coefficients as well as rather high total redundancy values suggest that recovery indicators directly influence HRV and HRR values, especially during pre-, in- and post-match periods. Therefore, coaches and sport scientists should consider and correct for recovery indicators when employing HRV and HRR in their protocols. Secondly, the relationship between HRV and recovery indicators appears to be the most relevant during matches due to the fact that the strongest correlation was obtained for this period. On the other hand, HRV and HRR during in-match rest periods seem to be the least affected by recovery indicators. Therefore, coaches and sport scientists who wish to evaluate ANS status during this time period will be able to do so without correcting for recovery indicators. Thirdly, findings would suggest that mood state-related variables (i.e. energy index, vigour and confusion) and sleep quality influence the parasympathetic mediated HRV variables such as Ln-HFnu more than other recovery indicators. Mood state-related variables and sleep quality should therefore be considered when measuring HRV in sport and exercise settings.

However, in view that this was an exploratory study, future researchers should further investigate these relationships to confirm results. Furthermore, researchers should consider the following limitations when interpreting results: Players' HRV and HRR values were only measured over short time periods. According to Plews et al. (2013) longitudinal monitoring of HRV is needed to better understand an athlete's optimal HRV fingerprint. A true baseline measurement would also aid in the understanding of how the ANS reacts to competitive conditions. Lastly, future researchers should also measure recovery related indicators quantitatively in order to verify the qualitative results of questionnaires. Despite these recommendations, time and logistical constraints, especially during matches and competitions make it difficult to meet all recommendations.

Practical applications

This study showed that recovery indicators do in fact influence short-term HRV and HRR values measured during a real badminton competitive environment. Practitioners should therefore incorporate recovery indicators in their protocols when evaluating HRV and HRR in similar conditions. Failure to do so will most likely result in clouded and obscure results. Additionally, mood state-related variables (such as energy index, confusion and vigour) and sleep quality as measured by Likert scale-based questionnaires should be incorporated as recovery indicators as they have the biggest influence on HRV-related values during badminton competition participation.

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CHAPTER 5

ARTICLE 3:

RELATIONSHIP BETWEEN HEART RATE, HEART RATE VARIABILITY, HEART RATE RECOVERY AND GLOBAL POSITIONING SYSTEM DETERMINED MATCH CHARACTERISTICS OF ELITE, MALE, AFRICAN BADMINTON PLAYERS

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Relationship between heart rate, heart rate variability, heart rate recovery and global positioning system determined match characteristics of male, elite, African badminton players

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Abstract

The aim of this study was to investigate the relationship between heart rate (HR), heart rate variability (HRV), heart rate recovery (HRR) and global positioning system (GPS) determined match characteristics of male, elite, African, singles badminton players. Twenty-two players were fitted with a Fix Polar Heart Rate Transmitter Belt and a GPS unit to record HR and court movements every second during each match. Results revealed a strong, non-significant canonical correlation of Rc = 0.99 (p = 0.257) between HR, HRV, HRR and GPS determined match characteristics. The total redundancy values showed that 38.47% of the variance in the nine GPS-related variables could be accounted for by the ten HR-related variables. Likewise 38.88% of the variance in the HR-related variables could be accounted for by the nine GPS-related variables. Furthermore, distance covered at a low exercise intensity, the amount of low intensity accelerations and player load were highlighted as the highest external match load-related contributors whereas Ln-HFnu power, peak HF (Hz) and Ln-LFnu/Ln-HFnu were identified as the highest internal match load-related contributors. In conclusion, when evaluating badminton internal match loads practitioners should consider and correct for GPS determined external match loads of players to prevent clouded and inaccurate conclusions of autonomic nervous system behaviour from occurring.

Keywords: heart rate variability, heart rate recovery, badminton, global positioning system, match loads.

1. Introduction

The ability to predict and diagnose elite athletes' sport performances has become a reoccurring theme in sport science and exercise physiology over the past several years. In this regard various researchers have investigated the external and internal match loads of athletes to determine the demands of match play (Cornforth *et al*., 2015; Scanlen *et al*., 2014; Scott *et al*., 2013). External match loads are usually determined by making use of video and notational analyses (Laffaye *et al*., 2015) or more recently, global positioning system (GPS) analyses (Owen *et al*., 2014). On the other hand, heart rate (HR) (Buchheit, 2014) and blood lactate analyses (Halson, 2014) as well as the analyses of gas exchange values during graded maximal tests or sport participation (Wallace *et al*., 2014) are some of the most popular match analyses methods for determining athletes' internal match loads. Several researchers also consider heart rate variability (HRV) and heart rate recovery (HRR) to be effective measures of internal match loads (Cornforth *et al*., 2014; Halson, 2014; Roos *et al*., 2013). However, up until now, researchers have not investigated the possible relationship between internal (through HR, HRV and HRR) and external match loads (through GPS) of racquet sport participants such as badminton players.

Notational analysis results reveal that single badminton matches usually last between 30 and 35 minutes (32.5 ± 2.5 minutes on average), with sets between 13.4 and 18.6 minutes and rallies for 8.1 seconds on average (Chen and Chen, 2008; Tu, 2007). The average resting time between points is approximately 15 seconds with effective playing time averaging 31% of the total match time (Phomsoupha and Laffaye, 2015). The analysis of playing and rest times has also enabled researchers to calculate an average work to rest ratio of 1:2 for men's single matches (Chen and Chen, 2008; Tu, 2007). Despite the value of notational analysis to describe the external demands of badminton match play, several shortcomings with regard to the use of this type of analysis have been identified. For example, notational analysis is very time consuming (Hughes and Franks, 2009), not accurate for analysing total duration and frequency of individual movements (Duthie *et al*., 2003), and does not have the ability to assess the specific demands of certain activities (O'Donoghue, 2010).

The emergence of GPS allows researchers to analyse the external demands of badminton match play in a detailed, time efficient manner, and has the potential to circumvent or minimise the shortcomings of notational analyses (Townshend *et al*., 2008). However, the use of a tri-axial accelerometer, magnetometer and gyroscope in a GPS device for analysing real badminton matches is still a new phenomenon. Despite the shortcoming in existing research, various researchers proved that the use of these instruments in outdoor settings delivered valid and reliable results for determining match demands of contact sports such as Australian Football (Gastin *et al*., 2013) and were valid to measure the metabolic demands of netball (Cormack *et al*., 2013; Chandler *et al*., 2014). Boyd *et al*. (2011) found the between-device reliability of tri-axial accelerometers to be acceptable for determining the physical activity levels of football players during a three-hour long indoor exercise session. A study on sprinters revealed that an inertial measurement unit that included a 3-D accelerometer and a 3-D gyroscope was valid to determine the stride and stance durations in an indoor setting (Bergamini *et al*., 2012). Player load and accumulated player load of different mixed martial arts techniques showed satisfactory intra-unit reliability (Intra-class Correlation Coefficients (ICC) = 0.70-0.97 and 0.79-0.98, respectively) when tri-axial accelerometers in GPS units were used to determine the physical demands of fighters in indoor settings (Hurst *et al*., 2014). A construct validity approach employed by Montgomery *et al*. (2010) showed that there were only trivial differences in outputs derived from accelerometer data between several trials of the same basketball movement patterns. Tri-axial accelerometers, magnetometers and gyroscopes in GPS devices were also used successfully to analyse player load, running activities and the number of accelerations and decelerations at different intensities during indoor simulated badminton matches (Abian *et al*., 2015) as well as 20 min (Leite *et al*., 2013) and 40 min long basketball trial games (Hoffman *et al*., 2012).

The most common methods to determine the internal load of athletes during exercise is HR monitoring due the convenient, accurate and non-invasive manner in which it can be measured (Buchheit, 2014). HR analysis of elite, male badminton players revealed an average absolute HR value of 188 bpm and a relative average HR of 90% of maximum heart rate for singles match play (Phomsoupha and Laffaye, 2015). However, the use of HR alone in determining internal match loads may lead to an underestimation of match loads and intensities due to a delayed response to sudden high intensity movements (Jeukendrup and Van Diemen, 1998). Furthermore, HR inflation especially during match play due to HR that usually takes some time to return to pre-activity levels causes an overestimation of match intensity or loads (Achten and Jeukendrup, 2003; Jeukendrup and Van Diemen, 1998). Daily variations in maximal as well as sub-maximal HR of up to 6.5% may also lead to inaccurate results (Halson, 2014).

The ability to indicate overall fitness and readiness to perform (Buchheit, 2014) has highlighted the use of HRV and HRR as optional internal load determining parameters in sports such as basketball, ice hockey and swimming (Chalencon *et al*., 2015; Fronso *et al.*, 2012; Gocentas *et al*., 2011; Cipryan *et al*., 2007). However, HRV and HRR (along with HR) are influenced by a number of factors such as training status of athletes, environmental conditions and unique autonomic responses during competition (Buchheit, 2014; Halson, 2014), which also need to be considered when interpreting internal match loads. In this regard, Cornforth *et al*. (2015) investigated the relationship between HRV and GPS related variables namely distance walked and jogged during a match, player load and total distance covered during a match by Australian football players. They found that frequency-domain (very low frequency [VLF] components, low frequency [LF] components, high frequency [HF] components, and LF/HF ratio), time-domain (mean R-R intervals, and the proportion of R-R intervals that exceed 50 ms [pNN50]) and non-linear HRV indices (standard descriptor 1 [SD1] and standard descriptor 2 [SD2]) were significantly related to GPS-related variables (all regression results were above 0.7 at the 95% confidence interval) (Cornforth *et al*., 2015). These results would suggest that HRV-related variables may be significantly influenced by GPS-related variables.

However, the use of HR, HRV and HRR in the badminton environment, and more importantly, their possible relationship as determinants of internal match loads with GPS-related parameters as indicators of external match loads, have not been investigated. It is against this background that the primary aim of this study was to investigate the relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players. The hypothesis is that significant positive relationships will exist between the GPS-determined indicators of external match loads and HR-determined indicators of internal match loads. These results may provide sports practitioners with a better understanding of the match loads of male, elite, African, singles badminton players as well as the link between variables that are used to determine the internal and external match loads of players, respectively.

2. Methods

2.1. Design

A selected group, repeated measures, observational, descriptive and *ex post facto* design was used for the study. Approval for the study was obtained from the Health Research Ethics Committee of the North-West University (NWU) where the research was conducted (NWU-00199-14-A1). The study was conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and the ethical guidelines of the National Health Research Ethics Council of South Africa. Permission to conduct the research was also obtained from the Badminton World Federation (BWF), the Badminton Confederation of Africa (BCA), the Botswana Badminton Association (BBA), and Badminton South Africa (BSA).

2.2. Participants

Twenty-two male, elite, African, singles badminton players (age 23.3 ± 3.9 years; height 177.1 ± 3.0 cm; mass 83.4 ± 14.5 kg) who participated in the following championships during the 2014/2015 season gave written informed consent to participate in the study: All Africa Badminton Senior Championships, South African International Championships, Free-State National Championships, u/19 South African National Championships and the University Sport South Africa (USSA) Badminton Championships. Players represented ten African countries, namely Botswana, Cameroon, Congo, Egypt, Namibia, Nigeria, South Africa, Uganda, Zambia and Zimbabwe. Only players who were actively involved and competing as members of their respective teams and national badminton federations in above-mentioned tournaments as well as those who were injury free at the time of testing were eligible to participate in the study. Players' competitive badminton playing experience ranged between 4 and 12 years (mean = 9.5 ± 2.7 years). The following information with regard to the training regimen of the badminton players was also obtained: players trained for 4 ± 1 days a week which consisted of on-court training for 4 ± 1 days a week and weight training for 2 ± 2 days a week.

2.3. Procedures

On the first day of each of the tournaments informed consent was obtained from participating players and permission was also obtained from player's coaches in cases where they were available. Players then completed a general information questionnaire regarding their exercising habits, injury history and competing level. After completion of all the relevant documentation players' stature and body mass measures were taken.

Five minutes prior to each match warm-up players were fitted with a Fix Polar Heart Rate Transmitter Belt (Polar Electro, Kempele, Finland) and a MinimaxX GPS unit in vertical orientation (Catapult Sports, Victoria, Australia) to record HR every 1 ms (1000 Hz) and GPS data every 100 ms (10 Hz) during each match. During the warm-up period signals of HR monitors and GPS units were checked, players were familiarized with the equipment and HR transmitter belts as well as GPS vests were adjusted according to each player's preference. Before the start of each match a video camera was stationed on a tri-pod stand behind each of the courts that matches were played on. This aided the reserachers to divide the raw data into different match periods.

2.4. Measures

2.4.1. Demographic and general information questionnaire

Participants' demographic and personal information was collected by means of the last-mentioned questionnaire. Participants' ages, exercising habits, injury incidence, competing levels and best performances were also obtained by means of this questionnaire.

2.4.2. Anthropometric measurements

Body mass was recorded to the nearest 0.1 kg, using a calibrated BFW 300 Platform scale (Adam equipment Co. Ltd., U.K.) and body stature to the nearest 0.1 cm, using a Harpenden portable stadiometer (Holtain Ltd., U.K.) so as to describe the specific cohort of badminton players.

2.4.3. Video match recordings

Before the start of each match a video camera (Sony HDR-PJ790VE handycam, Sony Corporation, Tokyo, Japan) was stationed on a tri-pod stand behind each of the courts where matches were played. Live video recordings of each match were downloaded onto a laptop computer. Video footage was used to determine time periods of each match so that researchers were able to set the correct duration for HR analyses.

2.4.4. Heart rate variability (HRV)

A Fix Polar Heart Rate Transmitter Belt along with a Polar Heart Rate Monitor (Polar Team[2] Pro, Polar Electro, Kempele, Finland) was used to record variations in beat-to-beat intervals (R-R intervals) during matches. Polar Heart Rate Monitors are validated devices for measuring HR and for obtaining R-R intervals (Gamelin *et al*., 2006). Time- and frequency-domain HRV measurements also do not differ significantly ($p > 0.05$) between a Polar heart rate monitor (Polar S810i) and an ambulatory Holter electrocardiograph (ECG) recorder (Gamelin *et al*., 2006). Polar Heart Rate Transmitter Belts were adjusted according to each player's chest size and secured horizontally around the upper thorax at the level of the xiphoid process after the electrode areas were moistened by tap water. A Polar Heart Rate Monitor was then clipped onto the Polar Heart rate Transmitter Belt of each player before he stepped onto the court to begin his pre-match warm-up routine.

HRV-related measurements were calculated by measuring R-R values over 60-second intervals during the playing time of matches. Therefore, R-R data sets of each 60 second period were combined. Kubios HRV software (Version 2.1, Biosignal Analysis and Medical Imaging Group at the Department of Applied Physics, University of Kuopio, Kuopio, Finland) was used for final HRV analyses from the series of R-R-intervals. This software has become popular and has been used in several studies that employed HRV analysis software (Plews *et al*., 2014; Nakamura *et al*., 2009; Perandini *et al*., 2009). R-R data sets were exported from the Polar Heart Rate Monitors via the Polar Team software package. During this process the "error correct" function was selected which automatically filtered out any erroneous values before being exported as a raw R-R data set. Subsequently, the "error corrected R-R data sets" were imported to the Kubious HRV software and the built in artefact removal option was selected during the final HRV analysis (Tarvainen *et al*., 2014).
Results of the following 14 HRV indices were obtained by making use of the above-mentioned software and were used in subsequent statistical analyses:

Time domain-related HRV indices consisting of:

- The natural logarithmic transformation of the standard deviation of R-R intervals in milliseconds (Ln-SDNN);
- The natural logarithmic transformation of the square root of the mean squared differences between successive R-R intervals in milliseconds (Ln-RMSSD)
- The mean of R-R intervals in milliseconds (Mean R-R).

Frequency domain-related HRV indices consisting of:

- The very low band peak frequencies in hertz (Peak VLF Hz)
- The low band peak frequencies in hertz (Peak LF Hz);
- The high band peak frequencies in hertz (Peak HF Hz);
- The natural logarithmic transformation of LF relative power expressed as normalised units (Ln-LFnu)
- The natural logarithmic transformation of HF relative power expressed as normalised units (Ln-HFnu)
- VLF relative power expressed as percentage (VLF %);
- LF relative power expressed as percentage (LF %);
- HF relative power expressed as percentage (HF %) and

- The ratio between Ln-LFnu and Ln-HFnu components (Ln-HFnu/Ln-HFnu)

Non-linear domain related HRV indices consisting of:

- The natural logarithmic transformation of standard descriptor 1 (Ln-SD1) and
- Standard descriptor 2 (Ln-SD2)

2.4.5. Heart rate recovery (HRR)

HR was also calculated for rest periods between sets which lasted a minimum of 60 seconds. This was made possible by synchronising the chronological time indexes of the digital video camera, polar Heart Rate Monitor as well as the wrist watches being used by researchers. However, in cases where a player's post-set HR did not obtain a value above 85% of a player's theoretical maximal HR (208–0.7*age) (Roy and McCrory, 2015), the HRR measurement was discarded (Boullosa *et al*., 2013). Boullosa *et al*. (2013) successfully measured short-term HRR (20 seconds) from sub-maximal HR during periods of active recovery in soccer players who played small-sided soccer games. However, researchers only measured HRR in cases where players actively recovered for at least 20 seconds and did not exceed a walking pace of 4km per hour. HRR was also not measured if players did not reach at least 85% of their theoretical maximal HR. Some researchers also regard 60-sec HRR to be an accurate measure of parasympathetic reactivation (Daanen *et al*., 2012).

2.4.6. Match intensity

A GPS unit sampling at 10 Hz was fitted to the upper back of participants just before the warm-up period by using a harness supplied by the manufacturer. The GPS apparatus allowed researchers to obtain data with regard to the following match related variables (Casamichana *et al*., 2014; Owen *et al*., 2014):

Inertial Movement Analysis

Efforts performed at different intensities; number of accelerations performed at different intensities; number of decelerations performed at different intensities; changes in direction; free running events and jump height and frequency.

Individual Match Analysis

Total duration of a match and player load - data of a triaxial piezoelectric linear accelerometer in the MinimaxX were combined and expressed as player load in arbitrary units (au). Player load is an estimate of physical demand combining the instantaneous rate of change in acceleration in the following three planes: anterior-posterior X, mediolateral Y, and longitudinal Z (Randers *et al*., 2014). Player load zones were set as follow: 0-1, 1-2, 2-3, 3-4, 4-6 and 6-10, where 0-1 represented a low intensity (LI) work load, 1-2 a medium intensity (MI) work load and 2-10 a high intensity (HI) work load (Catapult-Sports, 2012a & b). Thus, player load is a modified vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the 3 planes divided by 100 (Boyd *et al*., 2011). Other match analysis-relatated variables that were also measured, were: equivalent distance ran during the entire match; peak player load; player load per minute; the minimum, mean and maximum heart rates (HR) achieved during the match; the number of efforts in each of the top 3 player load zones; rest time; work to rest ratio; HR exertion index (amount of time a players spent in a specific heart rate zone multiple exponential scale i.e. total exertion score equals time in HR zone 1 x 1 plus time in HR zone 2 x 2, etc.); the amount of time within the play period that a player kept active and did not take long breaks; the total accumulated player load that was obtained for a specific player load zone; the absolute and relative distance covered and time spent during the match within a specific player load zone; the number of efforts that was performed under each of the player load zones; the average, minimum and maximum length of time spent in each effort that was performed under each of the player load zones; recovery times; the absolute and relative amount of time that a player spent within a specific heart rate band; the average heart rate reached within a specific heart rate band; the different player load variations for the match; the total accumulated player load when measured over all movement planes as well as with the vertical accelerometer information omitted, only using the forward/backward movement planes and only using the upward or vertical movement plane.

Recordings from GPS units were downloaded to a PC and analysed using the Catapult Sprint 5.0.9.2 software (Catapult Sports, Victoria, Australia). MinimaxX GPS Doppler data was used to analyse the GPS-related variables.

2.5. Statistical analysis

The Statistical Data Processing package (Statsoft Inc., 2015) was used to process data. Firstly, all GPS-related variables were corrected for match duration by dividing the specific GPS-related variable by match duration in seconds. Also, the log transformation was applied to HRV variables to improve the normality of data. Secondly, each variable's descriptive statistics (minimum and maximum values, averages, and standard deviation) were calculated. Thirdly, a tree clustering, single-linkage, 1-Pearson Correlation Coefficient cluster analyses (Wilkinson *et al*., 2012) of all GPS- and HR-related variables were performed to detect clusters of measures that are related to each other. Linkage distance for detection of different clusters was set at 0.2. Cluster analyses-reduced variables were then entered into a canonical correlation analysis, which is a technique for analysing relationships between different sets of variables. GPS-related variables were categorised as one set whereas HR-related variables were categorised as the other set for the canonical correlation analysis. The level of significance was set at $p \leq 0.05$.

3. Results

Descriptive statistics of different GPS- and HR-related variables of badminton players are presented in Tables 1-3. Table 1 shows that an average work to rest ratio of 0.74 ± 0.08 was achieved during matches. Players also attained a player load per second of 5.82 ± 0.75 and covered a distance of 0.92 ± 0.12 meters per second throughout matches. Most of the time was spent in the 0 - 1 and 1 - 2 player load bands accounting for 88.32 ± 3.18% and 10.34 ± 2.75% of the total playing time, respectively. Players performed 0.50 ± 0.46 efforts which consisted among other things of 0.03 ± 0.01 low intensity and 0.01 ± 0.00 high intensity accelerations per second on average during matches. Low intensity jumps reached a total of 0.05 ± 0.1 jumps per second per match. Players executed 0.09 ± 0.04 and 0.09 ± 0.08 low intensity efforts per second for the left and right side, respectively.

Table 1. Descriptive statistics of GPS-related variables collected during badminton matches.

GPS-related variables	**Averages** ± SD
Work to rest ratio	0.74 ± 0.08
Player load per sec	5.82 ± 0.75
Distance covered per sec (m)	0.92 ± 0.12
Peak player load per sec	0.00 ± 0.00
Player load per minute	5.81 ± 0.77
0 - 1 Total load per sec	0.05 ± 0.01
0 - 1 Distance covered per sec (m)	0.48 ± 0.08
0 - 1 Percentage distance (%)	54.17 ± 8.41
0 - 1 Percentage time (%)	88.32 ± 3.18
1 - 2 Total load per sec	0.04 ± 0.01
1 - 2 Distance covered per sec (m)	0.33 ± 0.10
1 - 2 Percentage distance (%)	35.45 ± 6.78
1 - 2 Percentage time (%)	10.34 ± 2.75
2 - 3 Total load per sec	0.01 ± 0.00
2 - 3 Distance covered per sec (m)	0.08 ± 0.03
2 - 3 Percentage distance (%)	7.93 ± 2.67
2 - 3 Percentage time (%)	1.13 ± 0.55
3 - 4 Total load per sec	0.00 ± 0.00
3 - 4 Distance covered per sec (m)	0.02 ± 0.01
3 - 4 Percentage distance (%)	2.23 ± 1.51
3 - 4 Percentage time (%)	0.01 ± 0.05
4 - 6 Total load per sec	0.00 ± 0.00
4 - 6 Distance covered per sec (m)	0.00 ± 0.00
4 - 6 Percentage distance (%)	0.69 ± 0.49
4 - 6 Percentage time (%)	0.01 ± 0.00
2 Dimensional movements per sec	0.07 ± 0.01
1 Dimensional forward movement per sec	0.04 ± 0.01
1 Dimensional side movements per sec	0.04 ± 0.01
1 Dimensional upwards movements per sec	0.06 ± 0.01
Low intensity efforts per sec	0.29 ± 0.22
Medium intensity efforts per sec	0.09 ± 0.09
High intensity efforts per sec	0.12 ± 0.16
All Efforts per sec	0.50 ± 0.46
Low accelerations per sec	0.03 ± 0.01
Medium accelerations per sec	0.01 ± 0.01
High accelerations per sec	0.01 ± 0.04
Low decelerations per sec	0.08 ± 0.13
Medium decelerations per sec	0.02 ± 0.03
High decelerations per sec	0.03 ± 0.06
Left low intensity efforts per sec	0.09 ± 0.04
Left medium intensity efforts per sec	0.03 ± 0.02
Left high intensity efforts per sec	0.04 ± 0.02
Right low intensity efforts per sec	0.09 ± 0.08
Right medium intensity efforts per sec	0.03 ± 0.05
Right high intensity efforts per sec	0.05 ± 0.10
Low jumps per sec	0.05 ± 0.10
Medium jumps per sec	0.02 ± 0.03
High jumps per sec	0.00 ± 0.00

SD = Standard deviation

Table 2 shows that players obtained an average and maximum HR of 166.76 ± 13.84 bpm (which was 86.50% of the HR maximum) and 192.78 ± 11.31 bpm, respectively during matches. Most of the match time was spent in the 185 - 220 bpm HR range (31.04 ± 21.15%) followed by the 120 - 160 bpm range (26.58 ± 22.63%). Players also exhibited an HR exertion index of 89.41 ± 46.02.

Table 2. Descriptive statistics of HR-related variables collected during singles badminton matches.

HR-related variables	**Averages** ± SD
HR minimum (bpm)	115.38 ± 21.40
HR mean (bpm)	166.76 ± 13.84
HR maximum (bpm)	192.78 ± 11.31
HR exertion index	89.41 ± 46.02
120 - 160 Time (min)	7.69 ± 7.60
120 - 160 Time (%)	26.58 ± 22.63
120 - 160 Average (bpm)	145.80 ± 6.11
160 - 170 Time (min)	4.96 ± 3.67
160 - 170 Time (%)	17.34 ± 10.52
160 - 170 Average (bpm)	162.56 ± 2.58
170 - 180 Time (min)	5.75 ± 3.72
170 - 180 Time (%)	19.13 ± 10.92
170 - 180 Average (bpm)	172.65 ± 1.48
180 - 185 Time (min)	3.23 ± 2.78
180 - 185 Time (%)	12.00 ± 8.01
180 - 185 Average (bpm)	172.66 ± 1.49
185 - 220 Time (min)	10.31 ± 7.79
185 - 220 Time (%)	31.04 ± 21.15
185 - 220 Average (bpm)	189.60 ± 3.04

SD = Standard deviation

From Table 3 it is clear that players' time domain related HRV measures obtained values of 3.12 ± 0.58 and 2.43 ± 0.75 for Ln-SDNN and Ln-RMSSD, respectively. With regard to the frequency domain related HRV measures, players displayed an average value of 0.98 ± 0.18 for the Ln-LFnu/Ln-HFnu ratio and 44.98 ± 19.20% for HF power. An average value of 12.90 ± 6.31% was obtained for HRR during rest periods in the match.

Table 3. Descriptive statistics of HRR- and HRV-related log transformed variables collected during singles badminton matches.

HRV- and HRR related variables	**Averages** ± SD
Mean R-R	354.19 ± 28.53
Ln-SDNN	3.12 ± 0.58
Ln-RMSSD	2.43 ± 0.75
Peak VLF (Hz)	0.03 ± 0.01
Peak LF (Hz)	0.09 ± 0.03
Peak HF (Hz)	0.24 ± 0.04
Peak VLF Power (%)	24.60 ± 19.13
Peak LF Power (%)	30.08 ± 10.45
Peak HF Power (%)	44.98 ± 19.20
Ln-LFnu Power	3.77 ± 0.37
Ln-HFnu Power	3.92 ± 0.32
Ln-LFnu/Ln-HFnu Ratio	0.98 ± 0.18
Ln-SD1	2.66 ± 0.82
Ln-SD2	3.26 ± 0.54
HRR (%)	12.90 ± 6.31

SD = Standard deviation

A cluster analysis reduced the number of GPS-related variables from 49 to the following 9 variables: Work to rest ratio, player load per second, 0 - 1 distance covered per sec, 3 - 4 distance covered per sec, 4 - 6 distance covered per sec, 0 - 1 percentage distance, low accelerations per sec, peak player load per sec and low intensity efforts per sec. With regard to the HR-, HRR- and HRV-related variables, the cluster analysis reduced the number of variables from 34 to the following 10 variables: HR exertion index, 180 - 185 Average (bpm), Ln-RMSSD, Ln-LFnu/Ln-

HFnu ratio, peak HF (Hz), LF power (%), Ln-HFnu power, 120 - 160 Time (%), 160 - 170 Time (%) and mean R-R. Only the cluster analyses-reduced variables were used for further analysis.

In a subsequent step, a canonical correlation analysis was performed to explain the relation between sets of GPS- and HR-related variables. Results of this analysis are presented in Table 4.

Table 4. Canonical analysis' summary of the relationship between GPS- and the HR-related variables of badminton players.

Canonical correlation (*Rc*): 0.991; Chi²(90) = 98.34; *p* = 0.257		
	Left set	Right set
Number of variables	9	10
Variance extracted	100.00%	84.11%
Total redundancy	38.47%	38.88%
Variables:		
1	Work to rest ratio	HR exertion index
2	Player load per second	180 - 185 Average (bpm)
3	0 - 1 Distance covered per sec	Ln-RMSSD
4	3 - 4 Distance covered per sec	Ln-LFnu/Ln-HFnu
5	4 - 6 Distance covered per sec	Peak HF (Hz)
6	0 - 1 Percentage Distance	Power LF (%)
7	Low accelerations per sec	Power HF nu
8	Peak player load per sec	120 - 160 Time (%)
9	Low intensity efforts per sec	160 - 170 Time (%)
10		Mean R-R

A non-significant correlation of 0.99 (p = 0.257) was found for the canonical correlation between GPS- and HR-related variables of players. The canonical function, therefore, accounted for 98.01% (r^2 x 100) of the total variation between the two canonical variants. In a further analysis, the variance extracted values were also calculated. These values indicated the average amount of variance extracted from the variables in the respective set by all canonical roots. Both roots, therefore, extracted 100% of the variance of the left set and 84.11% of the variance of the right set. Lastly, the total redundancy values showed that, on average, 38.47% of the variance in the nine GPS-related variables could be accounted for given the ten HR-related variables. Likewise, 38.88% of the variance in the HR-related variables could be accounted for given the GPS-related variables.

4. Discussion

The primary aim of this study was to investigate the relationship between HR-, HRV-, HRR- and GPS-related variables in male, elite, African, singles badminton players. Our results revealed a strong, non-significant, positive canonical correlation of Rc = 0.99 (p = 0.257) which means that the canonical function accounted for about 98.01% of the total variation between the two canonical variants. Furthermore, the total redundancy values showed that 38.47% of the variance in the nine GPS-related variables could be accounted for by the ten HR-related variables. Likewise, 38.88% of the variance in the HR-related variables could also be accounted for given these nine GPS-related variables. The novelty of this study is that a wide range of HR-related variables were determined in a real badminton championship environment. More importantly, the relationship between these HR-related variables (as indicators of internal match loads) and GPS-related variables (as indicators of external match loads), were determined.

Studies by Montgomery *et al.* (2010) and Casamichana *et al.* (2013) also identified strong relationships between internal (such as HR-related) and external match load (such as GPS-related) variables. Researchers reported significant relationships (CI of 90%) between player load and both peak HR and average HR measured during basketball competitions (Montgomery *et al*., 2010). Similarly, player load and internal match load-related variables, such as HR exertion index and rating of perceived exertion (RPE), also obtained large relationships ($r < 0.70$; $p < 0.01$) during soccer training sessions (Casamichana *et al*., 2013). Furthermore, significant relationships were established between internal load measures (through HR and RPE based scores) and the total distance covered during a soccer match as well as player load and the amount of low intensity movements ($r = 0.71$ - 0.84; $p < 0.01$) in soccer players during training matches throughout a season (Scott *et al*., 2014). Lastly, Scalan *et al*. (2014) found moderate, significant relationships ($r < 0.61$; $p < 0.001$) between internal training load models (composed of summated HR zones and RPE ratings) and an external training load model (composed of an accepted accelerometer algorithm) in semi-professional basketball players during training sessions throughout their pre-season period.

Above-mentioned findings would suggest that the moderate total redundancy values (38.47 - 38.88%) found in our study were not unexpected. Redundancy values (also used to indicate practical significance) imply that HRV- and GPS-related variables share a medium, practical significant relationship (Statsoft, 2016). From a physiological point of view this is expected due to the fact that increases in external training loads such as a longer duration, increased distance and intensity of training directly affects the autonomic nervous system and associated HR-related measures (Cornforth *et al*., 2015; Buchheit, 2014; Halson, 2014). In this regard, metabolic demands of singles badminton matches can vary considerably from match to match depending on the styles and tactics employed by players (Phomsoupha and Laffaye, 2015). Therefore, it is important to consider external match load-related parameters when interpreting internal match loads.

However, we were rather surprised by the fact that the high canonical correlation coefficient in this study did not deliver a statistical significant value. Despite the high canonical correlation coefficient, the standard deviations for some of the variables were high, implying that the data pertaining to these variables were widely distributed. As mentioned before, data of the HRV-related variables which showed a wide distribution were corrected using the log transformation. However, this transformation did not have the desired effect on all variables. It is, therefore, possible that outliers and variability in results could have pulled the canonical correlation results skew and caused a non-significant relationship.

It is noteworthy that a further analysis also revealed that Ln-HFnu power, peak HF (Hz) and the Ln-LFnu/Ln-HFnu (canonical weight values of 2.43, 1.54 and 1.94, respectively) influenced GPS-related variables the most. On the other hand percentage time spent and distance covered in the 0 - 1 intensity zone (canonical values of 2.01 and 1.69 respectively) as well as the amount of low accelerations per second (canonical weight value of 1.61) had the biggest influence on HR-related variables. The relationship between the percentage time spent and distance covered in the low intensity zone and HRV variables is anticipated due the fact that HRV measured during exercise is intensity dependant and parasympathetic activity has a larger impact on over-all HRV when exercising below the first ventilatory threshold (Buchheit, 2014).

Lastly, HRR was not identified as a variable that could be included in the canonical correlation analysis. This was unexpected as HRR (like HRV) is considered to be a measure of internal load and acts as a portal to gauge ANS regulation (Daanen *et al*., 2012). However, some researchers suggest that a dissociation exists between HRV and HRR and that both these indices are independently linked to the autonomic nervous system (Esco *et al*., 2010). This could serve as a possible explanation for why HRR did not stand out as a HR-related parameter that holds any value when measured during service breaks in badminton matches. However, the exploratory nature of this study warrants future researcher to verify these results.

5. Conclusion

This study revealed a strong, non-significant, positive relationship between HR, HRV and HRR as determinants of internal match loads and GPS-related parameters as indicators of external match loads in male, elite, African, singles badminton players. GPS-related variables were expected to be significantly associated with HR-, HRV- and HRR-related variables in male, singles badminton players. Therefore, although the hypothesis is rejected, the correlation coefficient suggests that the canonical function accounted for a very high amount (98.01%) of the total variation between the two canonical variants. However, despite the non-significance of the relationship between these two categories of measures, the total redundancy values indicate a medium, practical significant relationship. Results further revealed that Ln-HFnu power, peak HF (Hz) and Ln-LFnu/Ln-HFnu as well as time spent and distance covered in the 0 - 1 intensity zone as well as the amount of low intensity accelerations per second were the primary HR- and GPS-related variables, respectively to contribute to the relationship. Researchers should therefore consider and correct for activities that are performed at a low intensity when analysing and interpreting HRV-related measures in sport settings.

However, although the internal and external match load determining protocols that were used in this study create a platform from which data can be collected in a real world competitive badminton setting, certain shortcomings need to be addressed. For example researchers suggest that individualised HR zones and HR reserve should rather be used when describing HR responses of players during competition (Alexandre *et al.*, 2012) instead of fixed and generalized HR categories. In this study HR intensity zones for all players were based on maximum HR which may not be the most accurate method of predicting match intensities. Furthermore, individual determined speed thresholds must rather be used to determine movement intensity classifications zones instead of general movement speed categories which are completely independent of players' individual capabilities (Abt and Lovell, 2009). In addition, the possible effects of different match characteristics such as the number of unforced errors, winning shots or match outcomes on the relationship between external and internal match load determining methods were not considered. Therefore, future researchers should consider above-mentioned recommendations when compiling protocols for determining the internal and external match loads of players.

6. Practical applications

Firstly, when evaluating internal match loads (through HR- and HRV-related variables) in badminton it is paramount that coaches and sport scientists consider the external match loads (specifically GPS-related variables) of a match when interpreting results. As demonstrated in this study, GPS-related variables have a profound effect on the autonomic regulation of HR during competitive badminton matches. Consequently, practitioners and researchers need to acknowledge the possible influence of external match loads to avoid clouded and inaccurate conclusions of autonomic nervous system behaviour during competition participation. Secondly, the following HRV-related variables should be given preference when investigating the relationship between these variables in competition settings: HFnu power, peak HF (Hz) and Ln-LFnu/Ln-HFnu. Likewise, time spent and distance covered in the 0 - 1 intensity zone, as well as the amount of low intensity accelerations per second were the GPS-related variables that had the biggest influence on HRV-related measures. Thirdly, HRR did not emerge as an internal load determining measure and should therefore be used with caution when evaluating player loads. Finally, the study succeeded in showing that the GPS characteristics of badminton matches affect the autonomic nervous system-related measures of players.

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CHAPTER 6

SUMMARY, CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

6.1 SUMMARY

The purposes of this study were three-fold, firstly, it was to determine if pre-match, in-match, in-match resting and post-match HRV as well as post-match and in-match resting (as measured during breaks between sets) HRR can serve as significant predictors of male, elite, African, singles badminton players' performance levels; secondly, to determine if HRV and HRR are related to several subjective indicators of recovery status for different match periods in male, elite, African, singles badminton players and thirdly, to investigate the relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players.

Chapter 1 provided a concise problem statement that formed the literature base for the research questions. This chapter also included the research questions itself, objectives and related hypotheses of this study as well as the structure of the thesis.

Chapter 2 consisted of a literature study titled: "Heart rate variability and recovery as indicators of performance in sport and exercise". The aims of this review were firstly, to discuss the physiological properties of the autonomic nervous system (ANS) as well as physiological mechanisms that underlie HRV and HRR as measures of ANS function; secondly, to discuss the procurement, quantification and interpretation procedures of HRV and HRR in sport and exercise settings; thirdly, to reveal relationships between HRV, HRR and sport as well as exercise performance; fourthly, to highlight possible influences of sleep quality and quantity, muscle soreness, hydration status, match intensity and pre-competition anxiety on HRV and HRR as measures of ANS function; fifthly, to discuss the match characteristics of elite, male, singles badminton players as well as the possible use and application of the global position system units (GPS) in indoor sports and finally, to indicate the limitations of using HRV and HRR as measures of ANS function in sport and exercise settings.

The literature review therefore started by illustrating that the ANS entirely or partially control arterial pressure, sweating, body temperature, gastrointestinal motility, gastrointestinal secretion, bladder emptying and many other physiological functions. Literature also indicates that the ANS is divided into the sympathetic (SNS) and parasympathetic nervous system (PNS) which have antagonistic characteristics but function synergistically. Functions of these branches of the ANS differ with the SNS that prepares and sustains the body to face a crisis, danger or stress whereas the PNS is more active when a person is calm and relaxed, and little physical demand is put on the body. The collaborative nature of the SNS and PNS leads to effective and responsive regulation of the cardiovascular system. In this regard both HRV and HRR are regarded to be established measures of cardiac ANS function and are used in sport and exercise settings due to their time-efficient and non-invasive qualities.

HRV is usually measured by determining the oscillations in time that elapses between successive R-R cycles and by quantifying these values through HRV analysis software in order to obtain different HRV measures for interpretation. HRV derived variables can be divided into time-, frequency- and non-linear-based categories with each category portraying different branches of ANS status (SNS and PNS activity). Currently, two ways in which researchers measure HRV are single-day and daily/weekly rolling average HRV measurements. HRV measured on a more longitudinal basis (daily, weekly or during competition) is a widely accepted approach to monitor the ANS over time. With this approach meaningful negative or positive changes in HRV can be detected. Research that has used this approach showed that HRV can be effectively used as a training prescription tool to detect early signs of fatigue and prevent over-training, thereby ensuring that training days are used optimally. Additionally, HRV can also serve as a predictor of on-field, team sport and individual performances in aerobic related sports.

Literature also indicates that Ln-RMSSD is the preferred HRV-related parameter when daily/weekly rolling average HRV measurements are used in sport and exercise settings in order to evaluate ANS activity. However, the success of the daily/weekly rolling average HRV measurement approach lies in the creation of a unique cardiac autonomic profile (using a repertoire of HRV measurements) for each individual athlete. This profile is required because of the unique response of each athlete’s ANS during training and competition participation. In addition, HRV has to be measured in the same manner and conditions every time to ensure that external factors do not influence measurements.

On the other hand, researchers who wish to investigate the acute effects of exercise and sport on ANS activity usually measure HRV within a single day. Research that made use of this approach show that significant relationships do exist between established performance indicators such as aerobic fitness, anaerobic capacity and match/game results and HRV-measures. Therefore, HRV can be employed in a range of sport and exercise settings as well as in a competitive environment. However, the single day measurement approach limits researchers to only a few opportunities to capture HRV. In view of this, researchers need to use a large number of HRV-measures to quantify HRV. Different HRV-measures capture different branches of ANS activity and enable researchers to fully investigate ANS status.

Overall, the literature study identified several practical uses for HRV and presented different methodological approaches through which HRV can be measured in training or competition settings. Guidelines and recommendations on how to measure HRV in sport and exercise settings were also discussed in order to highlight advances made by researchers and practitioners in this regard. These guidelines and recommendations focused on the following aspects that must be considered when HRV measuring protocols are applied in sport and exercise settings: time duration and frequency of measurements, raw data analysis and type of HRV-related parameters used.

HRR is widely accepted as an index of parasympathetic reactivation and overall ANS health. HRR values are usually obtained by measuring HR with a HR monitor at cessation of a maximal or sub-maximal exercise and again post-exercise at a certain time point. HRR is then calculated as the decrease in HR (in bpm) or as a percentage decrease of exercise to post-exercise HR. HRR after one minute is the most widely used parameter due to the practicality of exploiting this HRR variable in sport and exercise settings as it is almost immediately available. Generally HRR is measured after standardised $\dot{V}O_{2max}$ tests or field tests in order to regulate exercise intensities and durations so that intra- and inter-group HRR values can be compared. HRR that is measured in this way can be used as an indicator of aerobic fitness and training status as well as a measure of exercise capacity. However, more recently several researchers and practitioners started to use HRR measures that were obtained during sport participation. These studies revealed that HRR can be used as a predictor of on-field performance and may act as a discriminator between different levels of athletes (elite over sub-elite). Despite the value of HRR measures, researchers must realise that HRR values can only be compared if athletes are of the same sport and were measured by making use of the same methodological approach. Furthermore, the type of body position during recovery, reliability and practicality of different HRR indices, time frame from which HRR is measured and effects of circadian rhythms on HRR should not be ignored. In addition, researchers should standardise the percentage of individuals’ maximal- and sub-maximal HR from which HRR is taken and consider co-founding factors such as atmospheric conditions, the training modality and the possible effects of exercise intensity on HRR.

In the penultimate part of the literature review it was acknowledged that external factors such as decreases in sleep quality and quantity, high levels of muscle soreness, dehydration, heightened levels of pre-competition anxiety, and high training/match intensities have the potential to negatively influence HRV, HRR and ANS regulation. These external factors are all present during competition participation and should therefore be considered when interpreting HRV and HRR measurements. The use of subjective questionnaires (based on a Likert scale) seems to be the most practical approach to measure and evaluate last-mentioned factors in competitive settings where time is limited.

Lastly, the review discussed the use and application of GPS in indoor sports as well as the match characteristics of elite, male, singles players. GPS units are able to determine the external demands of match play through the use of a tri-axial accelerometer, magnetometer and gyroscope. Several studies have validated the use of tri-axial accelerometer, magnetometer and gyroscope in sports such as Australian football, netball, sprinting, snowboarding, and swimming to determine external match loads as well as to define match charateristics of a specific sport. These instruments are regarded to be invaluable tools to replace time-consuming notational analyses and to serve as training aids to coaches and sport scientists. However, several indoor sports have also taken note of the advantages of using last-mentioned instruments. In this regard accelerometers have been successfully employed to determine the effects of supplements (caffeine and L-alanyl-L-glutamine) on match performance in badminton and basketball; to determine differences in physical and physiological responses between sport specific drills and actual match play in basketball as well as to determine the physical demands of MMA. The interchangeable use of these GPS units have also been proven in sports such as MMA and volleyball. Therefore despite a scarcity in research that have thusfar used GPS units (integrated with tri-axial accelerometers, magnetometers and gyroscopes) to monitor and determine the demands of competitive badminton match play, results suggest that GPS can be used to monitor the demands of indoor sports such as badminton.

Studies that investigated thet match characteristics of elite, male, single badminton players revealed that average match durations vary between 32.5 and 39.6 minutes, individual sets between 13.4 and 18.6 minutes and rallies for 8.1 to 10.1 seconds on average at work-to-rest ratios of between 1:2 and 1:2.7. Players reach absolute heart rates of between 188 and 194 beats per minute during matches which fall between 90 to 94% of maximal HR. Therefore, badminton is considered to be a physiologically demanding sport that requires very high fitness levels for players to be able to effectively and successfully play several matches in a short period of time during a tournament.

Chapter 3 consisted of the first article which was compiled in accordance with the guidelines of the *Journal of Strength and Conditioning Research* and titled: Heart rate variability and heart rate recovery as predictors of male, elite, African, singles badminton players' performance levels. The purpose of this article was to determine if pre-match, in-match, resting and post-match HRV as well as post-match and in-match (as measured during breaks between sets) HRR can serve as significant predictors of male, elite, African singles badminton players' performance levels. The article succeeded in showing that only pre-match and in-match log transformed low frequency to high frequency ratio (Ln-LFnu/Ln-HFnu ratio) as well as post-match and in-match rest peak very low frequency power (VLF power (Hz)), served as significant HRV-related predictors of successful and less successful badminton player's group allocation. Overall model fit was good and 75% of players could be classified into their original groups by making use of the HRV-based logistic regression formulas. Furthermore, all models had a large effect in predicting classification of players, although only pre- and in-match models emerged as useful models. Neither in-match resting nor post-match HRR were identified as significant predictors of group allocation.

Chapter 4 consisted of the second article which was compiled in accordance with the guidelines of the *Journal of Sports Science and Medicine* and titled: Relationship between autonomic markers of heart rate and subjective indicators of recovery status in male elite, badminton players. The purpose of this article was to determine if HRV and HRR are specifically related to several subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players. Findings of this article revealed that canonical correlations for relationships between HRV- and HRR-related variables and several recovery indicators for each of the match time periods, were as follow: $Rc = 0.98$ ($p = 0.626$) for the pre-match period; $Rc = 0.96$ ($p = 0.014$) for the in-match period; $Rc = 0.69$ ($p = 0.258$) for the in-match rest periods and $Rc = 0.98$ ($p = 0.085$) for the post-match period. Canonical functions accounted for between 47.89% and 96.43% of the total variation between the two canonical variants. A strong, significant relationship was found between HRV, HRR and recovery indicators for the in-match period, but only strong, non-significant relationships were observed for pre-match and post-match periods and a low non-significant relationship for the in-match rest period. Results further revealed that log transformed normalised high frequency power (Ln-HFnu), sleep quality and mood state-related variables such as the energy index, confusion and vigour were the primary variables to contribute to relationships between the HRV-, HRR- and recovery-related variables.

Chapter 5 consisted of the third article which was compiled in accordance with the guidelines of the *International Journal of Performance Analysis* and titled: Relationship between heart rate, heart rate variability, heart rate recovery and global positioning system determined match characteristics of male, elite, African, badminton players. The purpose of this article was to investigate the relationship between GPS-, HR-, HRV- and HRR-related variables in male, elite, African, singles badminton players. Findings of the article revealed a strong, non-significant canonical correlation of $Rc = 0.99$ ($p = 0.257$) between HR, HRV, HRR and GPS determined match characteristics. The total redundancy values showed that 38.47% of the variance in the nine GPS-related variables could be accounted for by the ten HR-related variables. Likewise 38.88% of the variance in the HR-related variables could be accounted for given these nine GPS-related variables. Furthermore, distance covered at a low exercise intensity, the amount of low intensity accelerations and player load were highlighted as the highest external match load-related contributors whereas Ln-HFnu power, peak HF (Hz) and Ln-LFnu/Ln-HFnu were identified as the highest internal match load-related contributors to the overall canonical correlation coefficient.

6.2 CONCLUSIONS

Conclusions are presented in accordance with the set hypotheses in chapter 1.

Hypothesis 1: *Pre-match, in-match, resting and post-match HRV as well as post-match and in-match rest HRR will serve as significant predictors of male, elite, African, singles badminton players' performance levels*. Hypothesis 1 is partly accepted, due to the fact that only one HRV-related variable was identified as a significant predictor of group allocation for each of the named time periods, namely pre- and in-match Ln-LFnu/Ln-HFnu ratio as well as post- and in-match rest VLF power. Furthermore, all prediction models had a large effect in predicting the classification of players, although only the pre- and in-match models emerged as useful models. However, neither in-match resting nor post-match HRR were identified as significant predictors of group allocation.

Hypothesis 2: *Significant relationships exist between HRV, HRR and subjective indicators of recovery status (muscle soreness, hydration status, sleep quality and quantity as well as pre-competition mood states) for different match periods in male, elite, African, singles badminton players*. Hypothesis 2 is rejected, based on the fact that strong, non-significant relationships existed between HRV, HRR and several recovery indicators for the majority of match periods. Only in-match HRV values were significantly influenced by recovery indicators. On the other hand, the canonical correlation coefficient for rest periods during matches (service breaks) obtained a non-significant, low value.

Hypothesis 3: *Significant positive relationships will exist between the GPS-determined indicators of external match loads and HR-determined indicators of internal match loads*. Although the canonical function accounted for a very high amount (98.01%) of the total variation between the two canonical variants, GPS-related variables were not significantly related to HR, HRV and HRR-related variables in male, elite, African, singles badminton players. Therefore, hypothesis 3 is rejected.

Overall, findings suggest that badminton match performance can indeed be predicted by HRV parameters. Furthermore, results revealed that, depending on the period of analysis, Ln-LFnu/Ln-HFnu ratio and VLF power seem to be the most signficant HRV parameters to predict badminton match performance. However, despite that all prediction models had a large effect in predicting the classification of players, only the pre- and in-match models emerged as useful models. On the other hand, a significant relationship between in-match HRV values (which included Ln-LFnu/Ln-HFnu ratio) and several recovery indicators (which included most of the STEMS mood states, sleep duration and quality as well as muscle soreness) suggest that in-match HRV-related prediction models of this nature should consider the named recovery indicators as possible covariats in model functions. A more in-depth examination of the canonical correlation analysis results focussed our attention to especially STEMS energy index as the most prominent recovery indicator in this regard.

Another possible covariant, namely GPS-determined, external match loads do not seem to significantly influence HRV and should therefore not be considered when compiling in-match HRV-related prediction models. Then again, the fact that the canonical function accounted for a very high amount (98.01%) of the total variation between the two canonical variants (GPS-determined indicators of external match loads and HR-determined indicators of internal match loads), suggest that researchers should maybe regard this covariant when constructing in-match HRV-related prediction models. Canonical weights of especially percentage time spent and distance covered in the 0 - 1 intensity zone as well as the amount of low accelerations per second further indicate that these are the GPS-determined indicators of external match loads that should be considered the most as covariants when compiling HRV-related badminton performance prediction models.

To the researcher’s knowledge, this is the first study to investigate the predictive power of HRV and HRR to gauge badminton performance as well as to investigate relationships between HRV and HRR with subjective recovery indicators and GPS unit derived external match loads in male, elite, African, singles badminton players. The measuring protocol that was developed for and used in this study is unique and results suggest that this newly developed short-term measuring protocol can be used to accurately measure HRV and HRR during different time periods in real competition settings. Therefore, the methodology of this study provides coaches and sport scientists with a more practical approach (compared to more traditional methodological approaches) to obtain and evaluate HRV and HRR values of athletes during competitive settings.

Furthermore, the study accentuates the importance of correcting for recovery indicators and external match loads when making use of HRV and HRR to evaluate ANS status during matches. Researchers and sport practitioners should therefore incorporate recovery indicators and external match loads into their measuring protocols when evaluating HRV and HRR in similar conditions as failure to do so will most likely result in clouded and obscure results. Surprisingly, neither in-match resting nor post-match HRR was identified as significant predictors of group allocation for the successful and less successful badminton players. This was unexpected due to results of previous research which showed that HRR served as the distinguishing factor between elite and sub-elite football players as well as highly trained and moderately trained wrestlers. Researchers also found superior HRR to be associated with on-field match performance in sports such as basketball and soccer. Consequently, our findings cast a shadow of doubt over the use and value of ultra-short-term (less than 60 seconds) HRR measures in sports settings for the prediction of performance.

6.3 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCHERS

Although the study is the first of its kind to show that spectral HRV indices are significantly related to badminton performance and to prove that covariants such as recovery indicators and external match loads should be considered when compiling badminton performance prediction models, several shortcomings of the study should be considered for future researchers that wish to focus on this field of study:

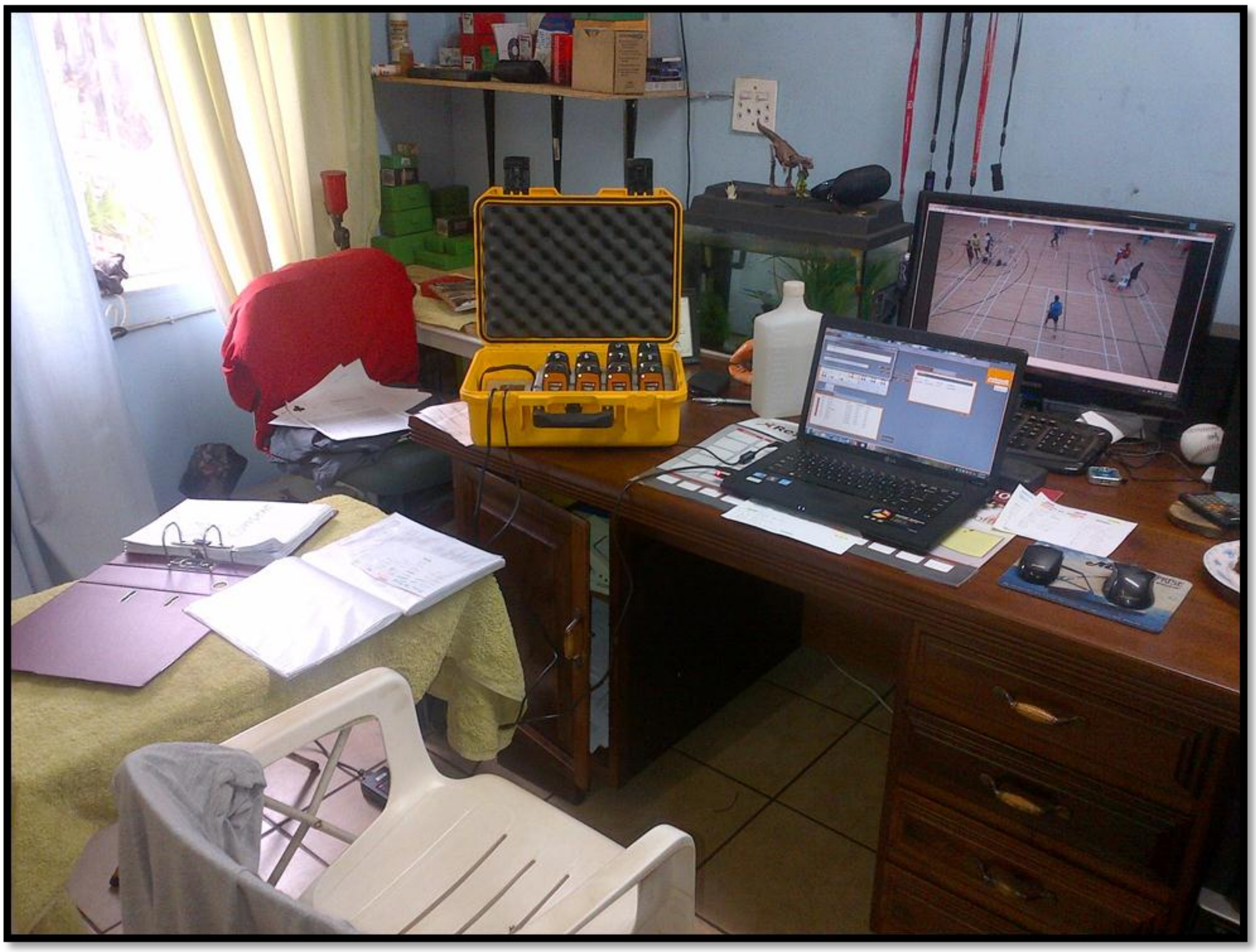
- **Limitation**: The binary forward stepwise regression logistic model used in this study was developed specifically for male, elite, African, singles badminton players. **Recommendation**: Therefore, the accuracy of this model should be tested and measured through longitudinal studies to evaluate its significance, adequacy, accurateness and usefulness among different populations of badminton players.
- **Limitation**: Furthermore, the absence of true baseline measurements, normally taken in the mornings during a fasting state, is a limitation of this study. However, time and logistical constraints that are present when measuring athletes in a real competition set-up make the measurement of baseline values difficult. **Recommendation**: Consequently, future researchers should make an attempt to obtain baseline values of badminton players before play.
- **Recommendation**: Although the HRV and HRR measuring protocol that was used in this study is the first of its kind to be employed in high profile badminton tournaments, the accuracy and reliability of this protocol should be confirmed by future research.
- **Limitation**: Although differences in fitness levels between players may have influenced HRV and HRR values, researchers did not measure or consider this variable in their measuring protocol. **Recommendation**: Future research should, therefore, consider players’ fitness levels when analysing and interpreting HRV and HRR results.
- **Limitation**: Players’ HRV and HRR values were only measured over short time periods. **Recommendation**: Some researchers suggest that longitudinal monitoring of HRV is needed to better understand an athlete’s optimal HRV fingerprint. Such a profile will allow researchers and practitioners alike to evaluate HRV changes and the impact of different factors on the ANS-profile of an athlete. Therefore, future researchers are advised to use a minimum of three days for elite athletes and five days for recreational athletes to build an adequate cardiac profile for research purposes.
- **Limitation**: Although researchers suggest that self-reported player ratings are useful tools to monitor different aspects of recovery (mood states, quality and quantity of sleep, muscle soreness and hydration levels) during training and competition participation, players’ perceptions may cloud results.

Recommendation: Therefore, future researchers should also measure recovery related indicators quantitatively in order to verify the qualitative results of questionnaires.

- **Limitation**: While the internal and external match load determining protocols that were used in this study create a platform from which data can be collected in a real world competitive badminton setting, the possible effects of different match characteristics such as the number of unforced errors, winning shots or match outcomes on the relationship between external and internal match load determining methods should also be considered. **Recommendation**: A notational analysis will prove helpful in determining the number of unforced errors, winning shots or match outcomes and give researchers more clarity on the badminton match performance and HR related parameters.
- **Limitation**: In this study heart rate (HR) intensity zones for all players were based on maximum HR which may not be the most accurate method of predicting match intensities. **Recommendation**: Therefore, individualised HR zones should rather be used when describing the HR responses of players during competition instead of fixed and generalized HR categories.

However, future researchers should acknowledge the time and logistical constraints, especially during matches and competitions which will make it difficult to meet all above-mentioned recommendations.

APPENDICES



APPENDIX A: ETHICAL APPROVAL FOR UMBRELLA PROJECT

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

Private Bag X6001, Potchefstroom
South Africa 2520

Tel: (018) 299-4900
Faks: (018) 299-4910
Web: http://www.nwu.ac.za

Ethics Committee
Tel +27 18 299 4849
Email Ethics@nwu.ac.za

ETHICS APPROVAL OF PROJECT

The North-West University Research Ethics Regulatory Committee (NWU-RERC) hereby approves your project as indicated below. This implies that the NWU-RERC grants its permission that provided the special conditions specified below are met and pending any other authorisation that may be necessary, the project may be initiated, using the ethics number below.

Project title: HEART RATE VARIABILITY AND RECOVERY AS WELL AS GPS MATCH ANALYSIS CHARACTERISTICS IN RELATION TO MATCH RESULTS IN AFRICAN MALE BADMINTON PLAYERS

Project Leader: Prof B Coetzee

Ethics number:	N	W	U	-	0	0	1	9	9	-	1	4	-	A	1
	Institution				Project Number						Year			Status	

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Approval date: 2015-04-01 **Expiry date:** 2016-12-16

Special conditions of the approval (if any): (none)

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, please note the following:

- *The project leader (principle investigator) must report in the prescribed format to the NWU-RERC:*
  - *annually (or as otherwise requested) on the progress of the project,*
  - *without any delay in case of any adverse event (or any matter that interrupts sound ethical principles) during the course of the project.*
- *The approval applies strictly to the protocol as stipulated in the application form. Would any changes to the protocol be deemed necessary during the course of the project, the project leader must apply for approval of these changes at the NWU-RERC. Would there be deviated from the project protocol without the necessary approval of such changes, the ethics approval is immediately and automatically forfeited.*
- *The date of approval indicates the first date that the project may be started. Would the project have to continue after the expiry date, a new application must be made to the NWU-RERC and new approval received before or on the expiry date.*
- *In the interest of ethical responsibility the NWU-RERC retains the right to:*
  - *request access to any information or data at any time during the course or after completion of the project;*
  - *withdraw or postpone approval if:*
    - *any unethical principles or practices of the project are revealed or suspected,*
    - *it becomes apparent that any relevant information was withheld from the NWU-RERC or that information has been false or misrepresented,*
    - *the required annual report and reporting of adverse events was not done timely and accurately,*
    - *new institutional rules, national legislation or international conventions deem it necessary.*

The Ethics Committee would like to remain at your service as scientist and researcher, and wishes you well with your project. Please do not hesitate to contact the Ethics Committee for any further enquiries or requests for assistance.

Yours sincerely

Linda du Plessis

Digitally signed by Linda du Plessis
DN: cn=Linda du Plessis, o=NWU, Vaal Triangle Campus, ou=Vice-Rector Academic, email=linda.duplessis@nwu.ac.za, c=US
Date: 2015.04.02 09:16:36 +02'00'

Prof Linda du Plessis
Chair NWU Research Ethics Regulatory Committee (RERC)

APPENDIX B: ETHICAL APPROVAL FOR PHD THESIS

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOM CAMPUS

Private Bag X6001, Potchefstroom
South Africa 2520

Tel: 018 299-1111/2222
Web: http://www.nwu.ac.za

Faculty of Health Sciences
Tel: 018-299 2092
Fax: 018-299 2088
Email: Minrie.Greeff@nwu.ac.za

1 April 2015

Prof B Coetzee
Human Movement Science

Dear Prof Coetzee

APPROVAL LETTER: ETHICS APPLICATION: NWU-00199-14-A1 (B COETZEE-CA BISCHOFF) "HEART RATE VARIABILITY AND RECOVERY AS WELL AS GPS MATCH ANALYSIS CHARACTERISTICS IN RELATION TO MATCH RESULTS IN AFRICAN MALE BADMINTON PLAYERS"

Thank you for amending your application. All ethical concerns have now been addressed and ethical approval for the sub-study, entitled "Heart rate variability and heart rate recovery in relation to match results in elite African male badminton players" is granted until 16/12/2016.

Please note that any changes to the approved application must be submitted to the Health Research Ethics Committee for approval before implementation.

Yours sincerely

Prof Minrie Greeff
HREC Chairperson

Original details: (10187308) C:\Users\13210572\DOCUME~1\HREC\HREC-A~4\2014HR~1\AP67E4~1\NW55E5~1\NWC1F6~1\NWU-00199-14-A1 (B Coetzee-CA Bischoff) - Approval letter.docm
1 April 2015

File reference: 9.1.5.3

1

APPENDIX C: PERMISSION LETTER FROM BADMINTON CONFEDERATION OF AFRICA

Mail From: "Larry Keys" <larrybca@gmail.com>

File Edit View Actions Tools Accounts Window Help

Close Reply Reply All Forward

Mail | Properties | Personalize | Message Source | Discussion Thread

From: "Larry Keys" <larrybca@gmail.com> 2015/01/15 01:38:04 PM
To: Ben Coetzee
Subject: Badminton Research project ref: B007.01.15

Dear Prof. Coetzee,

I have consulted with my Executive Board and advise we are happy to support this project.

I am also President of Badminton South Africa so please contact me should you require any other assistance or information.

Best regards,

Larry Keys
Acting-President
Tel: +27 12 663 3292
Cell: +27 82 444 3911
Email: larrybca@gmail.com

Badminton Confederation of Africa

APPENDIX D: PERMISSION LETTER FROM BADMINTON SOUTH-AFRICA

Ben Coetzee - Research Project Badminton

From: "Klaas Visser" <landas@lando.co.za>
To: "Ben Coetzee NWU" <Ben.Coetzee@nwu.ac.za>
Date: 2014/04/08 09:06 AM
Subject: Research Project Badminton
CC: <stewartjcarson@gmail.com>, "Badminton SA" <badmintonsa@mweb.co.za>

Dear Ben

We have discussed your proposal at our recent Board meeting and would like to become involved in your research project. We can clearly see the advantages for Badminton South Africa

How do you suggest we go about it? We are planning a training camp in Benoni from 20 to 22 April (prior to participating in the All Africa Badminton Championships in Lobatse, Botswana) All our National Players will be present. Perhaps it is the ideal situation to discuss this with the players. Or would you rather focus on our top u/19 players? They are currently in Malaysia participating in the World Junior Championships. The SA under 19 tournament is scheduled for Bloemfontein the 1st week of the schools holiday as another option

Our National Head coach Stewart Carson will run the training camp in Benoni

In future please direct all correspondence pertaining to your research to me as the High Performance Manager

Your research will play a vital role in updating and our "Badminton for Life" Long Term Participant Development Plan document, I will ask Stewart to give you a copy, otherwise I can sent it to you via Dropbox

Kind regards,

Klaas Visser
High Performance Manager
Chair Schools and Junior Section
Vice-President Administration

BADMINTON SOUTH AFRICA

Website: www.badmintonsa.org
Email: landas@lando.co.za
admin@stickbond.co.za

Tel: +27 28 271 5321
Fax: +27 28 271 5521
Mobile: +27 82 878 4566

APPENDIX E: PERMISSION LETTER FROM BADMINTON WORLD FEDERATION

BADMINTON WORLD FEDERATION

12.02.2014

Dear Ben

Thank you for your time during my recent visit to RSA. I was interested to discuss the Badminton research proposal you are currently developing concerning African player characteristics.

Badminton is a sport which is certainly under researched in Africa, with very little specific information available. BWF are therefore happy to confirm its support for this project and I look forward to seeing the outcomes.

If you require further assistance in terms of contacts or recommendations please do not hesitate to contact me.

Kind regards

Ian Wright

Director of Development

Badminton World Federation

Unit 17.05, Level 17, Amoda Building
22 Jalan Imbi
55100 Kuala Lumpur
Malaysia

T +603 2141 7155
F +603 2143 7155
E bwf@bwfbadminton.org
W www.bwfbadminton.org

APPENDIX F: PERMISSION LETTER FROM BOTSWANA BADMINTON ASSOCIATION

BOTSWANA BADMINTON ASSOCIATION

P O Box 201369
Gaborone
Botswana
Telefax
Email:info@botswanabadminton.com

24th February 2015

Prof. Ben Coetzee
Private Bag X6001
Potchefstroom
South Africa 2520

RE: RESEARCH PROPOSAL SUBMITTED TO BOTSWANA BADMINTON ASSOCIATION

The above subject matter refers.

The Executive Committee of the Botswana Badminton wishes to acknowledge receipt of your research proposal document and a confirmation letter from BWF dated 13th January 2015 and 12th February 2015 respectively.

In light of the above, we wish to confirm our agreement to grant you permission to conduct the research with our players, coaches and managers at your disposal.

Do not hesitate to contact the undersigned for more information.

Thank you.

Yours faithfully

Thuso Mudongo (Mr)

Secretary General

/For President

Mobile: (+267) 72151225 / 71661990 / 73399809

Email: secretary@botswanabadminton.com
tttndongos@yahoo.co.uk

APPENDIX G: PARTICIPATION LEAFLET AND CONSENT FORM FOR BADMINTON PLAYERS

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOM CAMPUS

APPROVED

HREC Stamp

PARTICIPANT INFORMATION LEAFLET AND CONSENT FORM FOR BADMINTON PLAYERS WHO ARE PARTICIPATING IN THE BADMINTON STUDY.

TITLE OF THE RESEARCH PROJECT:
Heart rate variability and recovery as well as global positioning system (GPS) match analysis characteristics in relation to match results in African male badminton players

REFERENCE NUMBERS: NWU-0199-14-A1

PRINCIPAL INVESTIGATOR:
Prof. Ben Coetzee

ADDRESS:
Physical Activity, Sport and Recreation
Faculty of Health Sciences
Building K21
North-West University
Potchefstroom
2522

CONTACT NUMBER:
0182991803

You are being invited to take part in the **Badminton Analysis Project** that forms part of post graduate, PhD-studies. Please take some time to read the information presented here, which will explain the details of this project. Please ask the researcher any questions about any part of this project that you do not fully understand. It is very important that you are fully satisfied that you clearly understand what this research entails and how you could be involved. Also, your participation is **entirely voluntary** and you are free to decline to participate. If you say no, this will not affect you negatively in any way whatsoever. You are also free to withdraw from the study at any point, even if you do agree to take part.

This study has been approved by the **Health Research Ethics Committee of the Faculty of Health Sciences of the North-West University (NWU-0199-14-A1)** and will be conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and the ethical guidelines of the National Health Research Ethics Council. It might be necessary for the research ethics committee members or relevant authorities to inspect the research records.

What is this research study all about?

- *This study will be conducted at LC de Villiers indoor training centre at the University of Pretoria and the indoor sport centre of the Show Grounds in Pretoria and will involve the analysis of matches via heart rate, Global Positioning System and video monitoring. Researchers will also determine your mood states and recovery status as well as your habitual dietary intake by making use of questionnaires and an interview, respectively. Experienced sport science researchers trained in human movement and sport science as well as dietetics will conduct the analyses. The aim is to recruit between thirty and forty male players to participate in this study.*
- *The objectives of this research are to determine the meaningful changes in the way that the heart rate varies from one beat to the next (HRV) and the degree in which the heart rate recovers (HRR) during the course of a tournament as well as the relationships between these last-mentioned variables and match results in elite African badminton players. Furthermore, to determine the influence of elite African badminton players' pre-competition dietary preferences, hydration status, sleep quality and quantity as well as mood states on HRV and HRR during the course of a tournament. Lastly, the researchers are also going to determine the singles match characteristics of male badminton players who participated in National and/or International Championships.*

Why have you been invited to participate?

- *You have been invited to participate because you are a male singles badminton player who is participating in a National or International Championship.*
- *You have also complied with the following inclusion criteria: You provided voluntary consent, while your manager and coach gave permission for you to participate in the study.*
- *Furthermore, you are actively involved and competing as a member of your provincial or national team and you are totally free of any injuries as well as illnesses.*
- *You will be excluded if: you become injured or ill at any time or if you are not prepared to play a match while wearing a heart rate and global positioning system (GPS) monitor. Furthermore, you will also be excluded if you do not fill in the questionnaires or undertake a 30 min long interview. Also, players who do not want to be video recorded during match play will also be excluded from the study.*

What will your responsibilities be?

- *You will be expected to undergo body mass and stature measurements in the bath room of the venue were you are participating, fill in a demographic and* *general information as well as a general recovery and hydration status questionnaire and the Stellenbosch Mood Scale. You will also be expected to wear a GPS and heart rate monitor during all matches that you play so that you can be monitored during match play. Lastly, you will also be expected to undertake a 30 minute long interview about you habitual dietary preferences in a secluded room where your privacy will be assured.*

Will you benefit from taking part in this research?

- *Among the direct benefits are, that you as a player will be able to gain access to your results as well as a personalized report explaining the results. Your data will also be used to explain to you and/or your coach orally during the duration of the different tournaments how your conditioning programmes can be changed in such a way that it prepares you for the demands of match play. Players and coaches will also be afforded the opportunity to talk to the researchers about any conditioning advice that they have a need for. Furthermore, the heart rate, HRV and HRR data will allow the researchers to evaluate players' recovery and fitness levels which may assist you and your coach to identify weak points and to identify factors that are detrimental to your recovery. As part of the research project you will also be afforded the opportunity to do an interview through which your dietary preferences and profile will be determined and evaluated by a dietician. Data with regard to hydration levels, mood states and sleeping quality and quantity will also allow researchers to provide you with feedback concerning these aspects. An indirect benefit of the study is an expansion of existing expert knowledge in the field of Applied Sport Science which can be transferred to the wider sporting community.*

Are there risks involved in your taking part in this research?

- *Risks will be minimised and the researchers will aim to maximise potential benefits that are likely to have a valuable impact on you, either directly or indirectly. No severe physical, psychological, social stress or other negative consequences beyond the risks encountered in normal match play are foreseen in this study. Each player and coach will be responsible for the warm-up before each match to prepare you physically and physiologically for the demands of match play and to decrease injury risk. The Badminton World Federation requires that medical staff must be available at all times during the tournament, which means that a medical physician and physiotherapist will be available during the course of the tournament, should any injuries occur. In case of illness or injury you will immediately be withdrawn from the study and will be allowed to leave at any time if you feel so. You may experience a bit of discomfort due to the Polar Heart Rate Transmitter Belt that is tied around your chest and the GPS harness that is worn on your back during match play. However, the warm-up period will be used to adjust the heart rate transmitter belt and GPS harness according to your preference and to make you use to the equipment. If you do not feel comfortable to wear the equipment during match play, you will be allowed to play without the equipment.*
- *For some players it may be uncomfortable to fill in the Stellenbosch Mood Scale questionnaires a few minutes before the match as it may make them feel more anxious.*

- *Some players may find it uncomfortable to talk about their dietary patterns to the researcher while they are being recorded. However, the interviewer will set the interviewee at ease by providing you with a short introduction of what the interview is going to entail and also by allowing you to ask any questions that are related to concerns about the interview. The interviewer will maintain a demeanour of friendliness, openness and genuineness. Furthermore, the interview will be conducted in a comfortable, good sized, quiet and private meeting room. The interviewer will also make sure that his questions are clear, well-phrased and as jargon-free as possible to help avoid any confusion.*

What will happen in the unlikely event of some form of discomfort occurring as a direct result of your taking part in this research study?

- *Should you have the need for further discussions after match play an opportunity will be arranged for you to do so. The Badminton World Federation requires that medical staff must be available at all times during matches, which means that first aid personnel will be available for the duration of each match, should any injuries occur. In case of illness or injury you will immediately be withdrawn from the study and will be allowed to leave at any time if you feel so.*

Who will have access to the data?

- *Anonymity will be partial due to the fact that the coaches and managers also want the feedback of the match analyses but the researchers will respect the decision of each player in order to protect his anonymity. Data will be coded to ensure that no link can be made to a specific player. Confidentiality will be ensured by deleting audio records of interviews after data has been captured. Reporting of findings will be anonymous by only authorising the head researcher to have control over the distribution of these findings. Only the head researcher and research assistants will have access to the data and will also sign a confidentiality agreement to protect players. Data will be kept safe and secure by locking hard copies in locked cupboards in the researcher's office and for electronic data it will be password protected. Data will be stored for 7 years after which the information will be shredded and e-copies deleted.*

What will happen with the data/samples?

- *This is a once off collection and data will be kept at the North-West University and analysed at the North-West University.*

Will you be paid to take part in this study and are there any costs involved?

- No, you will not be paid to take part in the study. There will also be no costs involved for you, if you do take part.

Is there anything else that you should know or do?

- You can contact Ben Coetzee at 018 2991803 if you have any further queries or encounter any problems.
- You can contact the Health Research Ethics Committee via Mrs Carolien van Zyl at 018 299 2089; carolien.vanzyl@nwu.ac.za if you have any concerns or complaints that have not been adequately addressed by the researcher.
- You will receive a copy of this information and consent form for your own records.

How will you know about the findings?

- ➢ The findings of the research will be shared with you if you are interested. You are welcome to contact us regarding the findings of the research. We will be sharing the findings with you as soon as it is available

Declaration by participant

By signing below, I .... agree to take part in a research study titled: **Badminton Analysis Project**

I declare that:

- I have read this information and consent form and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions to both the person obtaining consent, as well as the researcher and all my questions have been adequately answered.
- I understand that taking part in this study is **voluntary** and I have not been pressurised to take part.
- I may choose to leave the study at any time and will not be penalised or prejudiced in any way.
- I may be asked to leave the study before it has finished, if the researcher feels it is in my best interests, or if I do not follow the study plan, as agreed to.

Signed at (*place*) .... on (*date*) .... 20....

....

Signature of participant **Signature of witness**

Declaration by person obtaining consent

I *(name)* .... declare that:

- I explained the information in this document to ....
- I encouraged him/her to ask questions and took adequate time to answer them.
- I am satisfied that he/she adequately understands all aspects of the research, as discussed above
- I did/did not use an interpreter.

Signed at (*place*) .... on (*date*) .... 20....

....
Signature of person obtaining consent **Signature of witness**

Declaration by researcher

I *(name)* ……………………………………………………… declare that:

- I explained the information in this document to ……………………………………
- I encouraged him/her to ask questions and took adequate time to answer them.
- I am satisfied that he/she adequately understands all aspects of the research, as discussed above
- I did/did not use an interpreter.

Signed at (*place*) …………………………………………… on (*date*) ………………………… 20....

....
Signature of researcher **Signature of witness**

APPENDIX H: GENERAL INFORMATION AND DATA COLLECTION QUESTIONNAIRES

General Information Questionnaire and Test Protocol for the GPS, HRV and HRR badminton match analyses project

GENERAL INFORMATION

Please write clearly!

1. <u>GEOGRAPHICAL INFORMATION</u>

1.1 Surname: **Initials** **First Name**

1.2 Age:

<u>Years:</u>	<u>Months:</u>

1.3 Birth date:

<u>Year:</u>	<u>Month:</u>	<u>Day:</u>

1.4 Permanent residential address:

______________________________ ______________________________ ______________________________ ______________________________ ______________________________ ______________________________

1.5 Permanent postal address:

1.6 Phone numbers:

Home:	Work:
Fax:	Cell:
E-mail:	

1.7 Country that you are presenting during this championships

In the next few question cross out the answers that are applicable to you!!

2. INFORMATION REGARDING TRAINING HABITS

2.1 Years you've been playing badminton.

1-2 years	3-4 years	5-6 years	7-8 years	8-9 years	10-11 years	12 or more

2.2 Frequency of training - how many days per week do you normally train?

1 day	2 days	3 days	4 days	5 days	6 days	7 days

2.3 Frequency of training - how many days per week do you normally do weight training?

1 day	2 days	3 days	4 days	5 days	6 days	7 days

2.4 Frequency of training - how many days per week do you normally have court sessions?

1 day	2 days	3 days	4 days	5 days	6 days	7 days

2.5 Frequency of training - how many <u>days per week</u> do you normally do training on the field or road?

1 day	2 days	3 days	4 days	5 days	6 days	7 days

2.6 How many <u>hours per day</u> do you normally train?

1 hour	2 hours	3 hours	4 hours	5 hours	6 hours	7 or more

2.7 How many <u>hours per day</u> do you normally spend on weight training?

1 hour	2 hours	3 hours	4 hours	5 hours	6 hours	7 or more

2.8 How many <u>hours per day</u> do you normally spend on training on the court?

1 hour	2 hours	3 hours	4 hours	5 hours	6 hours	7 or more

2.9 How many <u>hours per day</u> do you normally spend on training on the field or road?

1 hour	2 hours	3 hours	4 hours	5 hours	6 hours	7 or more

2.10 Do you spend any time on psychological preparation for badminton and competitions?

Never	*Sometimes	*Often	*Always

*** Please specify the type of psychological preparation you do if you marked any of the above-mentioned options:**

____

____

____

____

____

____

____

3. MEDICAL INFORMATION

3.1 Please describe any past or current musculoskeletal conditions you have incurred (i.e., muscle pulls, sprains, fractures, surgery, back pain, or any general discomfort):

Head/Neck: __________ __________ __________ __________ __________
Shoulder/Clavicle: __________ __________ __________ __________ __________
Arm/Elbow/Wrist/Hand: __________ __________ __________ __________ __________
Back: __________ __________ __________ __________
Hip/Pelvis: __________ __________ __________ __________

Thigh/Knee:

Lower leg/Ankle/Foot:

3.2 Please list any medication being taken currently and/or taken during the last year:

3.3 List any other illness or disorder that a physician has told you of:

4. COMPETITION DATA

4.1 At what level are you competing this year?

4.2 What is the highest level that you competed at last year?

Club:	Provincial:	National:	International:

4.3 How many matches, approximately, have you played?

Club:	Provincial/National:	International:

4.4 What were the highest achievements you attained during the past two years (2013/14)?

Achievement	Competition	Date

NAME AND SURNAME: ____

1ST MATCH – DATE AND TIME OF MATCH: ______________________	
TEST COMPONENT	**VALUES**
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	
2ND MATCH – DATE AND TIME OF MATCH: ______________________	
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	

NAME AND SURNAME: ____

3RD MATCH – DATE AND TIME OF MATCH: ______________________	
TEST COMPONENT	**VALUES**
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	
4TH MATCH – DATE AND TIME OF MATCH: ______________________	
TEST COMPONENT	**VALUES**
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	

NAME AND SURNAME: ____

5TH MATCH – DATE AND TIME OF MATCH: ______________________	
TEST COMPONENT	**VALUES**
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	
6TH MATCH – DATE AND TIME OF MATCH: ______________________	
TEST COMPONENT	**VALUES**
SINGLES (S) / DOUBLES (D) / MIXED DOUBLES (M)	
GPS MONITOR NUMBER (LONG AND SHORT)	
POLAR TRANSMITTER NUMBER	
TIME - START OF MATCH (H:MIN)	
TIME DURATION BEFORE FIRST BREAK (SEC)	
BREAK 1 (H:MIN)	
TIME DURATION BEFORE SECOND BREAK (SEC)	
BREAK 2 (H:MIN)	
TIME DURATION BEFORE THIRD BREAK (SEC)	
BREAK 3 (H:MIN)	
TIME DURATION BEFORE FOURTH BREAK (SEC)	
BREAK 4 (H:MIN)	
TIME DURATION BEFORE FIFTH BREAK (SEC)	
BREAK 5 (H:MIN)	
TIME DURATION BEFORE SIXTH BREAK (SEC)	
BREAK 6 (H:MIN)	
TIME - END OF MATCH (H:MIN)	

THE STELLENBOSCH MOOD SCALE

Name and Surname:	**Date and time:**	

Below is a list of words that describe feelings people have. Please read each one carefully. Mark [X] the answer that best describes **how you feel right now**. / *Hieronder is 'n lys van woorde wat gevoelens beskryf wat mense ervaar. Lees asseblief elkeen noukerig en merk [X] die antwoord wat die beste beskryf* ***hoe jy op hierdie oomblik voel****.*

AFRIKAANS	*Gladnie* / Not at all	*Effens* / A little	*Taamlik* /Moderately	*Baie* / Quite a bit	*Uiters* / Extremely	ENGLISH
Verward	❑	❑	❑	❑	❑	**Confused**
Vermoeid	❑	❑	❑	❑	❑	**Worn out**
Vererg	❑	❑	❑	❑	❑	**Annoyed**
Verbitterd	❑	❑	❑	❑	❑	**Bitter**
Vaak	❑	❑	❑	❑	❑	**Sleepy**
Uitgeput	❑	❑	❑	❑	❑	**Exhausted**
Senuweeagtig	❑	❑	❑	❑	❑	**Nervous**
Paniekerig	❑	❑	❑	❑	❑	**Panicky**
Op en wakker	❑	❑	❑	❑	❑	**Alert**
Ontwrig	❑	❑	❑	❑	❑	**Muddled**
Onseker	❑	❑	❑	❑	❑	**Uncertain**
Ongelukkig	❑	❑	❑	❑	❑	**Unhappy**
Neerslagtig	❑	❑	❑	❑	❑	**Depressed**
Moeg	❑	❑	❑	❑	❑	**Tired**
Mismoedig	❑	❑	❑	❑	❑	**Downhearted**
Lewendig	❑	❑	❑	❑	❑	**Lively**
Kwaad	❑	❑	❑	❑	❑	**Angry**
Humeurig	❑	❑	❑	❑	❑	**Bad tempered**
Energiek	❑	❑	❑	❑	❑	**Energetic**
Ellendig	❑	❑	❑	❑	❑	**Miserable**
Deurmekaar	❑	❑	❑	❑	❑	**Mixed up**
Bekommerd	❑	❑	❑	❑	❑	**Worried**
Angstig	❑	❑	❑	❑	❑	**Anxious**
Aktief	❑	❑	❑	❑	❑	**Active**

RECOVERY INDICATORS

NAME AND SURNAME: ____

Please insert the following data that relates to the time period before your competition participation:

BEFORE MATCH

DATE, TIME AND TYPE OF MATCH:_____________________________________

1. How many hours did you sleep during the previous night?

2 hours	3 hours	4 hours	5 hours	6 hours	7 hours	8 hours	9 hours	10 hours

2. Rate the quality of sleep of the previous night:

Very poor	Poor	Average	Good	Very good

3. Are you currently experiencing any muscle soreness?

None	Some	A lot

4. What was the shade of your urine the last time that you went to the toilet?

Transparant	A shade of light yellow	Light yellow	Yellow	Dark Yellow	Very dark yellow

APPENDIX I: INSTRUCTIONS FOR AUTHORS OF THE JOURNAL OF STRENGTH AND CONDITIONING RESEARCH

MANUSCRIPT PREPARATION

Title Page

The title page should include the manuscript title, brief running head, laboratory(s) where the research was conducted, authors' full name(s) spelled out with middle initials, department(s), institution(s), full mailing address of corresponding author including telephone and fax numbers, and email address, and disclosure of funding received for this work from any of the following organizations: National Institutes of Health (NIH); Welcome Trust; Howard Hughes Medical Institute (HHMI); and other(s).

Blind Title Page

A second title page should be included that contains only the manuscript title. This will be used to send to the reviewers in our double blind process of review. Do not place identifying information in the Acknowledgement portion of the paper or anywhere else in the manuscript.

Abstract and Key Words

On a separate sheet of paper, the manuscript must have an abstract with a limit of 250 words followed by 3 – 6 key words not used in the title. The abstract should have sentences (no headings) related to the purpose of the study, brief methods, results, conclusions and practical applications.

Text

The text must contain the following sections with titles in ALL CAPS in this exact order:

A. Introduction. This section is a careful development of the hypotheses of the study leading to the purpose of the investigation. In most cases use no subheadings in this section and try to limit it to 4 – 6 concisely written paragraphs.

B. Methods. Within the METHODS section, the following subheadings are required in the following order: ''Experimental Approach to the Problem,'' where the author(s) show how their study design will be able to test the hypotheses developed in the introduction and give some basic rationales for the choices made for the independent and dependent variables used in the study; ‘‘Subjects,’’ where the authors include the Institutional Review Board or Ethics Committee approval of their project and appropriate informed consent has been gained. All subject characteristics that are not dependent variables of the study should be included in this section and not in the RESULTS; ‘‘Procedures,’’ in this section the methods used are presented with the concept of ‘‘replication of the study’’ kept in mind. ‘‘Statistical Analyses,’’ here is where you clearly state your statistical approach to the analysis of the data set(s). It is important that you include your alpha level for significance (e.g., P # 0.05). Please place your statistical power in the manuscript for the n size used and reliability of the dependent measures with intra-class correlations (ICC Rs). Additional subheadings can be used but should be limited.

C. Results. Present the results of your study in this section. Put the most important findings in Figure or Table format and less important findings in the text. Do not include data that is not part of the experimental design or that has been published before.

D. Discussion. Discuss the meaning of the results of your study in this section. Relate them to the literature that currently exists and make sure you bring the paper to completion with each of your hypotheses. Limit obvious statements like, ‘‘more research is needed.’’

E. Practical Applications. In this section, tell the ‘‘coach’’ or practitioner how your data can be applied and used. It is the distinctive characteristic of the JSCR and supports the mission of ‘‘Bridging the Gap’’ for the NSCA between the laboratory and the field practitioner.

References

All references must be alphabetized by surname of first author and numbered. References are cited in the text by numbers [e.g., (4,9)]. All references listed must be cited in the manuscript and referred to by number therein. For original investigations, please limit the number of references to fewer than 45 or explain why more are necessary. The Editorial Office reserves the right to ask authors to reduce the number of references in the manuscript. Please check references carefully for accuracy. Changes to references at the proof stage, especially changes affecting the numerical order in which they appear, will result in author revision fees.

Below are several examples of references:

Journal Article

Hartung, GH, Blancq, RJ, Lally, DA, and Krock, LP. Estimation of aerobic capacity from submaximal cycle ergometry in women. Med Sci Sports Exerc 27: 452–457, 1995.

Book

Lohman, TG. Advances in Body Composition Assessment. Champaign, IL: Human Kinetics, 1992.

Chapter in an edited book

Yahara, ML. The shoulder. In: Clinical Orthopedic Physical Therapy. J.K. Richardson and Z.A. Iglarsh, eds. Philadelphia: Saunders, 1994. pp. 159–199.

Software

Howard, A. Moments ½software_. University of Queensland, 1992.

Proceedings

Viru, A, Viru, M, Harris, R, Oopik, V, Nurmekivi, A, Medijainen, L, and Timpmann, S. Performance capacity in middle-distance runners after enrichment of diet by creatine and creatine action on protein synthesis rate. In: Proceedings of the 2nd Maccabiah-Wingate International Congress of Sport and Coaching Sciences. G. Tenenbaum and T. Raz-Liebermann, eds. Netanya, Israel, Wingate Institute, 1993. pp. 22–30.

Dissertation/Thesis

Bartholmew, SA. Plyometric and vertical jump training.Master’s thesis, University of North Carolina, Chapel Hill, 1985.

APPENDIX J: EXAMPLE OF ARTICLE PUBLISHED IN THE JOURNAL OF STRENGTH AND CONDITIONING RESEARCH

An Examination of Muscle Activation and Power Characteristics While Performing the Deadlift Exercise With Straight and Hexagonal Barbells

Kevin D. Camara, Jared W. Coburn, Dustin D. Dunnick, Lee E. Brown, Andrew J. Galpin, and Pablo B. Costa

Department of Kinesiology, Center for Sport Performance, California State University, Fullerton, California

Abstract

Camara, KD, Coburn, JW, Dunnick, DD, Brown, LE, Galpin, AJ, and Costa, PB. An examination of muscle activation and power characteristics while performing the deadlift exercise with straight and hexagonal barbells. *J Strength Cond Res* 30(5): 1183–1188, 2016—The deadlift exercise is commonly performed to develop strength and power, and to train the lower-body and erector spinae muscle groups. However, little is known about the acute training effects of a hexagonal barbell vs. a straight barbell when performing deadlifts. Therefore, the purpose of this study was to examine the hexagonal barbell in comparison with the straight barbell by analyzing electromyography (EMG) from the vastus lateralis, biceps femoris, and erector spinae, as well as peak force, peak power, and peak velocity using a force plate. Twenty men with deadlifting experience volunteered to participate in the study. All participants completed a 1 repetition maximum (1RM) test with each barbell on 2 separate occasions. Three repetitions at 65 and 85% 1RM were performed with each barbell on a third visit. The results revealed that there was no significant difference for 1RM values between the straight and hexagonal barbells (mean ± *SD* in kg = 181.4 ± 27.3 vs. 181.1 ± 27.6, respectively) ($p > 0.05$). Significantly greater normalized EMG values were found from the vastus lateralis for both the concentric (1.199 ± 0.22) and eccentric (0.879 ± 0.31) phases of the hexagonal-barbell deadlift than those of the straight-barbell deadlift (0.968 ± 0.22 and 0.559 ± 1.26), whereas the straight-barbell deadlift led to significantly greater EMG values from the bicep femoris during the concentric phase (0.835 ± 0.19) and the erector spinae (0.753 ± 0.28) during the eccentric phase than the corresponding values for the hexagonal-barbell deadlift (0.723 ± 0.20 and 0.614 ± 0.21) ($p \leq 0.05$). In addition, the hexagonal-barbell deadlift demonstrated significantly greater peak force (2,553.20 ± 371.52 N), peak power (1,871.15 ± 451.61 W), and peak velocity (0.805 ± 0.165) values than those of the straight-barbell deadlift (2,509.90 ± 364.95 N, 1,639.70 ± 361.94 W, and 0.725 ± 0.138 $m \cdot s^{-1}$, respectively) ($p \leq 0.05$). These results suggest that the barbells led to different patterns of muscle activation and that the hexagonal barbell may be more effective at developing maximal force, power, and velocity.

Key Words electromyography, vastus lateralis, biceps femoris, erector spinae, peak power, peak force, peak velocity

Introduction

The deadlift exercise is widely used by athletes of many sports, as well as recreational lifters, to enhance power and strength (20). The exercise is a multijoint movement that activates several large muscle groups. Research has shown that, compared to other free weight exercises, the deadlift involves the lifting of heavier loads (1,10). The ability to lift heavier loads elicits a larger stimulus to adapt, making it ideal for enhancing muscular strength, which contributes to power (20). The movement requires grasping a barbell while in a squatting position and then elevating the barbell by extending the hips, knees, and ankles. When the hips are fully extended the concentric portion of the movement has ended. The barbell traveling downward until it reaches the floor or starting position completes the eccentric portion of the deadlift. The movement begins with the barbell starting at the midleg level and should remain close to the leg, thighs, and hips as the barbell elevates (1). It is vital that the barbell remain close to the lower extremities throughout the lift to reduce the moment arm of the barbell at the individual joints, decreasing the resistance of the external load (7).

In comparison with other strength exercises, such as the squat, the deadlift has received comparatively little research interest (2,4,5,9,11,13,19). A common belief is that the deadlift and back squat have similar movement patterns and that it is acceptable to relate theories and new findings between the 2 exercises. However, this was shown to be false through

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Journal of Strength and Conditioning Research

a kinematic analysis showing different movement patterns between the 2 exercises (8). Clearly, further research is needed to better understand the deadlift and optimize its use in training.

Strength and conditioning professionals typically include the deadlift in their programs to strengthen the legs, hips, back, and torso musculature (1,20). Variations of the deadlift are also often performed to alter the movement patterns and muscular requirements of the exercise. One popular variation is the hexagonal-barbell deadlift. The hexagonal design of the barbell is theorized to shift the stress from the lower back, hips, and hamstrings to the quadriceps femoris. Theoretically, this would be a more advantageous position and reduce external forces and injuries to the lumbar spine. However, little research exists on performing deadlifts with a hexagonal barbell (Figure 1) (6,14).

To date, one study has compared the hexagonal barbell with a straight barbell during the deadlift exercise. The results indicated that the hexagonal barbell reduced stress on the lumbar region while enhancing force, velocity, and power (16). To our knowledge, however, no previous studies have simultaneously examined muscle activation and power characteristics while performing the deadlift exercise with a straight vs. hexagonal barbell. Therefore, the purpose of this study was to further investigate the hexagonal barbell in comparison with a straight barbell while performing the deadlift, through an analysis of electromyography (EMG), force, velocity, and power characteristics.

Methods

Experimental Approach to the Problem

A repeated-measures design was used to compare the effects of deadlifting with 2 different barbells on EMG (vastus lateralis, bicep femoris, and erector spinae) and force plate data (peak force, power, and velocity). Participants visited the laboratory for 3 testing sessions. Each session began with a dynamic warm-up consisting of knee pulls, walking lunges, and alternating leg swings. The first 2 sessions consisted of 1 repetition maximum (1RM) testing with each barbell in a randomized order. The third session consisted of 3 repetitions with submaximal loads of 65 and 85% 1RM for each barbell, with the order of barbells randomized for each participant. We chose these 2 loads to determine whether the 2 barbells had different effects when using loads associated with power (65% 1RM) vs. strength development (85% 1RM).

Subjects

Twenty men, 19 to 27 y, (mean ± SD age = 23.3 ± 2.1 y, height = 176.8 ± 7.6 cm, body mass = 89.9 ± 18.3 kg,) who performed three days per week of resistance training, including deadlifting once per week for the past year, volunteered to participate in the study. Participants were disqualified from the study if they were not capable of lifting one and one half times their body weight with either bar. All procedures were approved by the University Institutional Review Board for Human Subjects and the participants signed informed consent forms before any testing. Participants were also instructed to avoid any lower-body resistance training 48 hours before each session.

One Repetition Maximum Testing

For deadlift 1RM testing, subjects were required to warm up for 10 repetitions at 50%, 5 repetitions at 70%, 3 repetitions at 80%, and 1 repetition at 90% of their predicted 1RM (1). Three minutes of rest were given between warm-up sets. During 1RM attempts, the weight was increased in increments of 5–20 pounds until the subjects were able to only complete 1 repetition successfully. If the subjects were not able to execute the lift successfully, the weight was reduced by 5–10 pounds. Subjects were given up to 5 single-repetition sets to determine their 1RM. All deadlifts were performed using a conventional stance. A lift was deemed successful if at the end of the ascent phase the participant stood erect with knees and hips extended, the torso upright, and the shoulder girdle retracted. During each condition, participants were allowed normal deadlifting shoes and chalk; however, these remained consistent for all conditions. No belts or straps were used.

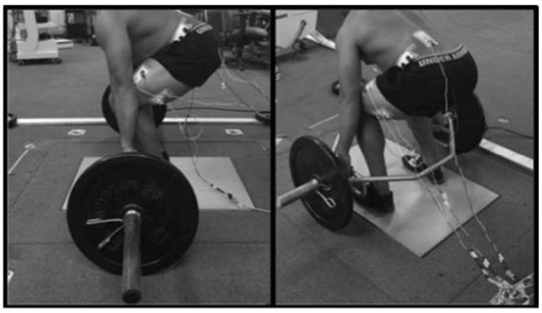

Figure 1. Deadlift performed with straight (left) and hexagonal (right) barbells.

Experimental Trials Testing Procedure

This testing session was separated by a minimum of 48 hours from the previous session. Data collection then consisted of 3 repetitions at 65% and 3 repetitions at 85% with each barbell. Participants were instructed to perform each repetition with maximal velocity during the concentric phase of the lifts, then to lower the bar under control during the eccentric phase. The order of bars was randomized. All repetitions were performed with 3 minutes of rest, and 5 minutes of rest was given between lifts with each bar.

Electromyography

Electromyography data were collected during each visit. Before collection, each participant's skin was prepared for EMG electrode placement by shaving the hair on the skin, mild abrasion, and cleaning with isopropyl alcohol. Electromyography data were collected and stored on a personal computer (Dell Latitude D610; Dell, Round Rock, TX, USA). Three separate bipolar (3.5-cm center-to-center) surface electrode (BIOPAC EL500 silver-silver chloride; BIOPAC Systems, Inc., Goleta, CA, USA) arrangements were placed over the biceps femoris, vastus lateralis, and erector spinae (longissimus) muscles, with the reference electrodes placed over the iliac crest. The biceps femoris electrodes were placed at 50% of the distance along the line between the ischial tuberosity and the lateral epicondyle of the tibia. Electrodes for the vastus lateralis were placed 2/3 of the distance on the line from the anterior superior iliac spine to the lateral side of the patella. For the erector spinae (longissimus), 2 electrodes were placed at a width of 2 fingers, lateral from the spinous process of L1. All measurements were taken on the left side of the participant's body. The EMG signals were preamplified (gain 1,000×) using a differential amplifier (EMG 100C, bandwidth = 1–500 Hz; BIOPAC Systems, Inc., Santa Barbara, CA, USA).

The EMG signals were band-pass filtered (fourth-order Butterworth) at 10–500 Hz. The amplitudes of the signals were expressed as root mean square values. All analyses were performed with custom programs written with LabVIEW software (version 7.1; National Instruments, Austin, TX, USA). The EMG values for the experimental condition repetitions were normalized to the EMG values achieved during the concentric phase of the straight-barbell 1RM tests. These normalized EMG values for the 3 repetitions performed with each load (65 and 85% 1RM) were then averaged before data analysis. Intraclass reliability values exceeding 0.9 were found for EMG amplitude values.

Force and Velocity

A velocity transducer (Model V-80-L7M; UniMeasure, Inc., Corvallis, OR, USA) was attached to the end of each barbell. An AMTI force plate (Watertown, MA, USA) was used to collect force data. Both the linear velocity transducer and the AMTI force plate were connected to a desktop computer running custom LabVIEW data collection and analysis software (version 2013; National Instruments Corporation). As with the EMG data, the 3 repetitions performed with each load (65 and 85% 1RM) were averaged before data analysis. Intraclass values between 0.8 and 0.9 for force plate measures have previously been reported from our lab.

Statistical Analyses

A 2 (barbell: straight and hexagonal) × 2 (phase of movement: concentric and eccentric) × 2 (load: 65 and 85% 1RM) × 3 (muscle: vastus lateralis, biceps femoris, and erector spinae) repeated-measures analysis of variance (ANOVA) was used to analyze the normalized EMG amplitude data for each muscle. Follow-up tests included ANOVAs and paired *t*-tests with Bonferroni corrections as appropriate. Three separate 2 (barbell: straight and hexagonal) × 2 (load: 65 and 85% 1RM) repeated-measures ANOVAs were used to determine differences for peak force, power, and velocity between barbells. An alpha level of 0.05 was used to determine statistical significance. IBM SPSS Statistics 21 was used to perform all statistical analyses.

Results

There was no significant difference in deadlift 1RM values between the straight and hexagonal barbells (mean ± *SD* in kg = 181.4 ± 27.3 vs. 181.1 ± 27.6, respectively). For

Table 1. Normalized electromyography (EMG) amplitude values (mean ± *SD*) for the straight and hexagonal barbells, collapsed across 65 and 85% 1 repetition maximum loads.*

	Straight barbell		Hexagonal barbell	
	Concentric	Eccentric	Concentric	Eccentric
Vastus lateralis	0.968 ± 0.22	0.559 ± 1.26	1.199 ± 0.22†	0.879 ± 0.31†
Biceps femoris	0.835 ± 0.19‡	0.347 ± 0.11	0.723 ± 0.20	0.315 ± 0.10
Erector spinae	0.989 ± 0.26	0.753 ± 0.28‡	0.880 ± 0.27	0.614 ± 0.21

*All concentric normalized EMG amplitude values exceed corresponding eccentric values.
†Significantly greater normalized EMG amplitude value for hexagonal vs. corresponding straight barbell value ($p \leq 0.05$).
‡Significantly greater normalized EMG amplitude value for straight vs. corresponding hexagonal barbell value ($p \leq 0.05$).

TABLE 2. Peak ground reaction force, power, and velocity for straight and hexagonal barbells, collapsed across 65 and 85% 1 repetition maximum loads.*

	Straight barbell	Hexagonal barbell
PGRF (N)	2,509.90 ± 364.95	2,553.20 ± 371.52†
PP (W)	1,639.70 ± 361.94	1,871.15 ± 451.61†
PV ($m \cdot s^{-1}$)	0.725 ± 0.138	0.805 ± 0.165†

*PGRF = peak ground reaction force; PP = peak power; PV = peak velocity.
†Significantly greater value for hexagonal vs. corresponding straight barbell value ($p \leq 0.05$).

normalized EMG amplitude (Table 1), there was no significant 4-way interaction ($p > 0.05$). There was, however, a significant 3-way interaction (barbell × phase × muscle) ($p \leq 0.05$). This was followed up with 2-way ANOVAs: (phase × muscle), 1 for each barbell; (barbell × phase), 1 for each muscle; (barbell × muscle), 1 for each phase. Significant interactions were then followed up with separate paired *t*-tests as appropriate. These results revealed that normalized EMG amplitude for the vastus lateralis was significantly greater with the hexagonal barbell than with the straight barbell, regardless of phase, whereas it was greater for the biceps femoris (concentric phase only) and erector spinae (eccentric phase only) with the straight bar than with the hexagonal bar ($p \leq 0.05$). For all 3 muscles and both barbells, the concentric phase demonstrated greater EMG amplitude values than the eccentric phase ($p \leq 0.05$).

For the force plate data (peak ground reaction force, peak power, and peak velocity), there were no significant 2-way (barbell × load) interactions ($p > 0.05$) (Table 2). There were, however, significant main effects for the barbell and load ($p \leq 0.05$). Peak ground reaction force, peak power, and peak velocity were all greater for the hexagonal barbell than for the straight barbell. In addition, peak ground reaction force was greater for the 85% 1RM load, whereas peak power and peak velocity were greater for the 65% 1RM load.

DISCUSSION

The purpose of this study was to examine the effects of performing the deadlift exercise (65 and 85% 1RM) with a hexagonal barbell vs. straight barbell on 1RM values, muscle activation, peak ground reaction force, peak power, and peak velocity. There were no significant differences in 1RM values between the bars. The EMG results revealed that the normalized EMG amplitude values from the vastus lateralis were significantly greater for the hexagonal barbell vs. straight barbell, during both the concentric and eccentric phases. More specifically, the hexagonal barbell led to a more quadriceps-dominant movement. Conversely, with greater normalized EMG amplitude values being evident from the biceps femoris and erector spinae muscles during the concentric and eccentric phases, respectively, the straight barbell seemed to use more of the hamstrings and lower back. Furthermore, deadlifts with the hexagonal barbell demonstrated higher peak velocity, peak force, and peak power than deadlifts with the straight barbell.

To our knowledge, only one previous study has examined deadlifts with a hexagonal barbell in comparison with a straight barbell (16). Although no significant difference in 1RM values between the bars were found in the present study, the participants in the study of Swinton et al. lifted an average of nearly 20 kg more with the hexagonal barbell compared than with a straight barbell (265.0 ± 41.8 vs. 244.5 ± 39.5 kg). These differences in findings may be a result of differences in the training experience of participants in the 2 studies. The participants of the present study consisted of resistance-trained men that had deadlifting experience (once a week for a minimum of 1 year). However, experience deadlifting with a hexagonal barbell was neither required nor common. The participants in the study of Swinton et al. consisted of competitive men powerlifters from the Scottish Powerlifting Association. Although no direct hexagonal-barbell deadlifting experience was reported, professional strength athletes, such as powerlifters and strongmen competitors, often use several variations of the deadlift, squat, and bench press to enhance their performance (15,18). Therefore, it is likely that these athletes had more deadlifting experience with a hexagonal barbell or other deadlift variations. Perhaps with more training experience with the hexagonal barbell, participants in the present study would have been able to lift more weight with the hexagonal barbell than with the straight barbell.

The EMG results of the present study are in agreement with the kinematic findings of Swinton et al. (16). Swinton et al. (16) concluded that the hexagonal barbell significantly increased the peak moment at the knee and reduced the peak moment at the lumbar spine and hip (16). The increased moment at the knee demonstrated with the hexagonal barbell should theoretically lead to increased muscle activation of the quadriceps femoris muscle group. This is precisely what was found in the present study, where normalized EMG amplitude data from the vastus lateralis was greater for deadlifts performed with the hexagonal barbell than the deadlifts performed with the straight barbell. Furthermore, it has been demonstrated that there is an increase in the moment around the hip when deadlifting with a straight barbell vs. a hexagonal barbell (16). The results of the present study are in agreement with this finding because EMG amplitude from the biceps femoris during the concentric phase was greater for the straight barbell vs. hexagonal barbell. Finally, Swinton et al. (16) reported that the straight barbell increased the moment at the lumbar spine, which is consistent with the present study because significantly greater normalized EMG values in erector spinae were demonstrated while using the straight barbell during the eccentric phase.

As with the present study, the higher force, power, and velocity demonstrated with a hexagonal-barbell deadlift in comparison with the straight-barbell deadlift has been reported previously (16,17). The weighted vertical jump is a common movement frequently used to enhance power. The results of a study by Swinton et al. (17) suggested that the straight-barbell vertical jump method is an inferior technique to the hexagonal-barbell vertical jump method. With a 20% load, peak velocity, peak force, peak power, average power, and rate of force development were all increased with the hexagonal barbell. The design of the hexagonal barbell seems to allow the user to maintain a more advantageous position in the starting phase and throughout the movement allowing for enhanced velocity, force, and power. The hexagonal barbell may be a more effective method for not only enhancing force production for the deadlift exercise but also increasing explosive power when performing squat jumps (16,17). It should be noted that these suggestions are drawn from studies examining acute effects, whereas long-term training effects are unknown.

When analyzing the starting phase of the deadlift with a straight barbell, it has been shown that the hip is flexed the greatest followed by the knee, torso, and ankle (5,12,16). In contrast, the starting phase of a deadlift with a hexagonal barbell demonstrates an increase of knee flexion, with no difference among the hip, torso, or ankle joints (16). This suggests that the hexagonal barbell is a more quadriceps-dominant movement and distributes the external load more evenly among the hip, ankle, and torso. When comparing barbell paths between hexagonal and straight barbells, the findings of Swinton et al. further support this claim. Swinton et al. (16) concluded that the design of hexagonal barbell allowed the load to be positioned closer to the body using the horizontal distance from the ankle as the point of measurement. As the lift with the hexagonal barbell progressed, the average horizontal displacement away from the lifter was reduced by 75% and increased displacement toward the lifter by 22% (16). The ability to maintain the load closer to the lifter's center of gravity may explain the greater force, power, and velocity found in the present study.

Practical Applications

The ability to manipulate joint range of motion and muscle activation through barbell selection is valuable information for practitioners. The conventional, straight-bar deadlift is a common exercise that is frequently performed within athletic and recreational weight rooms. However, when performed with heavy loads, it can be the most taxing exercise on the lumbar region (3). For individuals with lower-back injuries or pain, the results of this study suggest that the hexagonal barbell may be the better choice for barbell selection because of its ability to evenly distribute the load among all joints and reduce the moment at the lumbar spine. Conversely, if the goal of the training session is to emphasize strengthening of the lumbar region and hamstrings, the straight barbell seems to be the appropriate choice. Finally, the hexagonal barbell may be a more effective method for maximizing force, power, and velocity during the deadlift.

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APPENDIX K: LETTER FROM JOURNAL EDITOR AS PROOF OF ARTICLE SUBMISSION TO THE JOURNAL OF STRENGTH AND CONDITIONING RESEARCH

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Reply To: Journal of Strength and Conditioning Research
To: Ben Coetzee
Subject: A manuscript number has been assigned to your JSCR submission

Jun 11, 2016

Dear Prof Coetzee,

Your submission entitled "HEART RATE VARIABILITY AND HEART RATE RECOVERY AS PREDICTORS OF MALE, ELITE, AFRICAN, SINGLES BADMINTON PLAYERS' PERFORMANCE LEVELS" has been assigned the following manuscript number: JSCR-08-7834.

Our editors will review your manuscript within the next four to six weeks and will send their reviews back to our office. Reviewers do volunteer their time to complete the reviews of your article, and are very dedicated to getting reviews back as soon as possible. You will receive your reviews as quickly as possible. For updates, please check your status on this website, http://jscr.edmgr.com/.

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The purpose of this memo is to let you know that we have your paper and it is in the editorial process.

Please use the title, revision state, first author, corresponding author, and your R number when communicating with our office. It is important that R-number is always used in reference to this paper.

Please remember to properly format your paper so as to reduce time and mistakes in the redactory if accepted. Attention to detail is important. We certainly appreciate your help in this matter. We thank you for your support of the journal.

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Sincerely,

Joan M. Kraemer, BA
Managing Editor
Journal of Strength and Conditioning Research

The Journal of Strength and Conditioning Research has been a PUBMED, Medline journal since 2001. A full archive of all papers is on the NSCA web site at www.nsca-lift.org .

APPENDIX L: INSTRUCTIONS FOR AUTHORS OF THE JOURNAL OF SPORT SCIENCE AND MEDICINE

PREPARATION OF MANUSCRIPT

RESEARCH ARTICLE

Include the following sections in research articles without page space:

TITLE: Capital letters.

AUTHORS: Surname followed by initials and institution(s) where the study was conducted.

RUNNING HEAD: Maximum 5 words.

ABSTRACT: Include an abstract of not more than 300 words that includes objectives, methods, results and conclusions.

KEY WORDS: To assist in indexing the journal, list up to 6 key words (not from title), which your article could be indexed. If possible, use terms from the Index Medicus medical subjects headings (MeSH) (http://www.nlm.nih.gov/mesh).

INTRODUCTION

METHODS

RESULTS

DISCUSSION

CONCLUSION

ACKNOWLEDGMENTS: Provide information sufficient to identify sources of support, technical assistance, and intellectual contributions not associated with authorship.

REFERENCES: JSSM use Harvard referencing format. Each citation in the text must be noted by surname and year in parentheses and must appear in the reference section as an alphabetic order. Example for citation in the text; a) for single author (Gür, 1999), b) for two authors (Gür and Akova, 2001), c) more than two authors (Gür et al., 2000).

Journal article:

Akova, B., Sürmen-Gür, E., Gür, H., Dirican, M., Sarandöl, E. and Kücükoglu, S. (2001) Exercise-induced oxidative stress and muscular performance in healthy women: role of vitamin E supplementation and endogenous estradiol. *European Journal of Applied Physiology* **84,** 141-147.

Journal article, article not in English:

Seker-Aygül, Z., Akova, B. and Gür, H. (2001) The relationship of stress and stress management factors with injury in soccer players. *Turkish Journal of Sports Medicine* **36,** 71-80. (In Turkish: English abstract).

Journal article in press:

Gür, H., Cakin, N., Akova, B., Okay, E. and Kücükoglu, S (2002) Concentric versus combined concentric- eccentric isokinetic training: Effects on functional capacity and symptoms in patients with osteoarthrosis of the knee. *Archives of Physical Medicine and Rehabilitation,* in press.

Journal article in electronic format:

Weigand, D.A., Carr, S., Petherick, C. and Taylor, A. (2001) Motivational climate in Sport and Physical Education: The role of significant others. *European Journal of Sports Science (serial online)* **1(4),** (13 screens/inclusive page), October. Available from URL: http://www.humankinetics.com/ejss [Accessed 8 April 2015].

Abstract:

Gur, H., Şekir, U., Akova, B. and Kucukoglu, S. (2003) A multi-station proprioceptive exercise program in patients with bilateral knee osteoarthrosis: functional capacity, pain and sensoriomotor function. *8th Anual Congress European College of Sports Science, July 9-12, Salzburg-Austria.* Book of Abstract. 404.

Book:

Guyton, A.C. and Hall, J.E. (1996) *Textbook of medical physiology.* 9 th edition. London: W. B. Saunders Company.

Chapter in edited book:

Wilson, C.H. (1984) Exercise for arthritis. In: *Therapeutic exercise.* Ed: Basmajian, J.V. 4 th edition. Baltimor: Williams and Wilkins. 529-545. *Thesis:*

Özyener, F. (2000) *Effects of work intensity on dynamics of pulmonary gas exchange during exercise in humans.* Doctoral thesis, University of London, London. 79.

Thesis not in English:

Özer, Ö. (2001) *The effect of muscle exercise to oxygen kinetics in chronic smoker*s. Doctoral thesis, University of Uludag, Bursa. 1-54. (In Turkish: English abstract).

Units of Measurement:

Measurements of length, height, weight, and volume should be reported in metric units (meter, kilogram, or liter) or their decimal multiples. Temperatures should be given in degrees Celsius. Blood pressures should be given in millimeters of mercury. All hematological and clinical chemistry measurements should be reported in the metric system in terms of the International System of Units (SI). Alternative or non-SI units should be added in parenthesis.

Abbreviations and Symbols:

Use only standard abbreviations. Avoid abbreviations in the title and abstract. The full term for which an abbreviation stands should precede its first use in the text unless it is a standard unit of measurement.

LEGENDS

AUTHOR BIOGRAPHY: Please include a brief biography, approximately 50 words per author, for each author including (1) academic title/degrees, (2) institution affiliation, (3) research focus, (4) post and e-mail addresses and (5) photograph produced in JPEG format.

TABLES, FIGURES, VIDEO, ANIMATION ETC.: The location within the article where e.g. figures and tables appear should be indicated in the text. These materials (e.g. table, figure) should be submitted separately from the text document. Each item should be produced in Microsoft Office (Word, Excel, or PowerPoint), GIF or TIFF format. Electronically produced drawings, graphs, photographs, photomicrographs, animation and video are all acceptable. Limit still art files to 700 kilobytes of memory and use 96 dpi resolutions or consult with the editor-in-chief. Please have original photos or negatives available to submit on request of the editor-in-chief. Clearly identify digitally enhanced images as such and describe the method of enhancement. Include internal scale markers where appropriate. The author is responsible for ensuring that persons pictured in photographs have provided informed consent for the use of their picture. Please include the photographer's name with each photograph so that he or she can be properly acknowledged. Submit each item separately and number sequentially as (main author) Figure 1.jpg, (main author) Figure2.jpg, and so on, for example, GurFigure1.jpg, GurTable1.doc, and GurVideo1.avi. Video clips should be less than 8 seconds in length;

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Tables

Tables capture information concisely, and display it efficiently; they also provide information at any desired level of detail and precision. Including data in tables rather than text frequently makes it possible to reduce the length of the text. Type each table with double spacing on a separate sheet of paper. Number tables consecutively in the order of their first citation in the text and supply a brief title for each. Do not use internal horizontal or vertical lines. Give each column a short or abbreviated heading. Authors should place explanatory matter in footnotes, not in the heading. Explain in footnotes all nonstandard abbreviations. For footnotes use the following symbols, in sequence: *,†,‡,§,‖,¶,**,††,‡‡

Identify statistical measures of variations, such as standard deviation and standard error of the mean and give the variations in parentheses.

Be sure that each table is cited in the text.

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APPENDIX M: EXAMPLE OF ARTICLE PUBLISHED IN THE JOURNAL OF SPORT SCIENCE AND MEDICINE

©Journal of Sports Science and Medicine (2015) **14,** 602-605
http://www.jssm.org

Research article

Ultra-Short-Term Heart Rate Variability is Sensitive to Training Effects in Team Sports Players

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Abstract
The aim of this study was to test the possibility of the ultra-short-term lnRMSSD (measured in 1-min post-1-min stabilization period) to detect training induced adaptations in futsal players. Twenty-four elite futsal players underwent HRV assessments pre- and post-three or four weeks preseason training. From the 10-min HRV recording period, lnRMSSD was analyzed in the following time segments: 1) from 0-5 min (i.e., stabilization period); 2) from 0-1 min; 1-2 min; 2-3 min; 3-4 min; 4-5 min and; 3) from 5-10 min (i.e., criterion period). The lnRMSSD was almost certainly higher (100/00/00) using the magnitude-based inference in all periods at the post- moment. The correlation between changes in ultra-short-term lnRMSSD (i.e., 0-1 min; 1-2 min; 2-3 min; 3-4 min; 4-5 min) and $lnRMSSD_{Criterion}$ ranged between 0.45 - 0.75, with the highest value (p = 0.75; 90% CI: 0.55 – 0.85) found between ultra-short-term lnRMDSSD at 1-2 min and $lnRMSSD_{Criterion}$. In conclusion, lnRMSSD determined in a short period of 1-min is sensitive to training induced changes in futsal players (based on the very large correlation to the criterion measure), and can be used to track cardiac autonomic adaptations.

Key words: Court sports, athletic monitoring, cardiac autonomic system, futsal.

Introduction

Heart rate variability (HRV) is becoming one of the most used training and recovery monitoring tools in sports sciences (de Oliveira Ottone et al., 2014; Plews et al., 2013). The Task Force recommends a period of 10-min for the assessment of HRV (i.e., 5-min stabilization period and a 5-min post-stabilization measurement period). However, more recently, a shortened post-stabilization measurement period (i.e., 1-min duration) has been proposed for analyzing athletes (Esco and Flatt, 2014; Flatt and Esco, 2015a). In fact, when the natural log of the root-mean-square difference of successive normal RR intervals (lnRMSSD - a simple and practical vagally-mediated index) is measured during the standard 5-min post-stabilization period ($lnRMSSD_{Criterion}$) or the shortened 1-min post-stabilization measurement period, similar values have been observed. This was demonstrated using both electrocardiogram (ECG) and portable sports cardiofrequencimeters (Flatt and Esco, 2015a). Furthermore, the Bland-Altman analysis showed tight limits of agreement between 1-min lnRMSSD and $lnRMSSD_{Criterion}$ measures, while intraclass correlation coefficient (ICC) analysis have ranged between 0.84 and 0.97 (Flatt and Esco, 2015a). Therefore, the ultra-short-term HRV measurement method, demanding only 1-min of data acquisition after the stabilization period, may arguably improve the practicality of the cardiac autonomic activity monitoring on a daily basis.

The HRV indices (e.g., lnRMSSD) derived from traditional time-consuming methods have shown to be sensitive to training effects in team sports players (de Freitas et al., 2014; Oliveira et al., 2013; Soares-Caldeira et al., 2014). However, these studies used single measures per period of assessment, while recently some authors have proposed averaging multiple measures per week to increase the confidence of the data and sensitivity to detect changes related to variations in training loads (Flatt and Esco, 2015b; Plews et al., 2012; 2014). In this sense, shorter data acquisition procedures are appealing from a practical standpoint due to the difficulties in obtaining athletes' compliance to the standard 10-min procedure, and the necessity of simple monitoring tools to quantify adaptation/maladaptation to sports training.

The aim of this study was to test the possibility of ultra-short-term lnRMSSD to detect training induced adaptations. This was accomplished by comparing the changes induced by training in futsal players while using the standard and shortened HRV, before and after the preseason.

Methods

Participants

Twenty-four elite futsal players (22.9 ± 4.2 years; 1.74 ± 0.06 m; 74.4 ± 7.6 kg; 1262.0 ± 330.6 m in the Yo-Yo Intermittent Recovery Test, level 1) of two different teams, playing one of the most important state championships in Brazil (Paraná State Championship) took part in this study. The subjects of this study were directly involved in two different previous works published by our research group (Oliveira et al., 2013, Soares-Caldeira et al., 2014). The purposes of those studies were to verify the HRV and performance changes after a standard futsal preseason period. All studies were approved by the same Ethics Committee.

Procedures

All HRV assessments were conducted pre- and post-three

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or four weeks of a standard futsal preseason, before starting the most important competition of the year. The pre and post HRV measures were performed at the same hour on the bench, in the seated position, in a quiet futsal court. The athletes arrived at the futsal gym for the first training session of the week, after ≈ 48 h of rest from training sessions, in a fasted state for 2 h and free of caffeine or alcohol consumption for at least 24 h.

Prior to data collection, athletes were provided with cardiofrequencimeters and chest strap transmitters, and received verbal instructions about how to proceed. Subsequently, athletes sat down and were given <1-min to check for the functioning of the watch receiver for RR intervals acquisition. Participants received instructions to remain quiet, with eyes opened, and to breathe spontaneously (Bloomfield et al., 2001) over the acquisition period.

HRV analysis

The RR interval recordings were obtained using a portable heart rate monitor (Polar® RS800cx, Kempele, Finland) at a sampling of 1,000 Hz, continuously for 10-min[1] (Task Force, 1996, Gamelin et al., 2006, Wallen et al., 2012) . Data were visually inspected to identify artifacts and ectopic beats (<3%), which were manually removed and replaced by interpolation of adjacent RR intervals. The RR recordings were downloaded via accompanying Polar software (Polar® ProTrainer, Kempele, Finland) and exported for later analysis of time domain measures of HRV by Kubios v2 Heart Rate Variability software (Biosignal Analysis and Medical Imaging Group at the Department of Applied Physics, University of Kuopio, Kuopio, Finland).

The dependent variable analyzed was the root-mean-square difference of successive normal RR intervals (RMSSD), which was transformed in lnRMSSD to avoid outliers and simplify its analysis. This variable was expressed in milliseconds. From the 10-min HRV recording period, lnRMSSD was analyzed in the following time segments: 1) from 0-5 min (i.e., stabilization period); 2) from 0-1 min; 1-2 min; 2-3 min; 3-4 min; 4-5 min and; 3) from 5-10 min (i.e., criterion period); The 1-min measures will be collectively labeled as ultra-short-term measures.

Statistical analysis

Data is presented in means and standard deviations (SD). The differences based on magnitudes (Batterham and Hopkins, 2006) were calculated to check the differences in the pre and post moments. The quantitative chances for the post- measures having higher, similar or lower values than pre- measures, using a smallest worthwhile change (SWC) of 3% (Buchheit, 2014) and a confidence internal (CI) of 90%, were assessed qualitatively as follows: <1%, almost certainly not; 1% to 5%, very unlikely; 5% to 25%, unlikely; 25% to 75%, possible; 75% to 95%, likely; 95% to 99%, very likely; >99%, almost certain. If the chances of having better and poorer results were both >5%, the true difference was assessed as unclear. The spreadsheet available at: http://www.sportsci.org/index-.html was used. Finally, the correlations between the ultra-short-term period of analysis (1 min) and criterion (5 min) was analysed using the Spearman's ρ test. The threshold used to qualitatively assess the correlations was based on Hopkins (2002), using the following criteria: <0.1, trivial; 0.1 - 0.3, small; 0.3 - 0.5, moderate; 0.5 - 0.7, large; 0.7 - 0.9, very large; >0.9 nearly perfect.

Results

Table 1 presents the ultra-short-term lnRMSSD and $lnRMSSD_{Criterion}$ values, both before and after preseason training. The lnRMSSD was almost certainly higher (100/00/00) in all periods at the post- moment.

The Spearman's ρ correlation between changes in ultra-short-term lnRMSSD (i.e., 0-1 min; 1-2 min; 2-3 min; 3-4 min; 4-5 min) and $lnRMSSD_{Criterion}$ ranged between 0.45 - 0.75, with the highest value (p = 0.75; 90% CI: 0.55 – 0.85) found between ultra-short-term lnRMDSSD at 1-2 min and $lnRMSSD_{Criterion}$.

Discussion

This study revealed that the ultra-short-term lnRMSSD was as sensitive as $lnRMSSD_{Criterion}$ to training induced adaptations in elite futsal players. The changes were rated as almost certain for all periods, demonstrating the usefulness of HRV in detecting autonomic changes taking place in the preseason.

The vagal-related indices of HRV as measured using the standard procedures of the Task Force (1996), including the stabilization period, have been shown to be responsive to training effects in both non-athletes and athletes (Da Silva et al., 2014; de Freitas et al., 2014; Oliveira et al., 2013; Plews et al., 2013; Sandercock et al., 2005; Soares-Caldeira et al., 2014). In general, a proper adaptation to the training loads leads to increased cardiac-parasympathetic activity (Da Silva et al., 2014; de Freitas et al., 2014; Kiviniemi et al., 2007; Oliveira et al., 2013; Soares-Caldeira et al., 2014), while prolonged overloading decreases this activity and inversely leads to high sympathetic modulation (Morales et al., 2014; Schmitt et al., 2013). For this reason, several research groups have

Table 1. Means (±SD†) for the ultra-short-term lnRMSSD (i.e., 0-1 min; 1-2 min; 2-3 min; 3-4 min; 4-5 min) and $lnRMSSD_{Criterion}$ values obtained before and after 3-4 weeks of preseason training in futsal players (n = 24).

	Before	After	Δ% (90% CI)	Lower/Trivial/Higher (*rating*)
0-1 min	3.3 (.6)	3.7 (.6)	12.4 (9.0 - 18.1)	00/00/100 (*almost certainly*)
1-2 min	3.1 (.8)	3.7 (.5)	17.4 (9.5 - 25.4)	00/00/100 (*almost certainly*)
2-3 min	3.2 (.7)	3.6 (.5)	11.9 (6.2 - 15.5)	00/00/100 (*almost certainly*)
3-4 min	3.2 (.7)	3.7 (.5)	15.2 (9.4 - 18.9)	00/00/100 (*almost certainly*)
4-5 min	3.2 (.6)	3.6 (.5)	13.7 (9.5 - 18.9)	00/00/100 (*almost certainly*)
Criterion (5-10 min)	3.2 (.6)	3.7 (.4)	16.1 (12.5 - 18.8)	00/00/100 (*almost certainly*)

†: values are expressed in milliseconds; Δ%: percentage of change.

been proposing constant monitoring of HRV on daily bases (Kiviniemi et al., 2007; Plews et al., 2012; 2013). However, this is impractical because coaches find it difficult to perform the standard procedure due to its long duration, making it difficult to keep the athletes quiet and thus potentially decreasing their adherence in successive daily measurements.

The ultra-short-term lnRMSSD measured after less than 60-s of stabilization was previously shown to have a high agreement with $lnRMSSD_{Criterion}$ (Esco and Flatt, 2014). This made the RR interval data acquisition more convenient and practical for daily use by coaches and athletes, although studies testing its sensitivity to training effects were still lacking. In this study, we further demonstrate the applicability of the shortened procedure to quantify lnRMSSD in team-sport players by showing that each of the 1-min windows within the stabilization period provided indices that were equally responsive to the effects of training compared to the criterion measure. This finding may help coaches and sport scientists in implementing daily (e.g., every morning after waking) assessments of HRV to guide subsequent training methods and loads and to quickly identify changes in cardiac autonomic regulation. In fact, daily HRV is labile and responsive to recent stressors - especially when averaged weekly - to reflect the effects of a given training microcycle (Flatt and Esco, 2015b, Plews et al., 2012, Plews et al., 2014). It remains to be determined if ultra-short-term HRV is sensitive to reductions of vagal influence on the heart due to overloading.

To conclude, the results reported herein reveal that lnRMSSD determined in short periods of 1-min, following only 1-min of stabilization, is sensitive to training induced changes in futsal players. This advances the practical use of this measure when monitoring athletes in field conditions.

Practical applications

Coaches and sport scientists are encouraged to use the simplified procedure of acquiring RR intervals in only 1-min, preceded by 1-min for stabilization, in the seated position at rest, to monitor vagally-mediated lnRMSSD on a daily basis due to its responsiveness to training effects. The lnRMSSD collected in a 1-min window is capable of showing meaningful alterations in the physiological state in the same direction and magnitude as the lengthier traditional procedure. Finally, the fact that portable cardiofrequencimeters can be used for this purpose in field conditions and that this procedure can be performed quickly before a training session make the ultra-short-term HRV appealing in sports settings.

Conclusion

To conclude, the results reported herein reveal that lnRMSSD determined in short periods of 1-min, following only 1-min of stabilization, is sensitive to training induced changes in futsal players. This advances the practical use of this measure when monitoring athletes in field conditions.

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Key points

- The ultra-short-term (1 min) natural log of the root-mean-square difference of successive normal RR intervals (lnRMSSD) is sensitive to training effects in futsal players
- The ultra-short-term lnRMSSD may simplify the assessment of the cardiac autonomic changes in the field compared to the traditional and lengthier (10 min duration) analysis
- Coaches are encouraged to implement the ultra-short-term heart rate variability in their routines to monitor team sports athletes

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APPENDIX N: LETTER FROM JOURNAL EDITOR AS PROOF OF ARTICLE **ACCEPTANCE** TO THE JOURNAL OF SPORT SCIENCE AND MEDICINE

JOURNAL OF SPORTS SCIENCE & MEDICINE

ELECTRONIC JOURNAL (ISSN 1303-2968)

http://www.jssm.org

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October 05, 2016

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Manuscript: #4473-2016/JSSM
TITLE: "RELATIONSHIP BETWEEN AUTONOMIC MARKERS OF HEART RATE AND SUBJECTIVE INDICATORS OF RECOVERY STATUS IN MALE, ELITE BADMINTON PLAYERS"
Christo A. Bisschoff[1], Ben Coetzee[1] and Michael R. Esco[2]
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Dear Christo A. Bisschoff

I am glad to inform you that your manuscript is accepted for publication in the Journal of Sports Science and Medicine and it will be published in December 2016 Issue of JSSM. The manuscript will now be edited for style and format.

Please do not hesitate to contact me if you have any questions.

Thank you for giving the JSSM the opportunity to publish your work

Yours Sincerely

Hakan Gur, MD, PhD
Editor-in-Chief
Yours Sincerely

APPENDIX O: INSTRUCTIONS FOR AUTHORS OF THE INTERNATIONAL JOURNAL OF PERFORMANCE ANALYSIS IN SPORT

Format

Papers consist of a title page, blind title page and the main text of the paper. Figures and tables should be included in the text rather than following the text. Typical sections of the text are Introduction, Methods, Results, Discussion, Conclusions, any acknowledgements, References and author correspondence details. However, it is acceptable to have a conclusions paragraph at the end of the discussion. Further variation is possible for review articles or where papers report on a series of studies which are best reported in a study by study order.

Page Layout

Pages must be A4 using margins of 3cm at the top, bottom, left and right. Portrait orientation is used except where landscaped orientation clearly assists the presentation of tables and / or figures. Paragraph text should be single spaced.

Title Page

The title page should contain the title (Times Roman, size 18, bold), author names using first names, other initials and surnames and affiliations of authors, the abstract and key words. All text other than the abstract should use Times Roman size 12 font. The abstract should be bold and in italics not exceeding 200 words. It should be inserted in the article after the authors' affiliations and indented by 1 cm at the left and right. The abstract should not contain figures or tables.

Blind Title Page

This should include all of the information on the title page except the author names and affiliations. Where acknowledgements or information in the methods about ethical clearance may compromise the blind reviewing process, the General Editor will temporarily remove this information while the paper is being reviewed.

Headings

Headings and subheadings should all be in Times Roman font, bold and size 12. Headings should be numbered 1., 2., 3., etc with any subheadings being 1.1., 1.2., for example.

Tables

Tables should normally only include horizontal lines to mark the top and bottom and separate column headings from the main body of tables. Tables must be created in word to facilitate any necessary editing by the journal. There are occasions, where correlation tables, for example, require vertical lines and this is acceptable. Table captions should appear above the table.

Figures

Illustrations, photographs, screen dumps, charts, plates and any other artwork should be included in the electronic submission. Authors must have permission to use any photographs within the paper and copyrighted material from published sources must not be included as Figures in the paper. Figure headings should be placed below figures.

Symbols, units and abbreviations

Symbols, units and abbreviations in papers must conform to the Système International d'Unités (SI Units). Authors are advised to consult the National Physical Laboratory publication (R.J. Bell (ed.), 1993, SI: The International System of Units. London: HMSO). For all abbreviations other than units, write the word or words to be abbreviated in full on the first mention followed by the abbreviation in parentheses. If at all possible, group these definitions together near the beginning of the article. As indicated earlier, avoid use of nonstandard abbreviations, especially fabricated ones, within the text; words are much easier to read and follow than abbreviations.

References

References in the text are cited as follows: Smith (1985) ... or (Brown and Green, 1996) ... or, if there are more than two authors, as Jones *et al*. (1993) ... or (Jones *et al*., 1993). Citations of different publications by the same author(s) in the same year are differentiated as Green (1993a) (Brown *et al*., 1995b); the a, b, c, etc. , are normally in order of citation in the text. Multiple citations are listed in ascending chronological order. Multiple publications by the same authors are treated in lists: Smith (1991, 1995), Brown and Green (1992, 1993), Jones *et al*. (1993, 1996a,b); or (Smith, 1991, 1995; Brown and Green, 1992, 1993; Jones *et al*., 1993, 1996a,b). A list of all cited references should be collected at the end of the paper in alphabetical order by, in the first instant, the first author's surname. Where the name of the first author appears more than once, the order is determined by: first, the number of co-authors (zero, one, or more than one); secondly, for one co-author, the first co-author's surname then the year; for two or more co-authors, year then order as dictated by the use of 1990a,b,c (for example) in the citations. The following is an example of how references would be ordered in the reference list: Brown (1980), Brown (1990), Brown and Jones (1977), Brown and Smith (1973), Brown and Smith (1975), Brown *et al*. (1990a), Brown *et al*. (1990b), Brown *et al*. (1990c). Note that the last three examples would all have been cited as Brown et al. in the text, with the a, b and c relating to the order of citation. The names and initials of all authors should be given in the list of references. The style should follow the examples below:

Journal Papers

Newton, P.K. and Keller, J.B. (2005), The probability of winning at tennis, Theory and Data, **Studies in Applied Mathematics**, 114, 214-269.

Books

Ashe, A. (1981), **Arthur Ashe's Tennis Clinic**. London: Heinemann.

Chapters of Edited Books (including conference proceedings published as books)

Hughes, M. and Clarke, S. (1995), Surface effect on elite tennis strategy. In Reilly, T., Hughes, M. and Lees, A. (Eds.) **Science and Racket Sports** (pp. 272-277). London: E & FN Spon.

Conference abstracts published in journals

O'Donoghue, P.G. (2003), The effect of scoreline on elite tennis strategy: a cluster analysis. **Journal of Sports Sciences**, 21, 284-285.

APPENDIX P: EXAMPLE OF ARTICLE PUBLISHED IN THE INTERNATIONAL JOURNAL OF PERFORMANCE ANALYSIS IN SPORT

International Journal of Performance Analysis in Sport
2015, 15, 816-829.

Analysis of game variables to predict scoring and performance levels in elite men's volleyball

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Abstract

Sport games are characterized by their play structure. To date, the play structure of volleyball remains poorly understood. The aim of this study was to identify play structure variables that are appropriate for differentiating between top-level teams and second-level teams in elite international men's volleyball.
236 sets played by 14 teams during top international events were video recorded and analysed for variables related to action sequences (attack, counter-attack), attack tempo (fast, medium, slow), attack positions (1-6) and attack combinations (e.g., high passes on position 4 or 5). A discriminant analysis was conducted for the following dependent variables: (1) results (win vs. lose) and (2) team level (top-level teams vs. second-level teams).
The best predictors for results and team levels are variables (effectivity of counter-attack, effectivity of medium and slow attack-tempo) related to complex 2 (action sequences of defending, setting and counter-attacking). In contrast, the impact of complex 1 variables (action sequences of reception, setting and attacking) are marginal.
It is concluded that second-level teams must adjust their training schemes, i.e., spending more time for counter-attacks with medium and slow attack tempos to increase team performance in elite men's volleyball.

Keywords: play structure in volleyball; tactical analysis; classification of performance level

1. Introduction

Performance analysis seeks to understand the game structure by identifying the performance behaviours that are important in volleyball (Lames *et al.*, 2007). Based on

these analyses, it may be possible to predict future game conception more precisely and to deduce specific training schemes for improving team performance.
Indoor volleyball consists of different action sequences, e.g., serve reception, playing the ball to the setter, and the setter playing the ball to the attacker. In indoor volleyball, a rally is categorized based on standardized action sequences. Complex 1 (C1) consists of the action sequences reception, set and attack, whereas complex 2 (C2) consists of the action sequences service, block, dig and counter-attack.

Many studies reported in the literature have analysed the effect of single point elements (e.g., attack points after reception, block points, counter-attack points, service points and points due to opponent's error) on match results (Durkovic *et al.*, 2008; Marcelino *et al.,* 2008; Marcelino *et al.*, 2011; Patsiaouras *et al.*, 2009; Patsiaouras *et al.*, 2011; Rodriguez-Ruiz *et al.*, 2011; Silva *et al.*, 2013). It has been observed that service points or, rather, reception errors and block points are the most significant single point elements for winning (Patsiaouras *et al.*, 2011). The examination of the absolute frequencies of single point elements may lead to erroneous conclusions, especially if final set scores are balanced or differ largely (Rodriguez-Ruiz *et al.*, 2011).

Recent studies (Marcelino *et al.*, 2011) have calculated the effectivity of point elements. The effectivity of an event (e.g., point element) is defined as the number of successful events divided by the total number of events. However, the effectivity of point elements alone insufficiently expresses the process of the winning point. Thus, point elements have been analysed within the context of situated conditions, such as rotation of the setter (Silva *et al.*, 2013) or position of the attacker (Silva *et al.*, 2014).

One approach used to examine the complexity of the process of winning points is to describe the effectivity of action sequences between the setter and attacker (Zimmermann, 2008). Attacks are initiated by the setter and, considering various tactical possibilities, distributed to the attackers. Thus, settings are classified under *temporal* and *spatial aspects*. The classification *temporal aspects* is defined by attack tempo (Selinger *et al.*, 1986). Attack tempo is classified into 3 categories: 1-tempo (quick hits close to the setter (up to 3 m, fast tempo)), 2-tempo (attacks after medium pass in frontline (position 4/2) or backline (position 1/6/5)(medium tempo)) and 3-tempo (attacks after high pass in front line to position 4/2, high pass in backline to position 1/6/5 (slow tempo)) (Zimmermann, 2009). It has been observed that the attacks of 1-tempo are more effective than those of 2-tempo and 3-tempo (Castro *et al.*, 2011; Marcelino *et al.,* 2008). *Spatial ball distribution* by the setter to the attacker's position is defined as an attack combination (Neske, 2004). Attack combinations can be classified based on the attacker's position (front line position: P2, P3 or P4, back line position: P1, P5, P6). A pilot study indicated that teams of different performance levels may be differentiated with respect to the effectivity of attacks adopted in special field positions (Zimmermann *et al.*, 2012). To date, it has not been examined whether attack tempo and attack combinations are appropriate indicators to distinguish between team performance levels in elite indoor volleyball.

Recent studies have examined the effects of C1 and C2 on the dependent variable 'match result' or 'set result'. It has been observed that the counter-attack in C2 is a good predictor for match results, whereas block and dig are less appropriate indicators

(Monteiro *et al.,* 2009; Pena *et al.*, 2013; Zetou *et al.*, 2006). However, Santos (1992) observed, in women's elite indoor volleyball, that blocking had a high impact on match results. Pena et al. (2013) examined all winning points in C2 and showed that the feasibility of winning a match increased by a factor of 1.5 with every additional point in C2. Monteiro et al., (2009) demonstrated that the attack efficacy is associated with the set outcome and further depends on the dig efficacy since the frequency of attack points was higher when preceded by a perfect dig. Until now, it has not been investigated whether win points in C2 are appropriate predictors for distinguishing between volleyball teams of different performance levels. Based on the literature, it can be assumed that the effectivity of C2 might be a good predictor.

The aim of this study was to analyse the effectivity of game complexes (C1, C2) and action sequences with regard to their effect on set results. In a second step, the ability of these variables to distinguish between top-level teams (ranking 1-4 in international tournaments such as the Olympic Games, World League and European Championship) and second-level teams (ranking 5-8 in international tournaments) was analysed. It was hypothesized that C2 variables are proper predictors. The novelty of the study is that we examined predictors for the dependent variable 'performance level' (top-level teams vs. second-level teams). Furthermore, we used more as well as different independent variables as potential predictors than reported in the literature.

2. Methods

2.1. Data acquisition and dataset

The dataset consisted of matches from the 2012 Olympic Games (n=6), 2013 European Championship (n=7), 2012 World League (n=9) and 2013 World League (n=10). Altogether, 32 matches were selected. Matches between top-level teams (ranking 1-4) and second-level teams (ranking 5-8) based on particular tournament rankings and not world rankings (Table 1) were included in the dataset. All tie-break sets (n=12) were excluded from the dataset. Altogether, 236 sets played by 14 volleyball teams were analysed (Table 1).

Table 1. Team ranking in international competitions, namely World League (WL), Olympic Games (OS) and European Championship (EC).

Ranking	WL 12	OS 12	WL 13	EC 13
1	POL	RUS	RUS	RUS
2	USA	BRA	BRA	ITA
3	CUB	ITA	ITA	SRB
4	BUL	BUL	BUL	BUL
5	GER	ARG	CAN	FRA
6	BRA	GER	ARG	GER
7	FRA	POL	GER	BEL
8	RUS	USA	SRB	FIN

ARG – Argentina; BEL – Belgium; BRA – Brazil; BUL – Bulgaria; CAN – Canada; CUB – Cuba; FIN – Finland; FRA – France; GER – Germany; ITA – Italy; POL – Poland; RUS – Russia; SRB – Serbia; USA – United States of America

The data were recorded and processed by scouts of the German Volleyball Association (DVV). The data were then adjusted to standardized assessment criteria and analysed by 2 experts from the Department of Volleyball (Institute of Applied Exercise Science (IAT), Leipzig, Germany) using DataVolley (Version 3.0) and Microsoft Excel. The inter-observer reliability was tested in previous studies (Zimmermann *et al.*, 2009) using kappa-type statistics (Landis *et al.*, 1977). Substantial and perfect agreements ($\kappa = 0.74 - 1.00$) were found (Zimmermann *et al.*, 2009).

2.2. Data analysis

Data were analysed for each team separately, i.e., the total number of sets examined was 236 (118 sets x 2 teams). The dependent variables were results (sets won vs. sets lost) and performance level (ranking 1-4 vs. ranking 5-8).

Table 2. Names and descriptions of the variables (effectivity means the number of achieved successful events divided by the total number of events).

Category	Variable	Definition
game complex	$C1_{\%set}$	- Complex 1 – points earned after opponent's service until the end of rally; %-percentage of total set points
	$C2_{\%set}$	- Complex 2 – points earned after team service until the end of rally; %-percentage of total set points
action sequences	$C1\text{-attack}_{Eff}$	- Effectivity of attacks after opponent's service and team's reception
	CA_{Eff}	- Effectivity of attacks after dig or easy ball (except C1 attack)
point elements	$service_{\%set}$	- Points earned due to service divided by total set points
	$block_{\%Set}$	- Points earned due to block divided by total set points
	$attack_{\%Set}$	- Points earned due to attack divided by total set points
	$EO_{\%Set}$	- Points earned due to opponent's error divided by total set points
attack tempo	1-tempo_{Eff}	- Effectivity of quick hits close to the setter (up to 3 m, fast tempo)
	2-tempo_{Eff}	- Effectivity of attacks: medium-high pass in frontline (position 4/2), backline (position 1/6/5) (medium tempo)
	3-tempo_{Eff}	- Effectivity of attacks: high pass in front line to position 4/2, high pass in backline to position 1/6/5 (slow tempo)
attack position	$P4_{Eff}$	- Effectivity of attacks on position 4
	$P2_{Eff}$	- Effectivity of attacks on position 2
attack combination	$V5_{Eff}$	- Effectivity of attacks after high pass on position 4
	$V6_{Eff}$	- Effectivity of attacks after high pass on position 2
	$X5_{Eff}$	- Effectivity of attacks after combination pass on position 4
	$X6_{Eff}$	- Effectivity of attacks after combination pass on position 2
reception quality	# R	- Excellent reception – all settings are possible to play
	+ R	- Good reception – problems for setting 1-tempo
	! R	- Acceptable reception – settings to only one position are possible
	- R	- Bad reception – only a high pass can be played

The independent variables were summarised and are defined in Table 2. It should be noted that, for action sequences (C1-attacks, counter-attacks), attack tempo (1-tempo, 2-tempo, 3-tempo), attack positions (position 4, position 2) and attack combinations (e.g., high pass on position 4), the effectivity values were calculated as the sum of successful activities divided by the total sum of the same activity.

The points earned in the game complexes (C1, C2) and the points earned by technique (service, block, attack, error by opponent) were normalized to the total sum of set points (total sum of set points = points earned by team 1 + points earned by team 2).

2.3. Statistical Analysis
For further statistical analysis, means and standard deviations were calculated. The data were tested for normal distribution using the Kolmogorov-Smirnov test. Moreover, a discriminant analysis of the variable results (win vs. lose) and a second discriminant analysis of the variable performance level (ranking 1-4 vs. ranking 5-8) were performed. The discriminant analysis requires normal distributed data and no correlations between the independent variables. The discriminant analyses involved the following:

1. To test for quality of independent variables, a univariate analysis of variance (ANOVA) for the group means of the independent variables was calculated. Furthermore, the confidence intervals of the group means and the effect size were calculated. The effect size (f) for ANOVA was classified as trivial (<0.10), small (0.10-0.25), medium (0.25-0.40) or large (>0.40) (Cohen, 1992).
2. To test for quality of the canonical discriminant function the eigenvalue, canonical correlation and Wilks' lambda were calculated.
3. Calculation of the correlation between the standardized canonical discriminant function coefficients and z-values of the discriminant function.
4. Classification of cases based on the discriminant function.

The calculation of the correlation between the standardized canonical discriminant function and z-values of the discriminant function were used to assess the relevance of the variables to the discriminant function. Variables with correlation coefficients > 0.3 were assessed as relevant (Janssen *et al.*, 2013; Tabachnick *et al.*, 2011). All statistical analyses were conducted using IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, New York, USA).

3. Results

The Kolmogorov-Smirnov test revealed normal distributions for all variables except for $service_{\%set}$ and reception qualities. Therefore, these variables were excluded from further analysis.

3.1. Analysis of the group factor: Results
An ANOVA revealed significant differences for all variables except for the effectivity of combination attack at position 4 ($X6_{Eff}$) (Table 3).

Table 3. Mean, standard deviation (SD) and confidence intervals (CI) of the independent variables for the group factor result (win vs. lose). The table presents the results of the ANOVA (F-value), the significance value (p-value), and the effect size (f). The degrees of freedom (df) are 1 (df1) and 234 (df2) for all variables.

	Win		**95% CI**		**Lose**		**95% CI**		**F-value**	**p-value**	**f**
	mean	SD	lower limit	upper limit	mean	SD	lower limit	upper limit			
$C1_{\%Set}$	33.8	3.7	33.1	34.4	32.7	4.0	32.0	33.4	4.33	0.040	0.14
$C2_{\%Set}$	21.2	5.3	20.2	22.1	12.4	4.3	11.7	13.2	194.32	0.000	0.91
$C1\text{-}attack_{Eff}$	55.7	13.3	53.3	58.1	48.3	11.6	46.2	50.4	20.87	0.000	0.30
CA_{Eff}	48.7	16.2	45.7	51.7	36.4	17.2	33.3	39.6	31.84	0.000	0.37
$attack_{\%Set}$	30.8	5.4	29.8	31.8	26.7	5.1	25.8	27.6	36.01	0.000	0.39
$block_{\%Set}$	6.3	3.8	5.6	7.0	4.5	3.0	3.9	5.0	15.73	0.000	0.26
$EO_{\%Set}$	14.2	4.4	13.4	15.0	12.2	4.0	11.5	13.0	12.34	0.001	0.23
$1\text{-}tempo_{Eff}$	64.2	28.0	59.1	69.3	56.9	25.3	52.3	61.5	4.48	0.035	0.14
$2\text{-}tempo_{Eff}$	58.1	14.5	55.4	60.7	48.7	12.7	46.4	51.0	27.91	0.000	0.35
$3\text{-}tempo_{Eff}$	35.4	23.2	31.2	39.6	23.3	17.8	20.1	26.6	20.15	0.000	0.29
$P4_{Eff}$	47.1	17.1	44.0	50.2	37.4	15.1	34.6	40.1	21.24	0.000	0.30
$P2_{Eff}$	50.9	30.2	45.4	56.3	42.5	23.1	38.3	46.7	5.74	0.017	0.16
$X5_{Eff}$	52.4	23.1	48.2	56.6	45.6	21.8	41.6	49.6	5.44	0.020	0.15
$X6_{Eff}$	54.4	35.2	48.0	60.8	50.7	31.1	45.0	56.4	0.72	0.398	0.06

The results of the correlation analysis within groups revealed medium and high correlation coefficients of $C1_{\%Set}$ and $C2_{\%Set}$ compared to other variables. Thus, $C1_{\%Set}$ and $C2_{\%Set}$ were excluded from the calculation of the discriminant function.

The calculation of the canonical discriminant function revealed a high eigenvalue (1.29) and an intermediate Wilk's lambda (0.44), i.e., 44% of the variance could be explained by group differences. It is concluded that groups can be well distinguished from each other ($chi^2 = 189.0$, $df = 12$, $P < 0.001$).

Based on the discriminant function, 89.0% and 88.1% of the cases were correctly classified into the categories win and lose, respectively. The loading of single variables on the discriminant function revealed the highest correlations to the z-values of the discriminant function for the variables $attack_{\%Set}$, CA_{Eff} and $2\text{-}tempo_{Eff}$ (Table 4). High values of $attack_{\%Set}$, CA_{Eff} and $2\text{-}tempo_{Eff}$ suggest that these variables are the most important factors with respect to winning a set. Other variables have a lower impact on the set result.

Table 4. Correlation of independent variables to the z-transformed values of the discriminant function.

Variables	Function
$attack_{\%Set}$	0.345
CA_{Eff}	0.325
$2\text{-}tempo_{Eff}$	0.304
$P4_{Eff}$	0.265
$C1\text{-}attack_{Eff}$	0.263
$3\text{-}tempo_{Eff}$	0.258
$block_{\%Set}$	0.228
$EO_{\%Set}$	0.202
$P2_{Eff}$	0.138
$X5_{Eff}$	0.134
$1\text{-}tempo_{Eff}$	0.122
$X6_{Eff}$	0.049

3.2. Analysis of the group factor performance level

Overall, it is evident that teams of performance level 1 (ranking 1-4) won 76 sets and lost 42 sets. Significant differences between the performance levels were observed for the variables $attack_{\%Set}$, $block_{\%Set}$, $2\text{-}tempo_{Eff}$, $3\text{-}tempo_{Eff}$ and CA_{Eff} (Table 5). The discriminant function revealed a low eigenvalue (0.18) and a high Wilk's lambda (0.85), i.e., 85.0% of the variance cannot be explained by group differences. Thus, separation of the groups based on the input variables is difficult. However, the chi^2 test shows a significant difference ($chi^2 = 37.3$, $df = 12$, $p < 0.001$), which might indicate a sufficient separation of the groups based on the discriminant function.

Based on the discriminant function, 65.3% of the cases were correctly classified into the appropriate performance level. The highest loadings were observed for the independent variables CA_{Eff}, $2\text{-}tempo_{Eff}$, $3\text{-}tempo_{Eff}$, $attack_{\%Set}$ and $block_{\%Set}$ (Table 6). The remaining variables have a lower impact in distinguishing between performance levels.

Table 5. Mean, standard deviation (SD), and confidence intervals (CI) of the independent variables for the group factor performance level (ranking 1-4 vs. ranking 5-8). The table presents the results of the ANOVA (F-value), the significance value (p-value), and the effect size (f). The degrees of freedom (df) are 1 (df1) and 234 (df2) for all variables.

	ranking 1-4		**95% CI**		**ranking 5-8**		**95% CI**		**F-value**	**p-value**	**f**
	mean	SD	lower limit	upper limit	mean	SD	lower limit	upper limit			
$C1_{\%Set}$	33.3	4.0	32.5	34.0	33.2	3.7	32.5	33.9	0.019	0.891	0.01
$C2_{\%Set}$	18.5	6.2	17.4	19.6	15.1	6.4	13.9	16.3	16.927	0.000	0.27
C1-$attack_{Eff}$	52.7	14.4	50.1	55.4	51.3	11.3	49.2	53.3	0.773	0.382	0.06
CA_{Eff}	47.2	17.9	43.9	50.4	37.9	16.4	34.9	40.9	17.362	0.000	0.27
$attack_{\%Set}$	29.6	5.7	28.5	30.6	27.9	5.4	26.9	28.9	5.345	0.022	0.15
$block_{\%Set}$	5.9	3.6	5.3	6.6	4.8	3.4	4.2	5.4	6.362	0.012	0.16
$EO_{\%Set}$	13.3	4.5	12.5	14.1	13.1	4.2	12.3	13.9	0.109	0.742	0.02
1-$tempo_{Eff}$	60.5	27.4	55.5	65.4	60.7	26.4	55.8	65.5	0.004	0.951	0.00
2-$tempo_{Eff}$	55.9	15.7	53.1	58.8	50.8	12.5	48.5	53.1	7.794	0.006	0.18
3-$tempo_{Eff}$	33.0	24.1	28.7	37.4	25.6	17.8	22.3	28.9	7.267	0.008	0.18
$P4_{Eff}$	43.1	17.5	39.9	46.3	41.4	16.2	38.4	44.3	0.620	0.432	0.05
$P2_{Eff}$	49.2	29.1	43.9	54.5	44.1	24.8	39.5	48.6	2.124	0.146	0.10
$X5_{Eff}$	49.8	23.9	45.5	54.2	48.2	21.4	44.3	52.1	0.306	0.581	0.04
$X6_{Eff}$	53.3	34.6	47.0	59.6	51.8	31.8	46.0	57.6	0.118	0.731	0.02

Table 6. Correlation of independent variables to the z-transformed values of the discriminant function.

Variables	Function
CA_{Eff}	0.646
2-$tempo_{Eff}$	0.434
3-$tempo_{Eff}$	0.418
$block_{\%Set}$	0.391
$attack_{\%Set}$	0.359
$P2_{Eff}$	0.226
C1-$attack_{Eff}$	0.136
$P4_{Eff}$	0.122
$X5_{Eff}$	0.086
$X6_{Eff}$	0.053
$EO_{\%Set}$	0.051
1-$tempo_{Eff}$	-0.010

4. Discussion

The analysis of action sequences, point elements, attack tempo and attack combinations is important for extracting variables relevant to play structure and deducing particular training schemes. Our results revealed that the variables $attack_{\%set}$, CA_{Eff} and $2\text{-}tempo_{Eff}$ have the highest impact on game results. Furthermore, it is evident that the top-level teams can be distinguished from second-level teams by the variables effectivity of counter-attack as well as effectivity of 2- and 3-tempo. The point elements $block_{\%Set}$ and $attack_{\%Set}$ also have a strong effect in separating the performance levels. A correct classification may be possible by conducting a more detailed analysis of variables for game complex 2.

4.1. Game result

Using the discriminant function, we can distinguish the independent variables with high and low impacts on game result prediction. Our results revealed that $attack_{\%Set}$ has the highest loading, followed by CA_{Eff} and $2\text{-}tempo_{Eff}$. CA_{Eff} and 2-tempo are variables that are mainly related to C2. It is assumed in the literature that C2 is more important in determining game results than C1 (Pena *et al.*, 2013; Zetou *et al.*, 2006). Teams winning a set complete 49% of C2 successfully. The effectivity of 2-tempo is 58%. In summary, it is concluded that counter-attacks carried out at 2-tempo are the key components to winning or losing a game. This conclusion is indirectly confirmed by the literature. Zetou et al. (2006) observed that counter-attack (i.e., successful C2) is an important predictor of game results. Castro et al. (2011) observed a correlation between attack effectivity in C2 and attack tempo. They demonstrated an increased feasibility to win a point when playing 1- or 2-tempo. Our results confirm these findings because the effectivities of 1- and 2-tempo are higher than the effectivity of 3-tempo. However, the structure matrix (Table 4) shows that $1\text{-}tempo_{Eff}$ has lower correlation coefficients with respect to the discriminant function than do 2- and 3-tempo. Thus, we conclude that 1-tempo has a lower impact on game results than 2- and 3-tempo do. This result can be explained by the fact that, in C2, 1-tempo is played less often because excellent defence (all attack combinations can be played) rarely occurs. The reverse play (backlash) of the defending team depends on the opponent's activities in C1 and is particularly limited for 1-tempo.

In such action sequences, the block and its effectivity are significant to winning a game (Zimmermann *et al.*, 2012). However, the effect of 1-tempo on winning a game will be low, which is also confirmed by our results.

The structure matrix also shows that the variable effective attacks on position 4 ($P4_{Eff}$) barely misses the threshold of 0.3. This result might lead to the conclusion that the attacks on position 4 are mainly decisive for a game. The importance of further attack combinations in C2, such as pipe attacks on position 6 or backline attacks on position 1, should be examined in greater detail in future studies. It should be noted that the influence of different attack combinations depends on the abilities and skills of the single attack players.

Because the effectivities of attack tempo were analysed independently of the game complexes, we can hypothesize that the results would be more distinctive when the effectivities of the attacks and the attack tempo are analysed separately for game complexes.

Interestingly, our results reveal that both winning and losing teams earn approximately 34% and 33% of the sum of game points in C1, respectively (Table 3). Significant differences between winning and losing teams exist, but the effect size is small (f=0.14), i.e., the sum of points in C1 does not appear to be relevant. Conversely, the result confirms our primary findings indicating that the activities in C2 are more important than those in C1 and that games will be decided by the former.

4.2. Comparison of performance between top-level and second-level teams

This study is the first to compare top-level teams with second-level teams by considering game complexes, action sequences, game elements and attack tempo. In accord with Castro et al. (2011), we observed that top-level and second-level teams do not differ in action sequences (Castro *et al.*, 2011). Teams of both performance levels earn approximately 33% of their total game points in C1 (Table 5). Our results reveal that top-level teams earn 3% more points in C2 than second-level teams do ($C1_{\%Set}$ is significantly different from $C2_{\%Set}$, Table 5). This difference is due to the higher effectivity of the counter-attacks (CA_{Eff}) of top-level teams (47% top-level teams vs. 37% second-level teams, Table 5). This higher effectivity may be attributed to the higher effectivity of attack combinations using 2- and 3-tempo. 3-tempo plays are typically manifested as a high pass by the setter that is completed by the diagonal attacker or side-out attacker. These players must attack against their opponents' group blocks. It can be concluded that top-level teams and second-level teams differ in CA_{Eff}, particularly due to the higher effectivity of 2- and 3-tempo attacks (Zimmermann *et al.*, 2012). This conclusion contradicts that of Castro et al. (2011), who apportion higher relevance to 1- and 2-tempo within C2. We argue that the played attack tempo depends on the performance of the defence. However, the defence performance has no effect on game results (Castro *et al.*, 2011; Zetou *et al.*, 2006). Therefore, we further conclude that the individual skill level of attack players who complete an attack (2- and 3-tempo in C2) successfully is the most relevant component.

We observed that the effectivity of counter-attacks, their point elements and the attack tempo are the most relevant variables for winning a game and for differentiating between teams of varying performance levels. However, Durkovic et al. (2008) reported that serve and attack after reception are the best predictors for winning a game. The contradictory results may be based on the different samples examined. Durkovic et al. (2008) examined matches of male youth national teams, whereas, in our study, elite international male senior volleyball teams were investigated. Therefore, it appears that the relevance of winning a point within a complex shifts from C1 to C2 for senior national teams.

4.3. Considerations of data analysis

A fundamental problem associated with comparing the results of different studies is varying data analysis methods. Some studies use the absolute frequency of events, whereas others normalize the absolute frequency of events to a defined reference parameter (Drikos *et al.*, 2009; Marcelino *et al.*, 2008). The statistical analysis of absolute frequencies of single events (e.g., serve, attack) may lead to bias, particularly if game results are very close or diverge greatly (Rodriguez-Ruiz *et al.*, 2011).

A further problem is the definition of attack tempo. Some studies (Castro *et al.*, 2011) use the suggested classification of Selingers et al. (1986). This classification differentiates between attack tempos based on the time interval between the moments the setter and the attacker make contact with the ball. The disadvantage is that an unambiguous assignment is not feasible due to the increased pass speed in many action sequences. Thus, a more practical classification is used in the official volleyball scouting system (see methods). Unfortunately, it is difficult or may be impossible to compare studies using the different classification systems.

5. Conclusions and training recommendations

Our results pertaining to elite men's volleyball show that the effectivity in C1 is balanced between teams of different performance levels; however, huge differences exist with respect to the effectivity of C2. C2 training and the quality thereof are important in determining game results. Training must focus on variable situations involving high levels of difficulty in the "block-defence-set" action sequences and in the individual counter-attack solutions against group blocks. In this regard, it is necessary to develop flexible defence systems for block-defence-counter-attack and to apply them to opponent-related circumstances. The C2 should be played fast and variable whenever possible (as in C1). Usually, it is not possible to play fast in C2. Thus, high passes are played to the attacker (diagonal player or side-out player). In these situations, the attacker has to complete the attack using a power attack or clever solutions (e.g., lateral block hitting, cut shot).

Recent studies examined the effect of attack tempo, attack technique, defence effectivity and number of opponent block players during an attack on the effectivity in C2. They observed that the number of opponent block players and attack tempo are the best predictors for the variable C2 effectivity. In addition, our study shows that top-level teams differ significantly from second-level teams with regard to 2- and 3-attack-tempo. Therefore, it is concluded that devising 2- and 3-attack-tempo solutions to group blocks in C2 must be a dominant part of technical tactical volleyball training. Furthermore, our results suggest that the diagonal attacker and both side-out attackers serve key functions in the match strategy of their national teams. The profiles of these players must be developed purposefully and systemically during long-term training.

Further studies should examine the attack combinations in C2 as well as the relationships between setting and counter-attacks in C2 in greater detail. Moreover, it is important to examine the effect of the setter on game continuity in C2. We expect that these studies will demonstrate the most relevant variables for differentiating between top-level and second-level teams in terms of performance.

6. Acknowledgements

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There are no financial conflicts of interest related to the research reported in the manuscript.

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APPENDIX Q: LETTER FROM JOURNAL EDITOR AS PROOF OF ARTICLE **ACCEPTANCE** TO THE INTERNATIONAL JOURNAL OF PERFORMANCE ANALYSIS IN SPORT

Fri 9/23/2016 12:23 PM

Ben Coetzee <Ben.Coetzee@nwu.ac.za>

Fwd: RE: 16.2.82 paper -query

To Christo Bisschoff

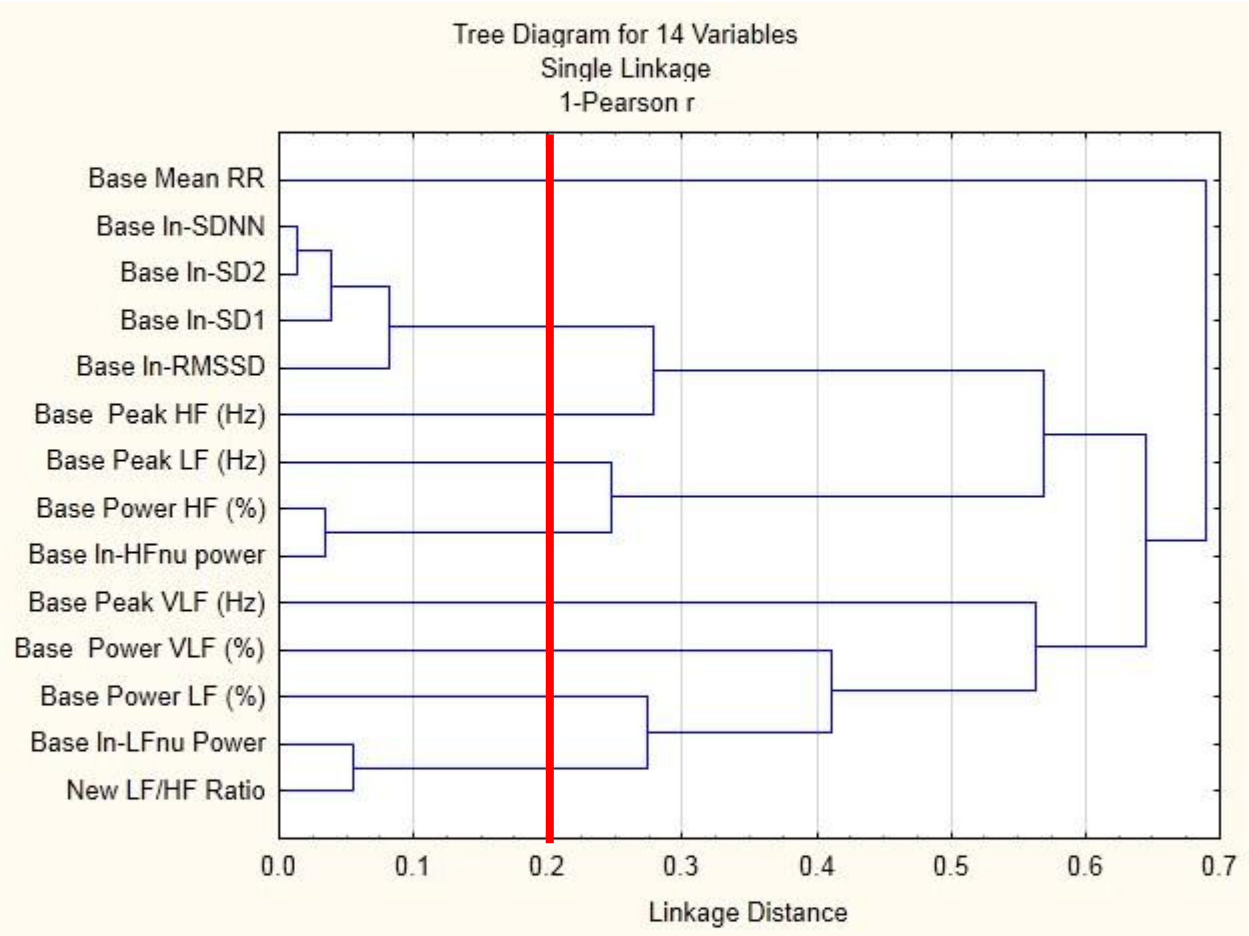
Cc Mike Esco

A bit of good news
Enjoy the weekend
Ben

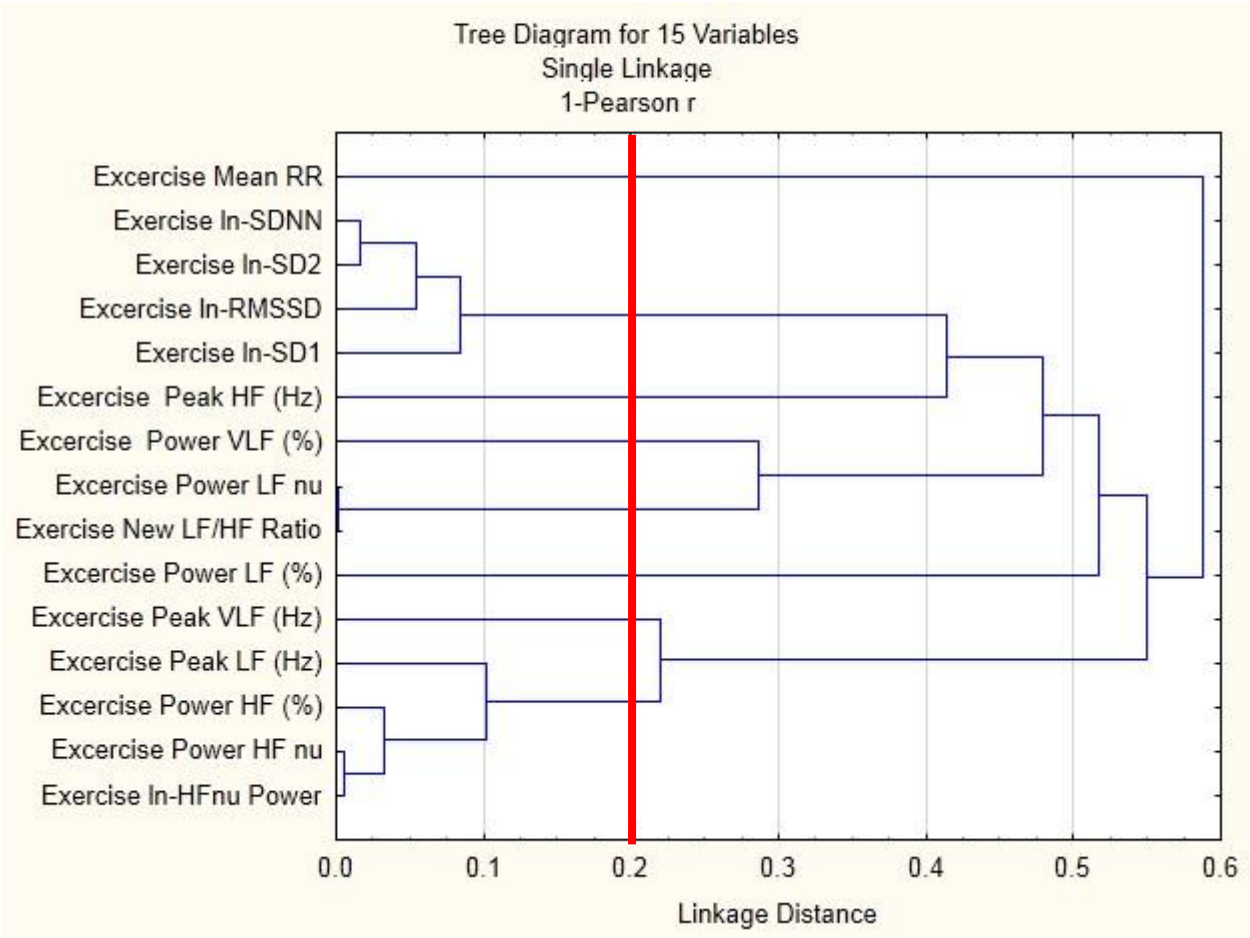
Vrywaringsklousule / Disclaimer: http://www.nwu.ac.za/it/gov-man/disclaimer.html
>>> "O'donoghue, Peter" <PODonoghue@cardiffmet.ac.uk> 2016/09/23 11:51 AM >>>
Thanks Ben
The paper is now accepted for the December issue
I will be in touch with an edited proof around 15th October for you to check.
Thanks for choosing IJPAS
POD

APPENDIX R: SINGLE-LINKAGE, TREE CLUSTER (1-PEARSON CORRELATION COEFFICIENT) ANALYSIS RESULTS OF HRV, HRR VARIABLES FOR ALL PERIODS OF THE MATCHES **(Chapter 3 and 4)**

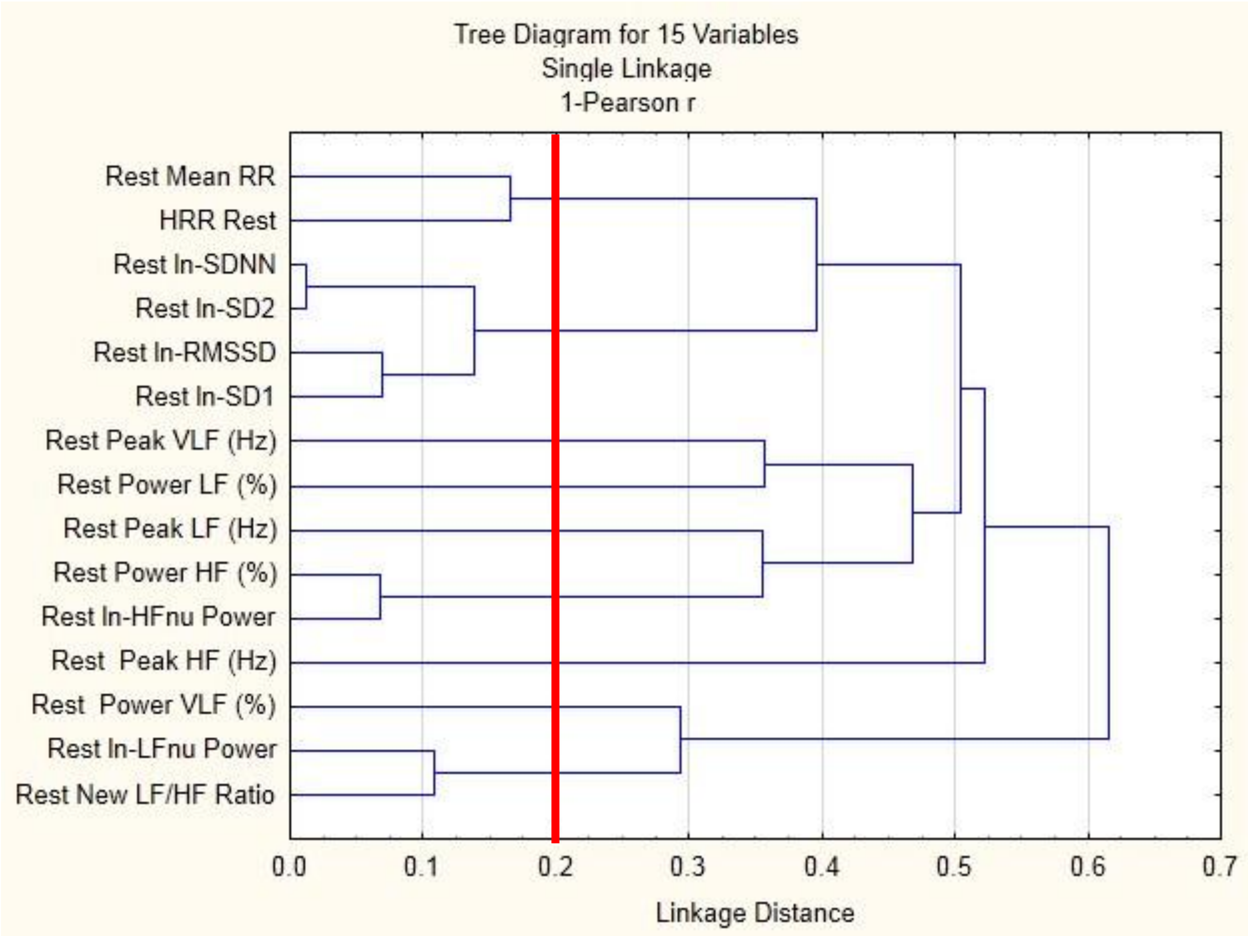
Before Match (Pre-Match)



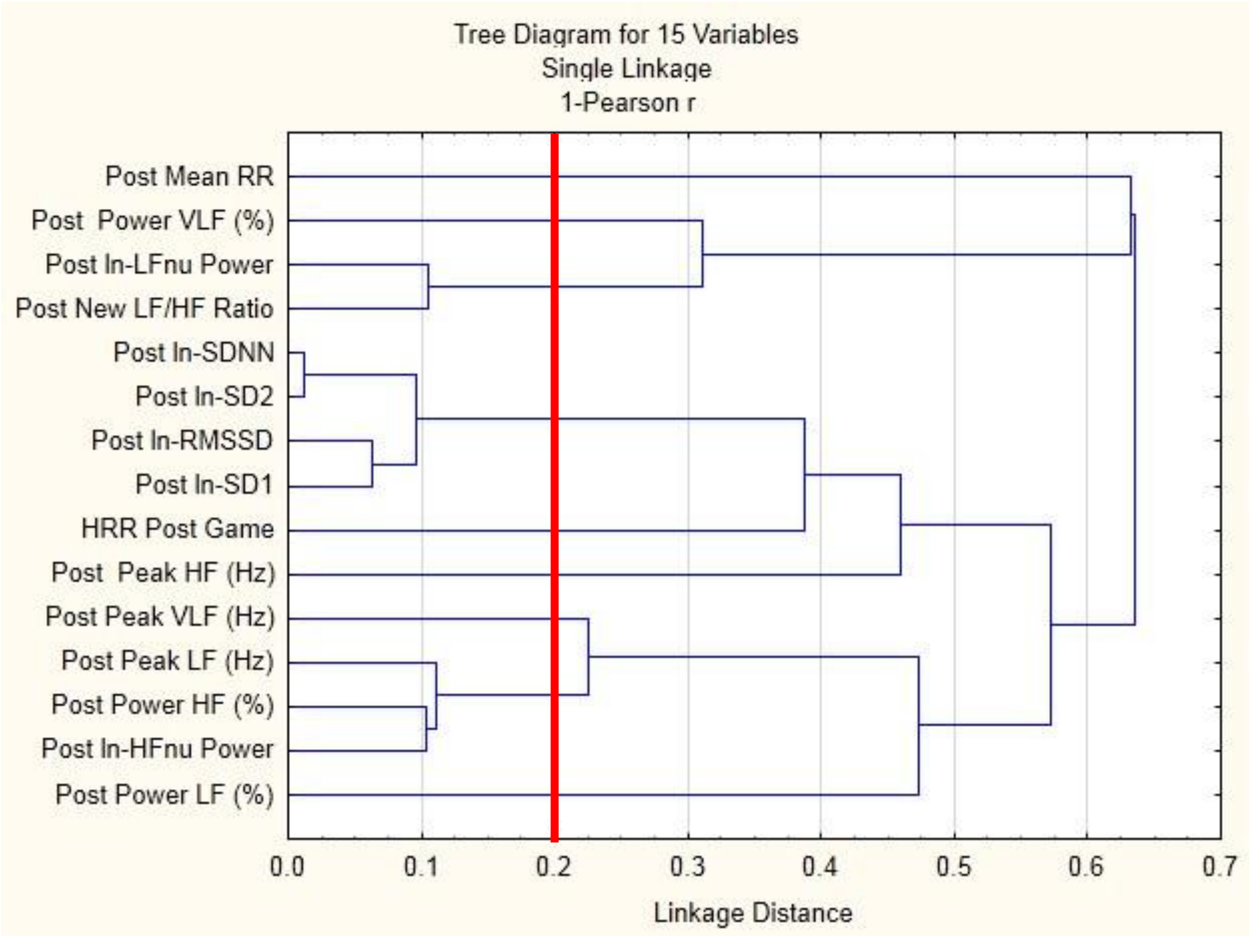
During Match (In-Match)



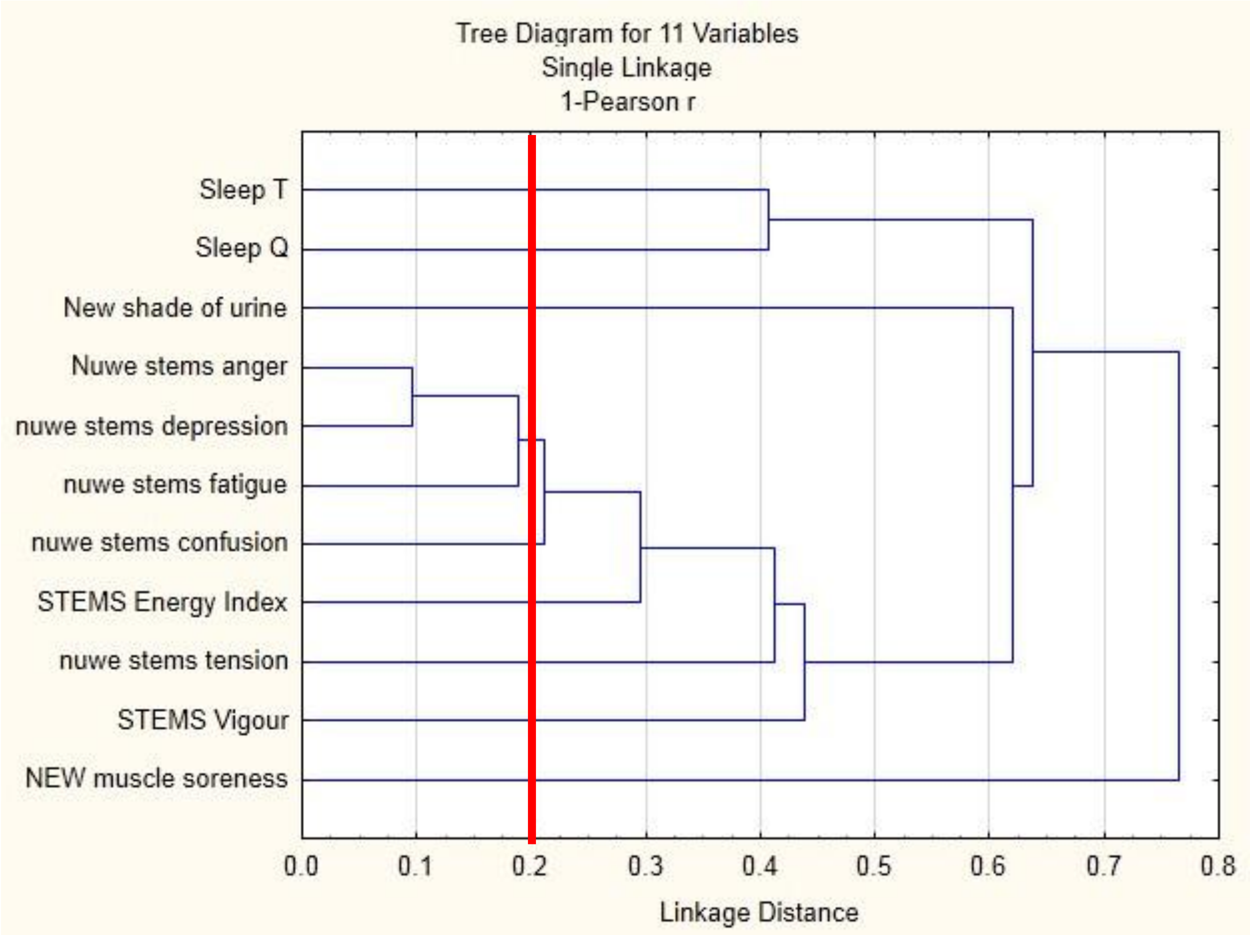
During Service Breaks in Match (In-Match Rest)



After Match (Post-Match)

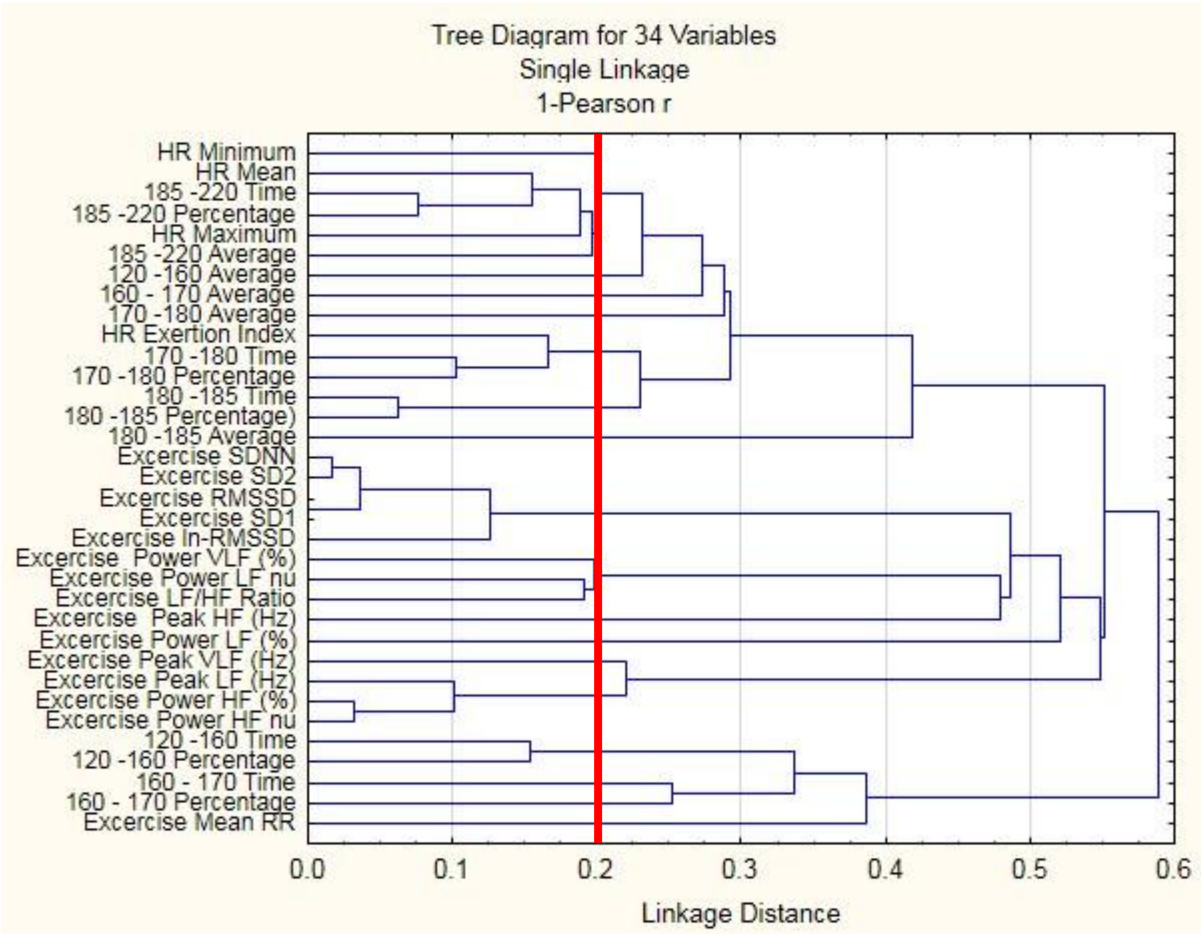


APPENDIX S: SINGLE-LINKAGE, TREE CLUSTER (1-PEARSON CORRELATION COEFFICIENT) ANALYSIS RESULTS OF RECOVERY INDICATOR VARIABLES (**Chapter 4**)

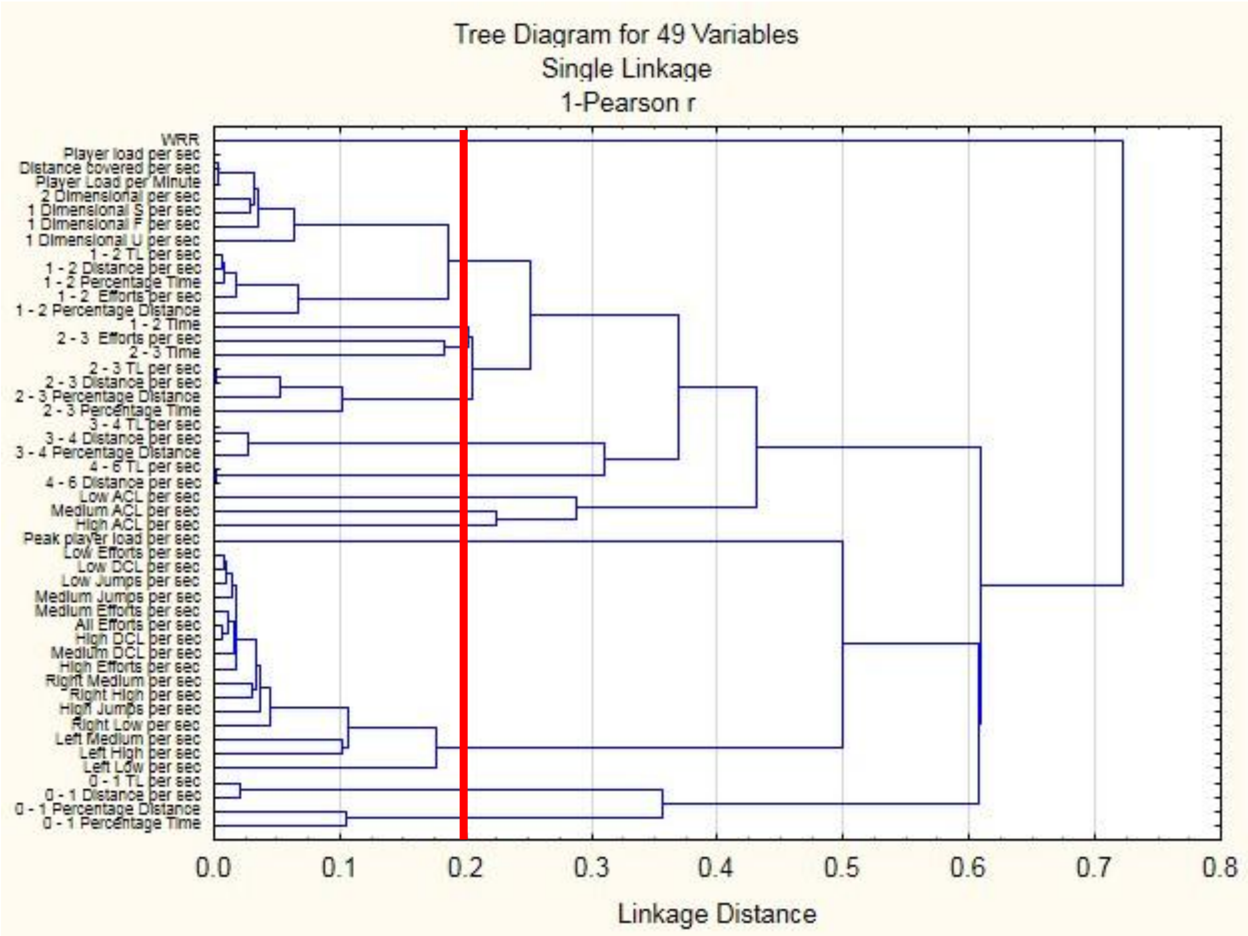


APPENDIX T: SINGLE-LINKAGE, TREE CLUSTER (1-PEARSON CORRELATION COEFFICIENT) ANALYSIS RESULTS OF HEART RATE RELATED AND GPS UNIT RELATED VARIABLES **(Chapter 5)**

HR Related Variables



GPS Related Variables



APPENDIX U: CHAPTER 4 AND 5: CANONICAL WEIGHTS

CHAPTER 4: CANONICAL WEIGHTS OF THE RECOVERY-RELATED VARIABLES

Canonical weights of the recovery-related variables for the pre-match period

Recovery variable	Canonical weight
Sleep Duration	-0.084
Sleep Quality	0.179
Shade of Urine	0.358
STEMS Anger	-0.647
STEMS Confusion	1.383
STEMS Energy Index	-0.679
STEMS Tension	-0.269
STEMS Vigour	0.583
Muscle Soreness	-0.251

Canonical weights of the recovery-related variables for the in-match period

Recovery variable	Canonical weight
Sleep Duration	0.097
Sleep Quality	-0.368
Shade of Urine	-0.126
STEMS Anger	-0.889
STEMS Confusion	0.545
STEMS Energy Index	0.919
STEMS Tension	-0.468
STEMS Vigour	-0.060
Muscle Soreness	-0.668

Canonical weights of the recovery-related variables for the in-match rest period

Recovery variable	Canonical weight
Sleep Duration	0.193
Sleep Quality	-0.531
Shade of Urine	-0.115
STEMS Anger	1.09
STEMS Confusion	-0.863
STEMS Energy Index	-1.459
STEMS Tension	1.072
STEMS Vigour	1.547
Muscle Soreness	-0.297

Canonical weights of the recovery-related variables for the post-match period

Recovery variable	Canonical weight
Sleep Duration	-0.146
Sleep Quality	-0.747
Shade of Urine	-0.078
STEMS Anger	-0.510
STEMS Confusion	-0.239
STEMS Energy Index	0.345
STEMS Tension	0.300
STEMS Vigour	-0.498
Muscle Soreness	0.329

CHAPTER 4: CANONICAL WEIGHTS OF THE HRV- AND HRR-RELATED VARIABLES

Canonical weights of the HRV-related variables for the pre-match period

HRV variable	Canonical weight
Mean RR Intervals	0.112
Ln-RMSSD	0.494
Ln-HFnu Power	1.736
Peak VLF (Hz)	-0.154
Peak HF (Hz)	0.083
VLF Power (%)	1.312
LF Power (%)	2.027
Ln-LFnu/Ln-HFnu Ratio	0.107

Canonical weights of the HRV-related variables for the in-match period

HRV variable	Canonical weight
Mean RR Intervals	-0.102
Ln-RMSSD	0.207
Peak HF (Hz)	-1.010
VLF Power (%)	4.354
Ln-LFnu/Ln-HFnu Ratio	5.930
LF Power (%)	0.672
Peak VLF (Hz)	2.095
Ln-HFnu Power	8.275

Canonical weights of the HRV- and HRR-related variables for the in-match rest period

HRV and HRR Variable	Canonical weight
HRR	-0.331
Ln-RMSSD	1.153
Peak VLF (Hz)	-0.126
LF Power (%)	0.323
Peak LF (Hz)	2.096
Ln-HFnu Power	-2.335
Peak HF (Hz)	0.164
VLF Power (%)	1.582
Ln-LFnu/Ln-HFnu Ratio	-1.141

Canonical weights of the HRV- and HRR-related variables for the post-match period

HRV and HRR Variable	Canonical weight
Mean RR Intervals	0.048
VLF Power (%)	-0.497
Ln-LFnu/Ln-HFnu Ratio	2.997
Ln-RMSSD	-1.347
HRR	0.077
Peak HF (Hz)	-0.069
Peak VLF (Hz)	-0.986
Ln-HFnu Power	3.328
LF Power (%)	0.298

CHAPTER 5: CANONICAL WEIGHTS OF THE HR-, HRV- AND HRR-RELATED VARIABLES

Canonical weights of the HR-, HRV- and HRR-related variables

HR, HRV and HRR variable	Canonical weight
Heart rate exertion index	-0.151
Average heart rate of the 180-185 bpm zone	0.877
Ln-RMSSD	0.381
Ln-LFnu/Ln-HFnu ratio	-1.947
Peak HF (Hz)	-1.548
LF Power (%)	-0.926
Ln-HFnu power	-2.438
Average heart rate of the 120-160 bpm zone	0.088
Average heart rate of the 160-170 bpm zone	-0.367
Mean RR intervals	-0.254

Canonical weights of the GPS-related variables

GPS Variable	Canonical weight
Work to rest ratio	0.168
Peak player load per second	-0.425
0-1 Distance per second	-1.693
3-4 Distance per second	0.413
4-6 Distance per second	0.060
0-1 Percentage distance covered	2.015
Low intensity accelerations per second	1.611
Player load per second	0.189
Low intensity efforts per second	1.083

APPENDIX V: LETTER FROM PROF FAANS STEYN (SENIOR STATISTICAL CONSULTANT)

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24 November 2016

Whom it concerns

CONFIRMATION OF STATISTICAL METHODS AND THE WAY IN WHICH RESULTS WERE PRESENTED – PHD THESIS OF CHRISTO BISSCHOFF

CHAPTER 3:
Comment: The candidate presented a thorough description of the statistical analyses, mentioning various statistical procedures and measurements. When the results are presented within the table, these mentioned results from the analyses are not presented in the tables of the result section.
Response: The under-mentioned person was consulted about the statistical methods and analysis as well as the presentation of statistical results and concur that researchers did follow the correct methods and presented the data correctly.

The following statistics were presented in article 1:

- Log-transformed values: Tables 2-5 contain the Log-transformed HRV values.
- Descriptive statistics: Tables 1-5 contain the descriptive statistics of the different variables.
- Independent t-test: Tables 1-5 contain the p-values of the independent t-tests that indicated significant differences in HRV- and HRR-related variables between successful and less successful groups of players.
- Cluster analyses: the results of these analyses are presented on page 109, paragraph 2.
- Binary forward stepwise logistic regression analyses: Table 6 contains the results of the analyses for each of the identified time periods.
- The significance of individual logistic regression coefficients or Wald statistic: significance of last-mentioned coefficients was indicated in Table 6.
- Odds ratios (OR) and 95% confidence intervals (95% CI): Last-mentioned results were indicated in Table 6.
- The Hosmer and Lemeshow Chi-square Goodness-of-fit test through the non-significant $\chi 2$-value ($p > 0.05$): Results of this analysis were presented in paragraph format in paragraph 1 on page 110.
- Classification tables: Results indicated in Table 7.
- The usefulness of models was determined by calculating the “hit rate” and “chance hit rate”: Results of this calculation was indicated on page 111, paragraph 1.

- The “better than chance” index (I): Results of this index were presented in paragraph 1 on page 112.

Comment: The results from the cluster analyses are also not presented. The statistical analyses section indicates regression analyses, together with the development of a model to classify successful and non-successful players accordingly.
Response: The under-mentioned person agrees that it is not necessary to include the cluster analyses' results in the article as these results did not form the primary basis of the analyses for the different articles. Journals all have cut-off points for the number of word used, pages or figures and tables which do not allow authors to present four extra figures that display the cluster analysis' results. However, these figures can be included in appendixes. However, the candidate did present the forward logistic regression analyses model correctly.

Comment: I would like to propose that the candidate report this model, since later in the manuscript the suggestion is made that the model should be tested in future studies.
Response: Although the article refers to prediction models, only one variable was identified under each time period as a significant independent variable. No other variables were identified through the models as independent variables that explained the likelihood that players would be categorised in a certain group. Furthermore, although the study referred to prediction models, practitioners would not use these HRV-related models to predict group allocation, but rather use it to determine if a player's specific HRV profile indicates that they he/she is ready to perform well during match play.

Comment: The candidate should report the model in order for the reader to understand the variables and their contributions to the model.
Response: Please see above-mentioned comments.

Comment: Finally, the I-statistic that was calculated, should also be presented with the results in the appropriate table.
Response: I think it rather belongs to the discussion of the table.

CHAPTER 4:
Comment: The name of the cluster analyses is not mentioned in the statistical section, I suggest you add it instead of just indicating that a cluster analyses was conducted. I suggest the candidate re-visit the presentation of the cluster analyses data.
Response: The tree clustering, single-linkage, 1-Pearson Correlation Coefficient cluster analysis method was used. This description of the cluster analysis will be included in each of the relevant parts of the thesis together with a proper reference. The reference is:

- Wilkinson *et al*. (2012:I85) - Wilkinson, L., Engelman, L., Corter, J. & Coward. M. 2012. Chapter 4: Cluster analysis. http://cda.psych.uiuc.edu/multivariate_fall_2012/systat_cluster_manual.pdf. Date of access: 24 November 2016.

Comment: There is an expectation that the weights of each of the variables in the two sets be reported. (See Sherry & Hensons (2005) for reporting of canonical correlation analysis).
Response: Since the primary aim of this study was to determine if groups of variables for HRV and HRR are related to several groups of subjective indicators of recovery status, the canonical weights do not need to be reported in detail. The candidate can only refer to the canonical weights of variables that had the biggest influence on the relationship between the two categories of variables. However, the candidate included the values of each of canonical weights for the biggest contributors of the relationship: Chapter 4, Discussion, par. 10: “A further analysis, in which canonical weights were examined revealed that Ln-HFnu was the primary HRV-related variable to contribute to relationships during the in-match (canonical weight = 8.28), in-match rest (canonical weight = -2.34) and post-match periods (canonical weight = 3.33). The recovery related variables that were identified as the primary variables in the relationships for different time periods were: STEMS confusion (pre-match, value = 1.38), STEMS energy index (in-match, value = 0.92), STEMS vigour (in-match rest, value = 1.55), and sleep quality (post-match, value = -0.75).” Furthermore, the candidate included the canonical weights of all relationships in the Appendix.

Comment: The candidate indicate the contribution of specific variables from the subjective indicators of recovery (energy index and vigour) to HRV-related variables (Ln-HFnu). In order to make this comments the weighting of the variables within the canonical correlation should have been presented.
Response: See above-mentioned comments.

Comment: On page 144 the candidate only states that "A further analysis of the canonical weights revealed……" You have to add what this analysis was and then also present the finding of this analysis in order to make the statement within the discussion of the results.
Response: See above-mentioned comments: Chapter 5, Discussion, par. 10: "It is noteworthy that a further analysis also revealed that Ln-HFnu power, peak HF (Hz) and the Ln-LFnu/Ln-HFnu (canonical weight values of 2.43, 1.54 and 1.94, respectively) influenced GPS-related variables the most. On the other hand percentage time spent and distance covered in the 0 - 1 intensity zone (canonical weight values of 2.01 and 1.69, respectively) as well as the amount of low accelerations per second (canonical weight value of 1.61) had the biggest influence on HR-related variables." Furthermore, the candidate included the canonical weights of all relationships in the Appendix.

CHAPTER 5:
Comment: The descriptive results in Table 1 and Table 2 are not very clear. The candidate should ensure that tables are able to be understood independent from the text. This is currently not the case with these two tables. From the methods section the data collection is indicate as per 60 sec. Could the candidate please clarify why the data was converted to per second?
Response: The candidate had to correct for match duration as longer compared shorter matches will influence the data. The candidate also had to correct for match duration in order to combine data of different matches. This article was accepted for publication in *The International Journal of Performance Analysis in Sport* after a thorough review process by two international reviewers and a renowned editor. No comments were received with regard to the descriptive statistics of the mentioned tables.

Comment: As in the previous chapter, this chapter also present data on cluster analyses and canonical correlations. There is the same lack of information in this chapters as presented in chapter 4 with regards to the results presented based on the statistical analyses indicated in the methods section. More information should be added to this manuscript in this regard.
Response: See the comments under chapter 4.

Comment: This chapter also report on the wide distribution of data, which may have been due to an outdoor system used during an indoor match? The candidate again states on page 164 that further analyses were conducted, please add these analyses to the methods section and also report on the results by reporting the data of these further analyses. These additional analyses should also be reported in the results section and not introduced in the discussion section.
Response: The wide data distribution was not caused by the use of the indoor system but rather by individual differences in movement and play patterns between players. The further analysis again refers to the fact that canonical weights were also considered in the analyses.

For further enquiries, contact me.
Yours sincerely,

Prof. Faans Steyn

(Statistical Consultant)

APPENDIX W: LETTER FROM LANGUAGE EDITOR

Dynamic Language &
Translation Specialists

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Sunday, 11 December 2016

To whom it may concern,

Re: Letter of confirmation of language editing

The thesis **Heart rate variability and heart rate recovery in relation to match results in elite African male badminton players** by **CA Bisschoff (13234358)** was language, technically and typographically edited. The citations, sources and referencing technique applied in Chapters 1, 2 & 6 were also checked to comply with the North-West University guidelines. Similarly, the scientific articles in Chapters 3 - 5 were checked to comply with the specific journal guidelines.

Final corrections as suggested remain the responsibility of the student.

Yours sincerely,

Antoinette Bisschoff

Officially approved language editor of the NWU since 1998
Member of SA Translators Institute (no. 100181)

Precision ... to the last letter