Bond University

DOCTORAL THESIS

Exploring heart rate variability as a human performance optimisation metric for law enforcement

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Award date:
2024

Exploring Heart Rate Variability as a Human Performance Optimisation Metric for Law Enforcement

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Submitted in total fulfillment of the requirements of the degree of Doctor of Philosophy

October 2023

Faculty of Health Sciences and Medicine

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This research was supported by an Australian Government Research Training Program Scholarship.

Abstract

Tactical personnel, inclusive of police officers, face complex challenges over potentially decades-long careers. These cumulative exposures may manifest as allostatic load, impairing health, fitness, and performance. Allostatic load describes increased vulnerability to psychophysiological dysfunction resulting from prolonged overstress exposure. Monitoring for this risk is an important step towards its mitigation. Heart rate variability (HRV) analysis can noninvasively acquire psychophysiological overstress information in tactical environments. HRV theory and principles are well established, however, the integration of HRV in tactical workflows, especially for end-users, has received limited research attention. Therefore, the overarching aim of this programme of research was to determine the utility of HRV assessment in the support of specialist police and their organisations and to alert stakeholders to potential instances of psychophysiological overstress.

Chapter 1 introduces HRV concepts within tactical contexts. Components of tactical work that may be best appreciated with HRV analysis are highlighted. Principles in this introduction are further articulated in a systematic review (Chapter 2). Chapter 2 reports on the undertaken systematic review which summarised and critically appraised studies of HRV applications across tactical populations. Of 296 initially identified studies, twenty were included. The volume of evidence suggested that HRV effectively supports health and performance measures in tactical environments. However, literature gaps were identified; most notably, there was limited evidence available regarding HRV in specialist police professions, thus warranting this research. As professional requirements and potential allostatic load sources differ during specialist police selection and subsequent specialist police operational contexts, two research arms were devised to pragmatically address this critical gap. Chapter 3 illustrates the research structure in further detail and outlines which studies address specific literature gaps within specialist police and in which of the two developed research arms. Methodological approaches are also described.

Chapters 4, 5, 6, and 7 encompass HRV application in initial specialist police selection. Chapter 4 introduces the first field study, building on the findings from Chapter 2 (Study

1) that HRV assessment may be more valuable than traditional heart rate (HR) measurement for monitoring tactical training as HRV is capable of measuring stress holistically. The primary aim therefore was to investigate whether HRV was more sensitive than HR at monitoring workload during specialist police selection activities. As aerobic fitness is associated with workload during these tasks, a secondary aim was to investigate relationships between HRV, HR, and maximal aerobic fitness. As illustrated by a time-series plot, HR values were unremarkable while HRV values were potentially depressed, and tentatively indicative of overstress. Estimated maximal aerobic fitness (20-m shuttle run) was significantly positively correlated with HRV, but there was no relationship with HR. When a linear regression model was applied, neither HRV nor HR were predicted by 20-m shuttle run scores.

Chapter 5 aimed to determine the effectiveness of HRV in differentiating between candidates that failed to complete specialist selection from those who succeeded. HRV was defined as the percentage of R-R intervals that varied by at least 50ms (pRR50). Data were summarised in a heat map. A logistic regression model was generated that effectively predicted attrition but did not identify the most successful candidate. Therefore, the aim of Chapter 6 was to profile HRV characteristics of that successful candidate and consequently a detailed HRV time series plot was generated. Contextual analysis was applied, and the candidate demonstrated continued performance even under apparent duress, both physical and psychological in nature. The subsequent studies (7-9) then aimed to consider HRV monitoring at the operational level where such duress exposures occur frequently.

Noting that success in training is distinct from operational performance, Chapters 7, 8, 9, and 10 examined the use of HRV monitoring in operational contexts. The purpose of Chapter 7 was to identify if HRV analysis could classify candidate performance in specialist police selection during occupationally realistic tactical operations scenarios which required fluid psychomotor skills, teamwork, and leadership while under duress. Qualitative analysis of descriptive statistics indicated that the HRV data of one participant were substantially different from his peers. This candidate was also the highest performer, suggesting a relationship between HRV and occupational aptitude.

Given that specialist police often work rotating shift schedules which may lead to sleep deprivation, introducing another source of allostatic load, the aim of Chapter 8 was to determine the extent to which HRV may detect differences between specialist police that worked an overnight shift and those that were off duty overnight. HRV was analysed in 11 male specialist police officers who were either off-duty or on overnight duty prior to engaging in specialist assessment activities. All officers experienced HRV perturbations from the assessment, but post-assessment HRV was greater amongst those who were coming on duty. HRV values continued to decline after assessment success amongst those that worked the night prior to training, potentially indicating greater stress loads in those that worked the overnight shift.

Chapter 9 further explored HRV changes observed in Chapter 8. The aim was to identify relationships between physical fitness as measured by completion time on a primarily anaerobic occupational obstacle course, and HRV response during firearms qualification and subsequent stress training. HRV was assessed as the within-operator change from pre- to post-qualification and post-training. HRV was reduced after training but not after qualification. A linear regression model indicated that obstacle course completion time predicted HRV changes from baseline to both post-qualification and post-training.

While stressful training and overnight shifts are regularly encountered in specialist police work, other tasks, such as serving in Directing Staff (DS) roles on selection courses for future candidates are also important duties and present as a nexus between operations and selection. Thus, Chapter 10 considered the critical operational role of DS cadre. The purpose of this study was to monitor and analyse the HRV of one DS member during their 24-hour shift on a candidate selection course. The findings of this case study suggested that DS may be subject to stress levels not unlike those of candidates. This is of note as selection courses are highly taxing and arduous, and officers may serve as DS on more than one course per year and still be required to perform their operational duties. DS requirements during selection courses should therefore be considered appropriately in the overall deployment and operational task scheduling paradigm.

Each previous chapter considered important elements of service in a specialist police organisation. The final chapter (Chapter 11) summated the findings from this programme of study, contextualised the works in terms of the bodies of literature with which they were most associated, and highlighted overall limitations as well as plausible future directions. A final supplementary chapter, aimed to provide an operational guide for utilising HRV data in tactical settings, contributed to further support translation of research to practice. In this supplementary chapter, shortcomings of using HRV were reviewed and solutions to avoid flawed analysis provided, as are the key lessons learned from this thesis. In essence, the presentation and visualisation of HRV data may be as critical to the application of HRV analysis as the measurements themselves in tactical settings.

Key words

Biosignals, Police, Stress, Occupational health, Data visualization, Training, Performance

Declaration By Author

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Doctor of Philosophy.

This thesis represents my own original work towards this research degree and contains no material that has previously been submitted for a degree or diploma at this University or any other institution, except where due acknowledgement is made.

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Date: 04 October 2023

Declaration of Author Contributions

Thesis research components by order of production:

Research Component	Est. Percent Contribution
Tomes, C., Schram, B., Orr, R.M. Relationships between Heart Rate Variability, Occupational Performance, and Fitness for Tactical Personnel: A Systematic Review, *Frontiers in Public Health.* 2020	CT 85% BS 7% RO 8%
Tomes C, Schram B, Orr R. Field Monitoring the Effects of Overnight Shift Work on Specialist Tactical Police Training with Heart Rate Variability Analysis. *Sustainability*. 2021 Jan;13(14):7895.	CT 70% BS 15% RO 15%
Tomes C, Schram B, Orr R. Applications of Heart Rate Variability Monitoring in Tactical Police Training. NSCA National Conference 2021	CT 75% BS 10% RO 15%
Tomes C, Schram B, Orr R. Part 1 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. *TSAC Report.* 2021	CT 75% BS 10% RO 15%
Tomes C, Schram B, Orr R. Part 2 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. *TSAC Report.* 2022	CT 75% BS 10% RO 15%
Tomes C, Schram B, Orr R. Part 3 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. *TSAC Report.* 2022	CT 75% BS 10% RO 15%
Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile Changes Associated with Sleep, Less-lethal Explosive Device Exposure, and Fear of Heights Training in Specialist Police Selection. *International Physical Employment Standards Conference.* 2023	CT: 65% EC: 20% BS: 7% RO: 8%
Tomes C, Canetti EFD, Schram B, Orr R. Incorporation of heart rate variability into police tactical group small unit tactics selection. *American Physiology Summit*. 2023	CT: 65% EC: 10% BS: 20%

	RO: 5%
Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage in Specialist Police Selection Training. *6th International Congress on Soldiers Physical Performance*. 2023	CT: 60% EC: 20% BS: 5% RO: 15%
Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile of a Specialist Police Selection Assessor. *6th International Congress on Soldiers Physical Performance*. 2023	CT: 65% EC: 15% BS: 5% RO: 15%
Tomes CD, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage Activities in Specialist Police Selection. *Healthcare*. 2023; 11(19):2677. https://doi.org/10.3390/healthcare11192677.	CT: 60% EC: 20% BS: 5% RO: 15%
Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile Changes Associated with Specialist Police Selection Activities: A Case Study. *WORK: A Journal of Prevention, Assessment & Rehabilitation.* 2023	CT: 65% EC: 20% BS: 7% RO: 8%
Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability is more Sensitive to Stress than Heart Rate in Specialist Police Undergoing Selection. *Bond University Tactical Research Unit Rapid Fire Mini Congress.* 2023.	CT: 55% EC: 25% BS: 5% RO: 15%

Research Outputs

Peer-reviewed Publications

- Tomes, C., Schram, B., Orr, R.M. (2020) Relationships between Heart Rate Variability, Occupational Performance, and Fitness for Tactical Personnel: A Systematic Review, Frontiers in Public Health
- Tomes C, Schram B, Orr R. Field Monitoring the Effects of Overnight Shift Work on Specialist Tactical Police Training with Heart Rate Variability Analysis. Sustainability. 2021 Jan;13(14):7895.
- Tomes C, Schram B, Orr R. Part 1 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. TSAC Report. 2021
- Tomes C, Schram B, Orr R. Part 2 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. TSAC Report. 2022
- Tomes C, Schram B, Orr R. Part 3 – Allostatic Load Theory: Principles for the Tactical Professional at home and on the Job. TSAC Report. 2022
- Tomes CD, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage Activities in Specialist Police Selection. *Healthcare*. 2023; 11(19):2677.
- Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile Changes Associated with Specialist Police Selection Activities: A Case Study. WORK: A Journal of Prevention, Assessment & Rehabilitation. 2023

Conference Presentations

- Tomes C, Schram B, Orr R. Effects of overnight shift work on psychophysiological stress in specialist police training. Virtual oral presentation at the Gold Coast Health Research, Quality, and Innovation Week. 16 – 19 November 2020, Queensland, Australia
- Tomes C, Schram B, Orr R. Applications of Heart Rate Variability Monitoring in Tactical Police Training. Poster presentation at the National Strength and Conditioning Association National Conference. 7 – 10 July 2021, Orlando, Florida, USA.

- Tomes C, Canetti E.F.D, Schram B, Orr R. Heart Rate Variability Profile Changes Associated with Sleep, Less-lethal Explosive Device Exposure, and Fear of Heights Training in Specialist Police Selection. Platform presentation at the International Physical Employment Standards Conference (IPES). 24 – 26 February 2023, Robina, Queensland, Australia
- Tomes C, Canetti E.F.D, Schram B, Orr R. Incorporation of heart rate variability into police tactical group small unit tactics selection. Poster presentation at the American Physiology Summit, 20 – 23 April 2023, Long Beach, California, USA
- Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage in Specialist Police Selection Training. Poster presentation at the 6th International Congress on Soldiers Physical Performance, 12 – 14 September 2023, London, UK
- Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile of a Specialist Police Selection Assessor. Poster presentation at the 6th International Congress on Soldiers Physical Performance, 12 – 14 September 2023, London, UK
- Heart Rate Variability is more Sensitive to Stress than Heart Rate in Specialist Police Undergoing Selection. Podium presentation at the Bond University Tactical Research Unit Rapid Fire Mini Congress, October 10, 2023, Robina, Queensland, Australia

Other Outlets

- Tomes C. Rhythm and Blues: Heart Rate Variability, Stress, and Police Officer Occupational Health. Three Minute Thesis. 2021. Available from https://vimeo.com/580503105

Ethics Declaration

The research associated with this thesis received ethics approval from the Bond University Human Research Ethics Committee. Ethics application numbers include 2019-022 amnd 2 and BS02165. This thesis also received ethics approval from the Messiah University Institutional Review Board. The ethics application number is 2019-022.

Copyright Declaration

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2. Tomes C, Schram B, Orr RM. Defining, measuring, and monitoring resilience for the tactical professional: Part 2-Allostatic load theory: Principles for the tactical professional at home and on the job. TSAC Report. 2022 (64):18-23.
3. Tomes C, Orr RM, Schram B. Applications of heart rate variability monitoring in tactical police training. Journal of Strength and Conditioning Research. 2021 Dec;35(12): e368-7. 10.1519/JSC.0000000000004141.
4. Tomes C, Schram B, Orr RM. Defining, measuring, and monitoring resilience for the tactical professional: Part 3- Heart Rate Variability Application Guide for Tactical Professionals. TSAC Report. 2022 (65):18-23.

Permissions are also cited in the preface of the relevant chapters within the thesis.

Chapter 1 contains the entirety of the peer-reviewed publication:
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Chapter 2 contains the entirety of the peer-reviewed publication: Tomes C, Schram B, Orr R. Relationships between heart rate variability, occupational performance, and fitness for tactical personnel: A systematic review. Frontiers in public health. 2020:729. https://doi.org/10.3389/fpubh.2020.583336 Made available under a Creative Commons CC BY 4.0 licence.

Chapter 4 contains the original content and supporting material of the accepted conference presentation: Heart Rate Variability is more Sensitive to Stress than Heart Rate in Specialist Police Undergoing Selection. Bond University Tactical Research Unit Rapid Fire Mini Congress 2023 October 10.

Chapter 5 contains the original content and supporting material of the presented conference abstract: Heart Rate Variability Assessment of Land Navigation and Load Carriage in Specialist Police Selection Training. 6th ICSPP 2023 September 12-14.

Chapter 5 also contains the original content and supporting material of the peer reviewed publication: Tomes CD, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage Activities in Specialist Police Selection. *Healthcare*. 2023; 11(19):2677. https://doi.org/10.3390/healthcare11192677. Made available under a Creative Commons CC BY 4.0 licence.

Chapter 6 contains the original content and supporting material of the published conference abstract: Tomes C, Canetti EF, Schram B, Orr RM. Heart Rate Variability Profile Changes Associated with Sleep, Less-lethal Explosive Device Exposure, and Fear of Heights Training in Specialist Police Selection. 4th International Physical Employment Standards Conference 2023 Feb 26. Available from https://research.bond.edu.au/en/publications/heart-rate-variability-profile-changes-associated-with-sleep-less

Chapter 6 also contains the original content and supporting material of the peer reviewed publication: Tomes C, Canetti EFD, Schram B, Orr R. Heart Rate Variability Profile Changes Associated with Specialist Police Selection Activities: A Case Study. WORK: A Journal of Prevention, Assessment & Rehabilitation. 2023
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Chapter 7 contains the original content and supporting material of the published conference abstract: APS Tomes C, Schram B, Canetti E, Orr R. Incorporation of heart rate variability into police tactical group small unit tactics selection. Physiology. 2023 May 23;38(S1):5763348. https://doi.org/10.1152/physiol.2023.38.S1.5763348. Available from https://journals.physiology.org/doi/abs/10.1152/physiol.2023.38.S1.5763348

Chapter 8 contains the entirety of the peer-reviewed publication: Tomes C, Schram B, Orr R. Field monitoring the effects of overnight shift work on specialist tactical police training with heart rate variability analysis. Sustainability. 2021 Jul 15;13(14):7895. https://doi.org/10.3390/su13147895 Made available under a Creative Commons CC BY 4.0 licence.

Chapter 9 contains the original content and supporting material of the published conference abstract: Tomes C, Orr RM, Schram B. Applications of heart rate variability monitoring in tactical police training. Journal of Strength and Conditioning Research. 2021 Dec;35(12): e368-7. 10.1519/JSC.0000000000004141. Reproduced with permission from the NSCA.

Chapter 10 contains the original content and supporting material of the presented conference abstract: Heart Rate Variability Profile of a Specialist Police Selection Assessor. 6th ICSPP 2023 September 12-14.

Chapter 12 contains the entirety of the peer-reviewed publication: Tomes C, Schram B, Orr RM. Defining, measuring, and monitoring resilience for the tactical professional: Part 3- Heart Rate Variability Application Guide for Tactical Professionals. TSAC Report. 2022 (65):18-23. Reproduced with permission from the NSCA.

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Acknowledgements

While no higher degree by research is a straightforward process for any student, I personally faced numerous challenges, not the least of which was more than a year spent separated from my supervisory team because of the COVID-19 pandemic. While it provided many opportunities to simply sit and write, which have become exceedingly scarce as time moves forward, the scientific and medical world temporarily ground to a halt as we knew them and focused on the more pressing and urgent needs at hand. My capacities as a Physical Therapist and researcher were both tested not only by the completion of this thesis, but also as a responder in what capacity I could to the pandemic. The accomplishment of completing this work and all the other critical work I have undertaken since beginning this process in 2019 would certainly not have been possible without the contributions of many friends, family, colleagues, and other supports in my home country of the United States, and of course, Australia. It goes without saying that I must firstly thank Dr. Robin Orr. Rob has been a mentor, role model, and friend since I first met him in 2016. Without Rob's guidance, I am not sure I would have found a direction after my undergraduate education, let alone pursued graduate education of any kind, least of all a PhD. Rob eased my transition from military to civilian life, and specifically helped me find a home in academia. It has truly been an honour to be a member of the TRU team. Rob's work is not alone though, and Dr. Ben Schram has also been an instrumental part of my educational journey. His sense of humour has yet to fail, even if my failures to detect his pithy sarcasm are in great abundance. Beyond this, Ben has often been a source of clarity when, in Rob's words, I tend to get 'twitchy' while writing a paper or sending off another abstract for presentation. Lastly, though certainly not least, is Dr. Elisa Canetti. Though she was not named to my committee of supervisors until later in my journey, she has been a considerable source of growth in my capacity as a researcher. This growth is frequently quite painful, though I imagine her regular and lengthy Zoom calls with me reviewing the finer details of data transformation and linear regression have been equally challenging for her at times. This thesis would also not have been possible without assistance from my alma mater, Messiah University, and specifically my mother, Cynthia Kerns, who got me going in my higher education journey, Dr. John Harms, Dr. Matthew Lewis, and Dr. David Foster. Not only have each of these people been valuable mentors when, what feels like ages ago I was an undergraduate student, but they also helped me springboard two early chapters of my thesis, connecting me with one of the host organizations that contributed to multiple research studies and products. I am most grateful for their time and hospitality and for mom's constant encouragement to keep going. This acknowledgement would also be thoroughly incomplete without thanks to the unit commander, training supervisor, and many other members and candidates of the Australian State Police Tactical Group that also contributed substantially to this work. Their engagement with the research process and genuine interest in the following research products was encouraging as a student. I am grateful to have been able to contribute something of value to their mission. Throughout this process I have also been growing as an educator and budding professor of Health Science at Moravian University. The flexibility, support, encouragement, and contribution of resources from my colleagues at Moravian have also been critical along this journey. I can imagine the only people more eager for me to graduate would be the Dean and Provost under which I am currently working. I would like to conclude this acknowledgement and dedicate this thesis work to my incredible wife Madi. I cannot imagine another person would dare to travel across the world to get married between rounds of data collection. While I suppose she knew what she was getting into by agreeing to my proposal at the International Congress on Soldiers' Physical Performance in February of 2020 in Canada, she nonetheless has stayed the course with me throughout this journey and has been my rock since we met. Her feedback, support, and unending love sustain me through my greatest challenges.

P.S.: To my grandfather, Louis, "Papa Luigi" Tomes: thank you for showing us all over so many years how to live for others and support our community in any way we can. Whether through military service, building and maintaining essential services, or painting homes for those in need, you taught me through your example that there is always more work to be done in the world. Without inheriting your stubborn commitment to hard work, I don't think I could have come this far. Most of all though, thank you for your sense of humour. Your dry jokes always lit up whatever room you were in until the very end. While I am deeply pained that I could not share my own hardest work with you before you passed from this life, I am glad to at least have finished the first draft while you were still here. I know and believe that you are still watching over me and pushing me towards the next challenge ahead.

COVID-19 Statement

This thesis research initially began as a collaborative effort between the Bond University Tactical Research Unit and my undergraduate alma mater, Messiah University. Through connection with my undergraduate mentors, I collected data and planned for further research with a specialist police team on the East Cost of the United States. However, not long after this initial data collection, several civil disturbances resulted in the operational tempo for this team increasing beyond the extent to which they would be able to host research efforts. When initial lockdowns began in early 2020, this further impaired research efforts with this team. Economic pressures resulted in my relocation and provided me both the challenge and opportunity to work from home during the extended lockdowns serving as an English language editor for a number of peer-reviewed journals. This included an early physical rehabilitation protocol for COVID-19 pulmonary rehab. While restrictions eased in the US by early 2021, Australian border restrictions remained in place until late 2021, prohibiting my entry to the country and return to data collection activities. Thankfully, and with much effort on behalf of Bond University's leadership, I was able to return to Bond in early 2022. This allowed me to conduct research with an Australian State Police Agency. However, the effects of COVID-19 were still being realized, first by interstate travel challenges, then attrition of study participants and local civil disturbances. Furthermore, the effects of long COVID specifically (and COVID-19 more generally) are still not well understood. The lasting impacts of even asymptomatic COVID on the cardiovascular and neurovascular systems may influence heart rate variability analysis and represent an unprecedented confounder in this research. Certainly, there is much more that needs to be understood surrounding how front-line personnel, such as law enforcement officers, have been affected by COVID-19.

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Abbreviations

Autonomic Nervous System	ANS
All Normal Sinus to Normal Sinus Interbeat Intervals	AVNN
Body Mass Index	BMI
Blood Oxygen Saturation	BOS
Bond University Human Research Ethics Committee	BUHREC
Critical Appraisal Skills Programme	CASP
Cumulative Index to Nursing and Allied Health Literature	CINAHL
Cardiorespiratory Fitness	CRF
Competitive Reaction Time Task	CRTT
Competitive State Anxiety Inventory	CSAI-2R
Directional Staff	DS
Defense Technical Information Center	DTIC
Electrocardiography	ECG
Estimated Energy Expenditure	EE
Functional Magnetic Resonance Imaging	fMRI
Gamma Aminobutyric Acid	GABA
High Frequency	HF
Higher Performing Group	HPG
Human Performance Optimisation	HPO
Heart Rate	HR
Heart Rate Variability	HRV
International Congress on Soldiers Physical Performance	ICSPP
Intermittent Fitness Test	IFT
Load Carriage	LC
Low Frequency	LF
Natural Logarithm	Ln
Logarithm Base-10	Log10
Lower Performing Group	LPG
Multidisciplinary Digital Publishing Institute	MDPI
Metabolic Equivalent	MET
Multistage Fitness Test	MSFT

North Atlantic Treaty Organisation	NATO
N-N interval	NNI
National Strength and Conditioning Association	NSCA
Normalised Unit	Nu
Doctor of Philosophy	PhD
Patient, Intervention, Control, Outcome	PICO
Percentage of interbeat intervals varying by more than 20 ms	pNN20
Percentage of interbeat intervals varying by more than 50 ms	pNN50
Parasympathetic Nervous System	PNS
Personal Protective Clothing	PPC
Photo Plethysmograph	PPG
Preferred Reporting Items for Systematic Reviews and Meta-Analyses	PRISMA
Perceived Stress Scale	PSS
Police Tactical Group	PTG
Post-traumatic stress disorder	PTSD
Percentage of interbeat intervals varying by more than 50 ms	pRR50
Percentage of interbeat intervals varying by more than 15 ms	pRR15
Percentage of interbeat intervals varying by more than X ms	pRRx
Relative Energy Deficiency in Sport	RED-S
Rating of Perceived Exertion	RPE
R Wave to R Wave Interval	R-R, RRI
Root-Mean Square of Successive Differences	RMSSD
Smith and Wesson	S&W
Selection Course	SC
Self-Contained Breathing Apparatus	SCBA
Geometric Standard Deviation 1 (X-axis)	SD1
Geometric Standard Deviation 2 (Y-axis)	SD2

Standard Deviation of R-R or N-N Intervals	SDNN, SDRR
Special Emergency Response Team	SERT
Sympathetic Nervous System	SNS
Total Power	TP
Tactical Strength and Conditioning	TSAC
Tactical Strength and Conditioning Facilitator	TSAC-F
Tactical Research Unit	TRU
Trier Social Stress Test	TSST
Very Low Frequency	VLF
Maximal Oxygen Consumption	$VO2_{max}$
United Kingdom	UK
United States	US

Chapter 1 – Who are tactical personnel and what is Heart Rate Variability (HRV)?

1.1 Preface

The aim of this chapter is to introduce Heart Rate Variability (HRV) concepts in tactical contexts. Specific examples are highlighted across professions to illustrate the components of tactical work and lifestyles that may be best appreciated with HRV analysis. The scope, role and importance of tactical professionals are thoroughly described, as is the theory and principles of HRV measurement. However, the integration of HRV into tactical workflows, especially at the end-user level, has received less attention. Therefore, the following aims to introduce the reader and end-user to essential concepts in both domains.

This chapter contains content adapted for publication in the 'TSAC Report'. The citations are as follows:

Tomes C, Schram B, Orr RM. Defining, measuring, and monitoring resilience for the tactical professional: Part 1-Allostatic load theory: Principles for the tactical professional at home and on the job. TSAC Report. 2021 (63):4-8. Reproduced with permission from the NSCA.

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Note: Formatting, introductory, and other minor content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

1.2 Part 1: Background

1.2.1 The Tactical Professional

Tactical personnel may be described as any individuals who have sworn to protect and serve their communities, and who may enter into harm's way for those purposes [1]. Professions included in this population have historically included military, fire and rescue, and law enforcement personnel but have developed more recently to include, prehospital emergency medical services personnel and other first responder groups [2]. These individuals are called upon regularly to face a multitude of physical and psychological challenges [2]. For example, military personnel typically must travel great distances to areas of operations, participate in war efforts, but also support civilians and develop local infrastructure in many cases [3]. Firefighting personnel are expected to save lives and protect property through fire suppression activities but are often also called to motor vehicle collisions and hazardous material incidents [4,5]. Prehospital emergency medicine providers also work in highly dynamic and increasingly risky environments, where their own safety is increasingly in jeopardy [6]. Law enforcement personnel perform an equally wide range of services, from pursuing and arresting offenders to responding to medical emergencies and natural disasters as well as civic engagements, search and rescue, and other tasks [7,8]. In Australia alone, there are over 80,000 full-time emergency workers. In 2021-22, there were 24,642 State Emergency Service (STES) volunteers and 879 paid staff. Additionally, each state and territory in Australia has its own State (or Territory) Emergency Service, with approximately 43,000 volunteers distributed throughout the country [9].

1.3 Mission Profiles by Profession

1.3.1 Introduction

While all tactical organisations are unique, tailoring their services to meet the geographical and demographic needs of their communities, most can generally be categorised into one of three main mission profiles. The mission profile dictates the types and frequencies of operations, the risks personnel may reasonably expect to encounter during operations, and level and intensity of required training. Many of these organisations will also have subspecialist teams with further training and more advanced capabilities. Personnel are developed along a continuum to achieve these goals, beginning with initial entry, or *ab initio*, training [10]. The primary objective of initial entry training is typically to provide essential skills for success and survival in the operating environment, with heavy emphasis on physical training and assessing trainee suitability for the profession [11]. Once personnel are sufficiently trained to participate in operations, ongoing training aims to provide higher-levels skills, enhanced competencies, and leadership [12]. Finally, personnel may attain specialist-level training, which will often combine the high-intensity physical elements and stress of initial entry training with high level technical skill acquisition and testing [13]. These personnel are then equipped to handle the most extreme mission scenarios within the organisation, and can in turn effectively train others [12,14].

1.3.1.1 Military

The modern military is characterised by technological innovation and a wide operational scope, beyond engagement in armed conflict [3]. While historically military personnel have been trained to engage in warfighting efforts with opposing nations [15], recent shifts in military operations towards those other than war have resulted in substantial occupational changes for the individual servicemember. Concepts such as "cyber" and "kinetic" personnel have evolved to help delineate between those who operate primarily from behind a computer or other technical equipment and those who engage in more traditional ground operations [16]. Regardless of assignment, all military personnel are expected to be able to engage in warfighting activities, which include heavy load carriage and the performance of relatively short, but high-intensity tasks in life threatening scenarios that define modern military engagements [17].

1.3.1.2 Fire and Rescue

Firefighting and rescue personnel perform physically demanding work across a wide scope of geographical and environmental theatres of operations [18,19]. In general, firefighting and rescue personnel suppress fires, rescue individuals, and conserve property in structures, vehicles, aircraft, and wherever else needed [20]. Firefighters may also be dispatched to conserve woodlands, forests, grasslands, brush, and other wildlands threatened by fire [21]. Fire and rescue personnel must wear and carry personal protective equipment intended to protect them from dangerous environmental exposures while also carrying and utilising fire suppression equipment [19,22]. These personnel are also subject to rotating shift work [23], unpredictable and dangerous environments [24], as well as elevated levels of cardiac disease beyond those normally encountered in the general population; In the United States, cardiovascular disease prevalence in the general population is around 48%[25], whereas 68% of firefighters have two or more risk factors [26-28].

While not all regions operate combined fire suppression and emergency prehospital care, the two professions often work cooperatively. Exposure to hostile persons has become an increasingly frequent danger, experienced primarily by prehospital workers [6]. The incidence of these threats have been recognised only recently, with the first academic publication on the topic not published until 1993 [29]. While scientific understanding of the impact of violence against emergency medical services personnel remains limited, the effect on operational personnel continues to be an important area of consideration when evaluating the occupational health and performance of personnel [30].

1.3.1.3 Law Enforcement

The duty of law enforcement personnel is primarily to enforce the laws of the jurisdiction and promote public safety, not only by engaging against criminal activity, but also by protecting and serving communities as first responders to other emergencies [2]. As such, police work is highly complex, extraordinarily unpredictable and can encompass a great variety of occupational demands [7]. General duties officers, only one of many discrete police professional roles, must check bona fides (pursuit of possible offenders), respond to domestic incidents, serve defective vehicle notices, drive urgently, attend noise complaints, and investigate persons on premises (possible trespassers), sometimes all within a single shift [7]. Additionally, as with firefighters and emergency prehospital medical workers, these shifts frequently rotate between day and night and can last up to 12 hours [31]. Officers must complete these tasks while wearing personal protective equipment and while utilising all equipment necessary to complete any of a wide range of tasks [32,33]. These loads can often exceed 20kg, with specialist officers often equipping more (generally around 8kg) [34,35]. Regardless of role, all police personnel are subject to environmental hazards, and change or reassignment of job duties in addition to the unpredictable nature of police work in the community [36-38]. Further, rigors are not even limited to on-duty time; personnel must also train regularly to maintain proficiency in critical skills outside of work hours. This training must be sufficiently intense enough to provide fidelity and translation to real-world scenarios but cannot place the ability of participants to function on duty at excessive risk.

The challenges in maintaining this dynamic balance between training, operations, and organisational demand are clearly manifested in Special Emergency Response Teams (SERT) or Police Tactical Groups (PTGs). These units respond to the most high-risk incidents and may utilise equipment and procedures that differ from conventional police work, requiring exceptional fitness levels and frequent exposure to high stress scenarios [35,39]. In addition, these officers often volunteer to join SERTs or PTGs as a collateral duty in addition to their regular police work, further extending their time on duty, loads carried, time spent in training, and administrative work [40].

1.3.1.4 Mission Profile Summary

As a result of the breadth and intensity of demands in tactical professions, the physical and mental health of these personnel are regularly pushed to extremes, regardless of specific role within an organisation. Such extremes may include rigorous physical training, irregular work hours, prolonged shifts, heavy occupational loads, and extensive psychosocial stressors associated with emergencies such as armed conflict, natural disasters, and motor vehicle collisions. While each domain of public safety operates under unique demands and requirements, models of care that can provide for these personnel are urgently needed. To meet this need, human performance optimisation (HPO) systems of care and performance have emerged [41,42].

1.4 The Tactical HPO

To maximise health, fitness, and operational outcomes of tactical personnel, especially specialist personnel, substantial research and clinical efforts have been undertaken with the aim of enhanced understanding and translation of that knowledge to practice. The continuum from theory to application and cooperation of operational personnel, clinical, and scientific efforts has evolved into the current tactical HPO model [41,43]. As above, the tactical HPO seeks to integrate theory, research, practice, and application, utilising the best available evidence, organisational needs, and preferences, as well as the expertise of a comprehensive team of health and human performance providers to maximise the human potential of each tactical trainee or operative.

While much of the progress in tactical HPO has drawn from elite athletic models of performance and care, the strategies and operating environments of sport and public safety are fundamentally different, and as such, methods effective in sport will not always effectively serve tactical personnel. For example, tactical personnel do not always know when their skills and service will be called upon, whereas athletes are typically aware of their competitive schedules years in advance [2]. Athletic attire has also been developed to maximise sport performance, whereas tactical personnel must be equipped to face a threat; this may include protection from weapons but may also include protection from the environment in terms of heat, cold, or toxic exposure [15]. Tactical personnel must also be prepared to operate with a scarcity of resources, which may then require the carriage of large amounts of additional weight to accomplish their tasks while staying as safe as possible [44,45]. All tactical environments are subject to rapid and unpredictable changes, rotating shift work, and opposition that will engage with asymmetrical, unconventional, or non-commensurate force. Threats may not even be human; fire, natural disaster, destruction from acts of terrorism, and accidents may all be as likely as any other mission threat [2]. Additionally, many tactical organisations must operate with limited organisational resources, not only for maintaining personnel health and wellness, but for their mission profiles, and for personnel, resulting in limited opportunities for recovery [46]. Finally, for tactical personnel, losses are measured not in points, scores, games or rounds, but in wounds and fatalities [47]. While the stakes are high, success may often simply be measured by returning home safely after the shift, deployment, or expedition.

However, many methods and technologies from sport and exercise science contexts have proven invaluable when implemented in tactical settings. For example, injury prevention programs employing multidisciplinary teams of sports medicine professionals have revolutionised many tactical training programs and improved outcomes for some of the most rigorous and elite units in the world [43,48,49]. As these teams continue to develop, the role of technological instruments to provide more data on the individual to further understand the challenges faced during training, active service, or on operations as well as to monitor their health and fitness continues to grow. Wearable technology has become commonplace in many elite sport organisations, allowing for the sports medicine team to obtain large amounts of data on players to inform their clinical and training decisions [50].

Heart rate variability (HRV), first pioneered in the cardiac hospital setting [51], is now being utilised by athletes and tactical personnel through wearable technology to inform health and performance optimisation teams [52]. Advances in measuring, analysing, interpreting, and applying HRV continue to be made in many settings [53,54], including tactical environments, where comprehensive and objective measures of holistic load are especially valuable [55]. Military, fire and rescue, and law enforcement agencies are now able to actively participate not only in improving the health and performance of their members, but also in pushing these scientific boundaries.

1.5 Part 2: Holistic Assessment

Providing optimal personnel support that considers allostatic load as an important variable influencing health and performance begins with obtaining the information needed to take data-driven and evidence-based action, whether HRV is considered or not [56-58]. Regardless of which tools or methods are used to obtain data, a scientifically valid, repeatable, reliable, and methodologically robust approach that integrates 1) the best available research, 2) the expertise of key support personnel, and 3) the needs and preferences of individual operators forms the basis of evidence-based practice [59,60]. This practice has been validated in sport and exercise science as the optimal approach for maximising health and performance in demanding settings [61-63]. However, while athletic pursuits are typically well controlled, account for the environment, and prioritise the needs of the athlete, tactical personnel are subject to unpredictable scenarios in austere environments that are often highly hazardous [2,41]. This endemic chaos establishes the critical need for evaluating personnel across as many domains as possible to provide a knowledge basis from which to build on safety, health, and performance outcomes. This multifaceted objective must often be accomplished with limited resources [64].

1.5.1 The Autonomic Nervous System

With these challenges in mind, cardiac rhythm may be an ideal starting point for such an integrative analysis. Not only is heart rate used to establish the most basic and essential levels of health in clinical settings, it is also one of the oldest and most common means of measuring exertion and conditioning status [65]. Heart rate has been used independently, and in combination with subjective ratings, to monitor exercise intensity for generations [66]. Heart rate also fluctuates with emotional responses and cognitive rigor, providing further utility for measurement and analysis [67,68]. Whether activity is occurring in training or on operations, understanding how exertion is imparted on personnel both in the moment and over time is a key component of ensuring maximum health, safety, and performance.

Cardiac contractions are under constantly varying regulation from both intrinsic and extrinsic influences, thus there is much more to measuring cardiac activity than quantity of beats over a unit of time [68,69]. While many factors such as certain medications, alcohol, tobacco, and caffeine (discussed further in 12.2.6 Important confounding variables), much of heart rate regulation is modulated by the two complimentary branches of the primary autonomic nervous system: the sympathetic (SNS) and parasympathetic nervous systems (PNS) [69,70]. The autonomic nervous system is the efferent, or outgoing, branch of the peripheral nervous system responsible for regulating most unconscious bodily activities: respiration, distribution of blood flow, digestion, pupillary response, waste excretion, arousal, and heart rate [70]. The SNS originates from the thoracic and upper lumbar vertebrae, and governs responses that require immediate action, such as the "fight, flight, or freeze" response to acute stress [71]. The PNS, located craniocaudally, or above and below the anatomical location of the SNS, is characterised as a more slow-moving, dampening response, and governs actions that do not typically require immediate action. It is sometimes referred to as the "rest and digest" or "feed and breed" response [70]. However, these systems should not be thought of as discrete or strictly antagonistic to each other. For example, while the SNS can suppress PNS activity, during cooldown after intense exercise, the PNS will gradually reactivate without any corresponding changes in SNS activity [72].

1.5.2 Cardiac and Autonomic Interactions

The SNS will act primarily to increase heart rate and cause a subsequent decrease in the variation in time between beats (R to R intervals, or RRI). This is accomplished not only through direct innervation, in which the heart musculature itself is stimulated to contract more quickly and more forcefully, but also through catecholamine activity at the adrenal glands. This is known as a "surge of adrenaline" experienced during high-threat activity [71]. Conversely, the PNS regulates the heart primarily through the vagus nerve. It does this by slowing conduction at the sinoatrial node of the heart and contributing to respiratory sinus arrhythmia, the natural increase in heart rate during inspiration and consequent decrease that occurs during expiration [73].

The physiology of this dual innervation at the heart has been long supported by laboratory research. Most notably through the double-blockade experiment in which atropine, an anticholinergic drug that blocks PNS activity via competitive antagonism at acetylcholine sites, and propranolol, a beta blocker drug which blocks SNS competitive activity via competitive antagonism at catecholamine (epinephrine and norepinephrine) sites are simultaneously administered (Figure 1) [72]. It might be expected that the two medications would nullify the effects of their antagonist and heart rate would remain the same. However, participants in these experiments show a mildly elevated heart rate above their normal resting rhythm [74]. This result would imply that the parasympathetic nervous system is typically continuously active in a healthy individual, modulating heart rate primarily through the above-mentioned respiratory sinus arrythmia and inhibiting or predominating over sympathetic activity during most situations.

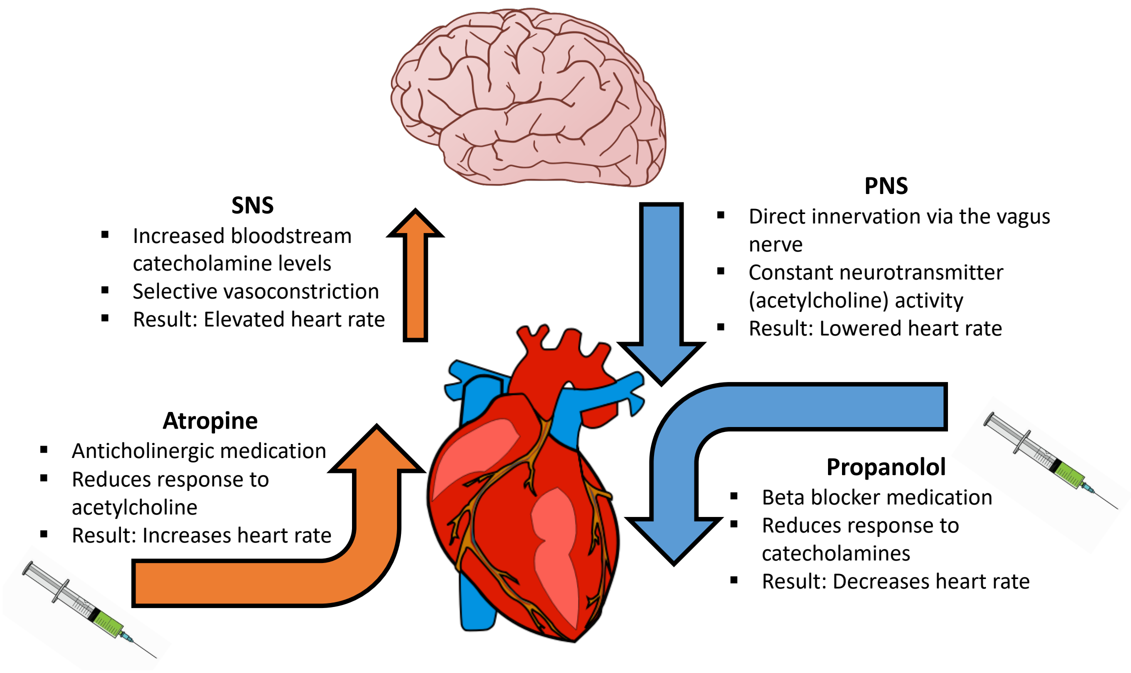

Figure 1. Visual Diagram of the Double Blockade Experiment

It is therefore widely accepted that the heart is typically under consistent inhibitory control by parasympathetic action [68]. Further, a typical series of heartbeats over time is characterised by high levels of variability, also implicating vagal (PNS) dominance. Sympathetic influence on the heart is not sufficiently rapid enough to produce such immediate beat to beat changes [68]. This is due in large part to the relatively slower actions of catecholamines, such as norepinephrine and epinephrine. Norepinephrine plays a greater role the modulation of blood vessel activity while epinephrine is the primary regulator of cardiac activity.

When measuring heart rate variability for performance maximisation, a “zero sum” balance within the autonomic nervous system should not be expected or desired. Rather, constant fluctuations in cardiac activity when measured over a sufficient length of time indicate a responsive and adaptive regulatory environment. While necessary to maintain health in all individuals, this adaptive reserve is especially necessary for professionals shifting effectively between high-intensity on-duty tasks that rely on the sympathetic response and recovery and relaxation when off duty that requires sufficient parasympathetic action [75]. It is the dysregulation of this dynamic relationship between the SNS, PNS, and other factors influencing cardiac regulation that are therefore thought to signal insufficient allostatic load [76]. In a tactical context, excessive stress imposed by an irregular work schedule, insufficient occupational support, physical exertion, poor diet, and psychosocial conflict on the job and at home may manifest in an overwhelmed tactical professional. This may, in turn, lead to a chronic undampened stress response or withdrawal of sufficient parasympathetic influence. The individual's heart rate when observed over time becomes chronically elevated and no longer displays adaptive modulation, even at rest, due to loss of the more precise influences thought to be driven primarily by parasympathetic action [77]. While visible when HRV analysis is undertaken, the individual may not yet display any otherwise notable signs or symptoms of a disease or injury [75,78]. However, they may be more susceptible to their development, as the ability to repair, recover, and improve relies on the balance and responsiveness of the autonomic nervous system [79].

1.6 Heart Rate Variability

Close analysis of these changes in cardiac regulation by monitoring HRV may provide substantial insight into psychophysiological responses to stress imposed from physical exertion or other demands, such as aforementioned psychological, social, or environmental stressors [53,78,80]. In general, the computational goal of heart rate variability analysis is to assess the stability or instability of various increasing or decreasing trends in heart rate. Much like daily temperature generally increases throughout the day and then decreases at night, and also more broadly increases in the summer and decreases in the winter, fluctuations in heart rate can also be observed and appreciated over both brief and lengthy windows. These patterns can be examined with respect to time, frequency, and nonlinear descriptions, which will be discussed in more depth in 1.8.1 HRV Analysis – Technical Overview. Based on the qualities of the pattern of interest, the physiological governing mechanism can be estimated – typically a signal is attributed to either the parasympathetic nervous system, sympathetic nervous system, or a combination of the two. HRV was first identified as an important clinical feature in the 1960s, when the physicians Hon and Lee determined that foetal distress was first signalled by fluctuations in inter-beat intervals [81], before appreciable changes in overall foetal or maternal condition occurred [82]. As such, from this initial discovery, HRV has since been applied in a wide range of clinical settings and has emerged as an imminently valuable tool for monitoring changes in cardiac regulation [51,52,69,83], as well as the consequent relationships between those influences, health, and human performance [36,53,54]. While tactical personnel and foetuses may at first seem to have little in common, both may be inaccessible by conventional laboratory measurements, and so a measurement that can be obtained noninvasively and without expensive equipment or time and resource intensive procedures can be of great advantage. For the purposes of measuring holistic stress response, HRV holds advantages over other approaches, such as stress neuroimaging [68]. This is because HRV can be measured noninvasively and can be interpreted computationally, reducing time and financial costs associated with traditional biological laboratory analyses [84,85].

1.7 Practical Applications

Essentially, HRV analysis can be deployed at fire departments, police stations and military barracks and forward operating areas where other clinical tools may not be feasibly integrated to provide information valuable to tactical professionals and their support teams across their careers [75]. These advantages in measurement, assessment, and ease of use can be leveraged without sacrificing precision.

For example, oxidative stress, the chemical common denominator in many chronic diseases including heart disease [86], may be measured in the lab by studying bloodstream levels of the compound 8-iso-PGF2α [87]. Individuals with a higher concentrations of this compound, and therefore a greater oxidative stress burden will have reduced HRV when measured either at night or in the morning ($r^2 = 0.699$, $p = 0.027$), despite the contribution of other factors to HRV [87]. Further, evidence supports low HRV as a predictor of impaired recovery of cardiovascular, endocrine, and immune markers following a stressful event [88], and that HRV may serve as a global index of flexibility and adaptability to stress scenarios [57]. HRV analysis can also signal important changes that have occurred in endocrine function, such as testosterone depletion, during periods of intense training over an extended period, not unlike those encountered during selection courses [77,89]. Likewise, HRV is sensitive enough to monitor the effects of shift work on performance and demonstrates that overnight shifts can affect cardiac regulation for as long as three days afterwards, even in experienced personnel [90,91]. Other high-intensity settings, largely in elite athletics, have demonstrated the utility of HRV in calibrating training loads [53,54,92].

Additionally, correlations between HRV and cardiorespiratory fitness specific to the tactical setting [93] and psychological stress [23,68,83] have been described. Further, HRV can also provide valuable insight into responses during extreme stress situations, such as awareness and regulation before, during, and after a firefight [94,95]. HRV may also affect motor control resiliency required to execute mission essential tasks, such as the manipulation of firearms [96,97]. Therefore, HRV may be considered as a plausible, non-invasive, and readily adapted indicator of psychological resilience [57,75].

1.8 HRV Analysis – Practical Overview

At the most essential level, HRV is the computational model for the complex, integrated, and holistic psychophysiological responses that occur when the time between consecutive heart beats, also known as beat-to-beat or inter-beat-intervals (IBI) is modulated by one or more influencing factors [69]. As described above in 1.5.2 Cardiac and Autonomic Interactions, these factors range from basic survival purposes and resting regulation (respiratory sinus arrythmia, circadian rhythm, among others), to the dynamic effects of mental and physical stress, exercise, and the cumulative biopsychosocial demands that contribute to allostatic load [56].

With recent technological developments, HRV data are now available and interpretable by coaches and individuals, and while careful interpretation is necessary, specialist appointments to read or understand results are no longer necessarily required to obtain actionable information [50]. Relationships between HRV measurements and process or outcome measures are allowing for readily accessible insights to valuable health and fitness data [52,98] and have been associated with the prediction of morbidity for a wide variety of chronic and acute disorders [55].

1.8.1 HRV Analysis – Technical Overview

The variety of mathematical strategies and data approaches to HRV may initially seem overwhelming but can generally be categorised into the following: frequency domain, time domain and nonlinear domain analyses. The roles and applications of each assessment technique are summarised in Table 1.

Table 1. HRV Measurements, Applications, and Interpretations.

Measurement	Units	Definition	Application	Interpretation
RMSSD	ms	Root-mean square of successive differences	Primary measurement for short term PNS assessment	Values generally increase with cardiovascular fitness[69]. Decreasing trends in time-domain components over repeated measurements may indicate failure to adapt[75]
pNN20	%	Percentage of adjacent intervals that differ by *more than* 20ms	Assessment of PNS Possible disease marker	
pNN50	%	Percentage of adjacent intervals that differ by *more than* 50ms		
SDNN (SDRR)	ms	Standard deviation of all interbeat intervals during the sample timeframe	Accepted cardiovascular disease risk assessment if recorded over 24 hours or longer	
LF	ms^2	Low-frequency power band (0.04 – 0.15Hz)	Baroreceptor activity Combined SNS and PNS activity	Increased LF values may indicate failure to adapt[75]
HF	ms^2	High-frequency power band (0.15 – 0.4Hz)	PNS and respiratory activity Cognitive and emotional response	Decreased HF values are associated with high stress[99]

			depending on measurement conditions	
TP	ms^2	Total power; summation of all frequency bands	General autonomic activity	Decreased TP may indicate failure to adapt[75]
SD1	ms	Standard deviation with the respect to the y-axis on Poincare plot	Nonlinear short term detrended assessment	Surrogate for RMSSD, pNN50 or SDNN when recordings contain noise or other flaws[100]
SD2	ms	Standard deviation with respect to the x-axis on Poincare plot	Nonlinear long term detrended assessment	Surrogate for LF power when recordings contain noise or other flaws[69]

In general, the computational goal of HRV analysis is to assess the stability or instability of various increasing or decreasing trends in heart rate. Much like daily temperature generally increases throughout the day and then decreases at night, but also more broadly increases in the summer and decreases in the winter, fluctuations in heart rate can also be observed and appreciated over both brief and lengthy windows. The patterns can be decomposed into time, frequency, and nonlinear descriptions. Based on the qualities of the pattern of interest, the physiological governing mechanism can be estimated – typically a signal is attributed to either the parasympathetic nervous system, sympathetic nervous system, or a combination of the two. As previously described, a balance and exchange between the SNS and PNS is ideal. Therefore, when personnel are healthy, adapting to challenges effectively, and managing the multifactorial stress influences in their lives and careers, the systems that create HRV patterns are stable and produce consistent oscillations. A failure to adapt, insufficient stress management capacity, injury, disease, or another source of allostatic load results in deviations from these patterns.

However, the precise manifestation of these systems and patterns is highly variable from individual to individual, and so the most effective strategy for detecting a problem is by comparing an individual today against their historical measurements; a 28-day rolling average is advised in the literature as the most precise and practical period for measurement comparison [75], but this is not always possible. Shorter measurements may still provide value, but must be interpreted with more caution [101]. When a tactical team member displays a marked change in one or more specific HRV measurements (Table 1) begins to demonstrate a trend that is not correcting, exhibits a large change in HRV between their initial and final values surrounding a rigorous event, or otherwise fails to return to an established baseline, the HPO team may be alerted for possible intervention [55,90]. This should be conducted in consideration of possible confounding factors, such as genetics [102], medications, caffeine [103], alcohol [104], tobacco [105], and even environmental variability including noise, pollution, and temperature [106]. These are discussed further in 12.2.6 Important confounding variables.

1.8.1.1 Summary of frequency-domain heart rate variability analysis

With respect to specifics of the analytical methods, the frequency domain aims to illustrate how much each cycle of increasing or decreasing heart rate lies within each established frequency band over a range of frequencies. The frequencies most typically encountered in HRV analysis are the very low (0.0033–0.04 Hz), low (0.04 – 0.15 Hz), and high frequency (0.15-0.4 Hz) bands [51,69]. LF power accounts for both SNS and PNS activity [72,107]. Baroreceptors, nerve endings found in the linings of arteries responsible in part for regulating blood pressure, and intrinsic cardiac ganglia also contribute to the LF component [108,109]. As a result of the multitude of influences on LF HRV, it may not be a suitable metric for determining if personnel are experiencing excessive holistic stress [55,75].

The HF power band however, a faster oscillatory period, much more directly reflects parasympathetic activity because the PNS generally functions over shorter timeframes than the SNS [68]. Respiratory and cognitive demands, as well as emotion can also contribute to HF HRV [68,73,95,110]. Decreased contribution of HF to the total spectrum of power observed in a recording may effectively indicate to the HPO team that an individual is at risk of overexertion, insufficient recovery, or impaired occupational performance; either psychosocial or physical [52].

Other bands exist but are generally not of interest in tactical human performance. Each component is associated with particular functional elements of autonomic nervous system (ANS) activity based on how fast or slow the influence occurs. However, the two main branches, the SNS and PNS, can overlap in terms of signal production, and the complexities of cardiac autonomic function are not limited to only SNS and PNS activity. Therefore, inferring autonomic function from the frequency domain alone requires careful consideration, and decisions regarding health, performance, or occupation should be in consideration of not only additional HRV measurements, but also additional subjective and objective data.

1.8.1.2 Summary of time domain heart rate variability analysis

Time domain is generally less complex than frequency domain but can still reveal critical information unavailable with the simple assessment of heart rate. The variability within a given time frame can provide insight as to which branch of the autonomic nervous system is more predominant; as explained in 1.5.1 The Autonomic Nervous System, the heart is dually innervated – both the SNS and PNS are active simultaneously, but because different neurobiological pathways are utilised by each system, the resulting effect on the heart of each branch will unfold over different timespans [74]. This can be reflected and measured in time domain HRV analysis. Two common approaches are the standard deviation of the N-N intervals (SDNN), a simple approach familiar to anyone with a background in statistics, and the root mean square of the differences in adjacent N-N intervals (RMSSD). The RMSSD utilises the absolute value of differences in time between adjacent heartbeats [69].

Other metrics, such as cut-off thresholds over a full sample, such as the percentage of total intervals that vary by more than 12, 20 or 50ms can also serve as approachable metrics [111,112]. These are the pRR or pNN intervals established in epidemiological research [112,113]. Personnel with values below reference ranges, for example under 3% for pRR50 [111,114], can be rapidly identified flagged for quick evaluation prior to training, active service, or operations [90]. While nonspecific, these strategies may allow for an opportunity for support teams to start conversations with particularly stoic individuals.

1.8.1.3 Summary of nonlinear heart rate variability analysis

The nonlinear domain of assessment may be the least thoroughly explored but shows particular promise for the tactical community because it is an especially robust approach that can yield valuable information, even from shorter or noisy samples [69,100]. For example, data which may be collected in a rush or with the confounding influence of protective equipment and load carriage that may interfere with equipment remain suitable for these analyses. The Poincare SD1 and SD2 are highlighted examples of nonlinear analytical methods. Poincare plots simply map the first RR interval on the x-axis against the difference relative to the next interval on the y-axis to yield a geometric analysis of HRV [115]. The standard deviations are the width and height of the general elliptical shape that is produced and correspond to short term (SD1) and long term (SD2) variability. The time windows generally considered are 1 to 5 minutes for short-term and 24 hours for long-term. SD1 correlates closely with HF and total power and can therefore serve many of the same applications mentioned above when traditional frequency domain analyses are confounded.

1.8.1.3 Monitoring strategies – time windows

The time windows typical in HRV research are usually designated long term (>10mins to 24 hours), short term (1-2 mins to 5 mins) and ultra-short term (10-30 seconds) recording windows [69]. Twenty-four hour recordings obtained from an ECG (generally between two and 12 leads) are generally considered the gold standard measurement as they allow for the most precise, accurate, and noiseless measurement of HRV [51]; both the longest, circadian oscillations, and shortest, respiratory sinus arrythmia oscillations, are observed. However, depending on the desired objective, shorter recordings of at least 5 minutes may still be sufficiently robust, and are generally more practically achieved in a tactical setting [75].

There are several windows of opportunity that may arise for HRV measurement and analysis, especially in training or selection courses, or surrounding regularly established rotating shift periods. While the continuous, 24-hour ECG monitoring solution is generally accepted as the gold standard, this may not be practical or even possible in many tactical units; resources may simply be unavailable, or equipment may become damaged or destroyed throughout the day due to the demands of tactical work. Five-minute recordings both preceding and following bouts of highly strenuous activity has demonstrated value in a variety of settings and can be effective as a tool to not only provide relatively real-time and meaningful feedback, but also resource sparing screening [55,75,116]. Intervals as short as 10-30 seconds have been described in the literature and have demonstrated utility but are likely not suitable for assessing long-term HRV patterns such as those assessed by VLF and SD2 [101,117,118].

HRV monitoring is also used to assess sleep health, though the relationship is complex and not fully understood. Nonetheless, wearable technologies have become increasingly popular [116], and given the well-established relationship between sleep and injury [119,120], in addition to other performance outcomes [121], the importance of sleep health in the tactical community cannot be overlooked [21]. While again not a replacement for a true 24-hour recording, utilising HRV analysis overnight when feasible in addition to five-minute recordings before and after rigorous activity may provide the most comprehensive analysis possible while remaining practical for use in tactical training or operations [75,116].

A combination of measurement tools may be required to maximise data availability. While 3-lead ECG has been defined in the literature as the gold standard and is preferable for short or ultra-short-term recordings to maximise precision, smaller, less obtrusive devices may be desired for overnight recordings. Devices worn on the finger utilise photo plethysmography (PPG), and rely on optical measurement of the arterial pulse, rather than direct electrical measurement of heart activity itself. While PPG, familiar to anyone with an emergency medical services background, has demonstrated validity and reliability as an HRV monitoring strategy [122], such devices may best be utilised for overnight use, or when ECG is unavailable or impractical.

1.9 Summation

In summary, HRV can be a useful tool within tactical organisations to holistically assess stress. Because of the dynamic, potentially dangerous, physically, cognitively, and psychologically demanding nature of work in tactical professions, a means of monitoring personnel that considers every aspect of encountered stressors that can be deployed in austere environments is called for. If personnel are unable to accommodate and respond to the summation of these stressors encountered in training and over a career, the resulting physiological decompensation can lead to severe health and performance consequences, known as allostatic load, detailed further in

1.10 Part 3: Allostatic Load. Allostatic load may be detected by HRV analysis as reduced fluctuations in expected patterns of variation that occur over cycles as short as drawing a breath and a long as the 24-hour circadian rhythm. HRV is a sensitive and effective means of measuring normal physiological variations in heart rate patterns over time. Personnel supporting tactical professionals can utilise HRV in both training and operational environments to maximise their capacity to detect and intervene, promoting maximal health and performance of the unit. HRV can be applied by recording heart rate with ECG or PPG devices, over timespans as short as five minutes or as long as 24-hours. The results must be interpreted with respect to the situational context, length of recording, noise or disruption encountered in the recording, and key influencing substances, such as alcohol, caffeine, and nicotine. However, when carefully and optimally applied, HRV analysis can be a cost and time effective augmentation to any high-performance team environment within tactical training and operations.

Attempting to quantify and assess cardiac regulation and its implications on health and fitness in tactical contexts remains crucial though, not only because of the diversity of stressors encountered in tactical environments and the complex interactions and manifestations of those stressors within an individual operator, but the downstream consequences for the individual, their organisation, and the community [123]. Further, tactical environments are not laboratories, and organisations and personnel are often not able to utilise or amenable to other physiological monitoring tools [5]. Therefore, HRV may possibly serve as a viable means of detecting insufficient coping before clinical manifestations are present, and as an objective measure of excessive stress in situations when other measures are not feasible. At first, an individual may experience subclinical disruption of optimal fluctuation between SNS and PNS influences on the cardiovascular system. Left unchecked, this decompensation may eventually lead to a devastating health or performance consequence such as injury, illness, or psychosocial catastrophe [76,124]. These initial chronic clinical or subclinical disruptions have been described as allostatic load [125].

1.10 Part 3: Allostatic Load

The allostasis model describes an increased vulnerability to physical breakdown and dysregulation that occurs as a person is exposed to stress levels above which they can adapt [125-127]. Essentially, the body seeks to maintain a consistent internal environment that is also ready to respond to an ever-changing external environment. This principle is widely known as homeostasis, and is the underlying foundation of all human physiology[128]. The body's effort to maintain homeostasis is not purely reactive. The allostasis model theorises that true homeostatic control requires at least some degree of anticipation. When a person's capacity to anticipate changes requiring control fails, the reactive processes within the body become persistently elevated, as if they were constantly responding to danger [125]. While this stress response activation is typically low-grade in nature, the health and performance consequences of this overactivity can accumulate over time and increase in severity.

The public health sector has combined this model into other theories seeking to explain underlying physiological processes that contribute to the disparities in health seen between socioeconomic groups. For example, those that work contingent jobs in logistics, fast-food, construction, and other sectors with low pay, relatively high levels of physical labour, and rotating shifts potentially experience allostatic load from almost every aspect of their lives [129]. The contingent or otherwise non-permanent nature of these jobs limits the capacity for a worker to plan financially for the future. The low pay may result in persons working multiple similar jobs, and constant physical labour coupled with poor nutrition and disrupted sleep as a result of working rotating shifts can all act to trigger the body's physical alarm systems. While those in tactical professions may not necessarily face all these socioeconomic challenges to the same extent or nature, many of these pressures will be very familiar to anyone who has worn a public service uniform. The vast body of literature exploring this holistic perspective can be leveraged to aid tactical personnel. For example, in terms of hardships faced, police officers work a second job at more than double the national (USA) average [130], volunteer firefighters receive no compensation for their work, and poor nutrition amongst tactical personnel of all backgrounds is a known concern [131].

As noted, allostatic load occurs when a person's efforts to manage for, and regulate in response to, uncertainty fail. As a result, neuroendocrine, cardiovascular, neurogenic, and emotional responses become persistently overactive [127]. This overactivity in bodily systems can cause blood flow in crucial arteries, most notably those supplying the heart and brain, to become abnormal. As a consequence of this negative adaptation, chronic disease development and severity may be accelerated [37,132]. Specifically, high blood pressure, cognitive dysfunction and depressed mood may also emerge or become more severe, impacting health and performance [133]. For example, in a study of 358 firefighters, those with a body mass index (BMI) over 30.2 kg/m^2 were almost twice as likely to experience job-related disability than those with lower BMI (<27.2 kg/m^2) [134].

Put more simply, the body responds to failures of anticipation in the same way as immediate physical threats. The same systems and responses that can be critical and lifesaving in a life-or-death scenario, such as escaping from a burning building, succeeding in a firefight, or apprehending a dangerous offender, can cause great harm when they are unable to be 'switched off'. When this occurs, the overactive crisis-management processes contribute to heart disease, dementia, diabetes, depression, anxiety, and other serious chronic diseases [125,132,135] with one study in older adults finding a six-fold increase in risk of all-cause mortality independent of age, sex, ethnicity, education, or income between those with the least approximated allostatic load and those with the most [136]. Further, allostatic load can result in additional depletions of the capacity to cope with and reduce uncertainty. This means that the onset of allostatic load may likely lead to additional and more severe allostatic load as time goes on (i.e., a progressive cumulative effect). Prevention and minimisation of allostatic load is likely an important health and wellness intervention. As such, and in order to address this system of pathology, a deeper understanding of allostatic load is of importance [132].

1.10.1 Underloading vs. Overloading

While negative health and performance effects can result from chronic underloading or overloading, excess load in any particular domain across the biopsychosocial spectrum can increase an individual's susceptibility to, and accumulation of, allostatic load [127].

When load is optimal, each system that is taxed responds to the imposed demand with growth and adaptation. Too little load, and positive changes are lost. Too much load, or too rapid a change in load, and the ability to grow and adapt is exceeded, and injury or ill health result. As such, the tactical professional must aim to achieve an optimal level of loading whereby there must be enough load to avoid the problems associated with a sedentary and under-stimulated lifestyle, but not so much that anticipatory capacity is lost. However, in order to obtain and keep an optimal balance in tactical environments a wide range of factors must all be considered.

1.10.2 Sources of Allostatic load in Tactical Environments

Given the great variety and intensities of stressors in tactical contexts, allostatic load can be incurred from any of a wide variety of sources. These can include insufficient or excessive physical activity in training or on the job, poor diet, insufficient or excessive job-specific training, psychosocial conflict, or the high levels of uncertainty and potential or actual danger that are inevitably encountered on the job [2,38,137]. These factors are further influenced by the combinations of factors within the individual's relationships and may present as one of the two types of allostatic load, briefly described as underload and overload in Figure 2.

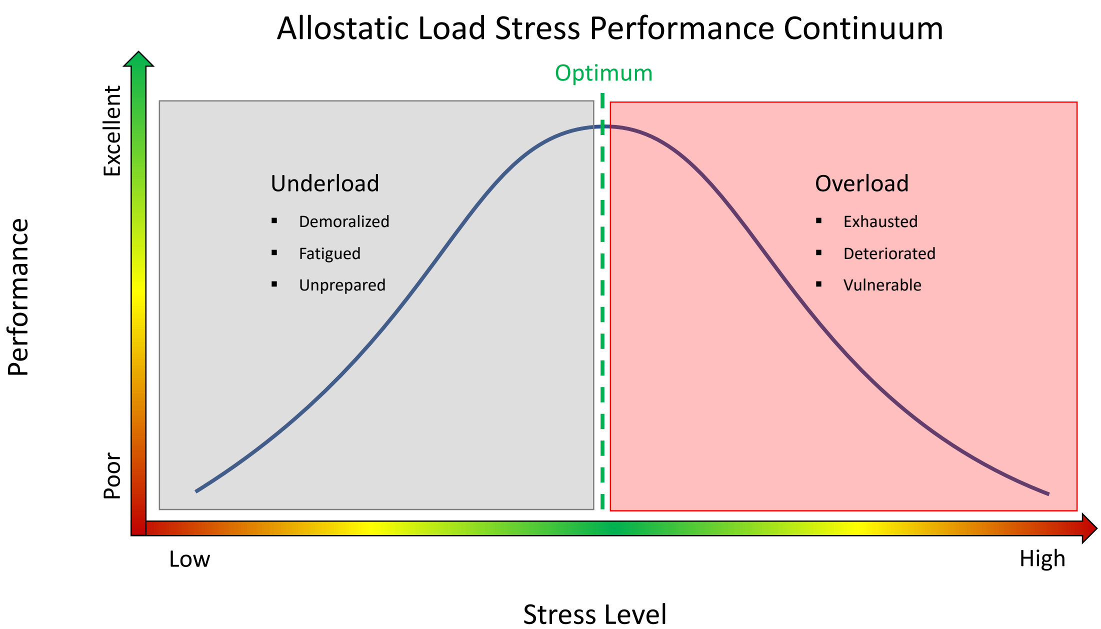

Figure 2. Allostatic Load Stress Performance Continuum

The stress-performance continuum visually describes the relationships between excessive and insufficient applications of stress to achieve optimal performance. Gray and red shaded regions indicate underload and overload.

1.10.2.1 Type I Allostatic Load

Allostatic loading of this type occurs in situations of energy insufficiency. When energy demand exceeds supply, and focus must be diverted wholly to survival and the maintenance of a positive energy balance [138]. This scenario may be most familiar to any personnel that have worked in austere environments for long periods of time, either for training or operational purposes. The most straightforward instance of this type of allostatic load is the emergence of resource scarcity. When basic essential needs become unavailable in the quantities needed to maintain health and performance, allostatic load can result. However, type 1 allostatic load can also develop as a result of changes in physical activity or exertion without sufficient increased energy intake [125,126]. This alternative mechanism may be familiar to personnel who have undergone rigorous training or other changes in their work routines.

In human performance contexts, this phenomenon was first described as the 'female athlete triad', but is now primarily termed relative energy deficiency in sport (RED-S) [139] as both males and females are susceptible. RED-S occurs during periods of 'energy mismatch', in which the athlete or individual expends more calories than they consume, with or without the presence of an eating disorder. While macronutrient insufficiency is the primary concern, micronutrient deficiencies, namely iron and electrolytes, may also occur [138]. This can lead to reduced cognitive performance, low bone mineral density, gastrointestinal disturbances, decreased immune response and menstrual dysfunction in females [140]. In tactical scenarios, both resource scarcity and RED-S situations are possible, and can occur in combination during training or operations [138].

1.10.2.2 Type II Allostatic Load

Type II allostatic loading is likely more prevalent in the general populations of developed nations. It can occur in situations with either adequate energy or energy abundance, and during social conflict or disruption [125,126]. In the case of energy abundance, allostatic load may either precede or advance metabolic syndrome, the cluster of adverse adaptations that includes abdominal obesity, dyslipidaemia, glucose intolerance and hypertension [37,124]. The interaction between psychosocial stress and energy abundance in type II allostatic load can be especially problematic, as both can act synergistically to manifest disease. Psychosocial stress and excess caloric intake drive the growth of adipose tissue, which is itself an endocrine tissue involved in inflammation and insulin resistance, furthering stress responses and contributing to metabolic syndrome development and type II allostatic load, as well as type II diabetes [135,141].

Tactical personnel, especially police officers [37,142] and firefighting personnel [143], may become burdened with Type II allostatic load from a number of sources despite the apparent physically strenuous nature of their duties. For example, while the calorie burn of wildland firefighting activities has been measured at approximately 4700 calories per day during firefighting activity [144], (the equivalent of about eight Big Macs™ of energy per day or running on a treadmill at five mph (8.0 km/hr) for over nine hours), the majority of time on duty is spent at the firehouse awaiting a call. Similarly, while law enforcement personnel can be called upon to perform extreme bursts of exertion, the majority of a police officer's time on duty is also sedentary [8,145].

Exposures to stress and physiological disruption due to rotating shift work cannot be ignored when considering allostatic load. Not only are sleep patterns disrupted [91], as may seem immediately apparent, but the limited availability of healthful food choices during unusual work hours and time constraints when on duty should also be taken into consideration when accounting for the incidence of type II allostatic load in tactical personnel [38]. Lastly, while external psychosocial stressors encountered when on duty are largely accepted as essential aspects of many tactical professions, the possibility of organisational stressors from within the members' units are also important to consider. Female personnel are especially encouraged to be aware of organisational stressors based on the results of studies exploring the impact of organisational support, or its absence, in tactical workplaces and the resultant effect on coping strategies when faced with stress or uncertainty [36,38,142].

The consequence of allostatic load, especially type II, cannot be overstated as it is a known contributor to the development of, and death from, heart disease [132]. This condition kills more police officers and firefighters than any other cause; between 2002 and 2012 47% of the 1153 documented firefighter fatalities were cardiovascular in nature [28,133]. Further, the relationship between tactical work and heart disease, especially in firefighting and police personnel who are known to be at greater risk (as high as 73% greater mortality ratio) than the general population [146], may be at least partially explained by type II allostatic load specifically [37,124].

With recent technological developments, HRV data are now available and interpretable by coaches and individual athletes, and while careful interpretation is necessary, specialist appointments to read or understand results are no longer required [50]. Correlations between HRV measurements and process or outcome measures are allowing for readily accessible insights to valuable health and fitness data [52,98] and have been associated with the prediction of morbidity from the chronic and acute disorders mentioned above [56]. In the athletic performance setting specifically, HRV data have been proven useful in improving the precision of energy expenditure estimates [122]. More recently, HRV has been investigated as a means of quantifying fatigue and recovery levels, detecting overuse injuries, and calibrating physical training loads [53,54,78]. Research continues to emerge linking HRV domains to HPO efforts, which have themselves recently gained interest within the tactical community [55].

1.10.3 Consequences, Warning Signs & Possible Solutions

While the two types of allostatic load differ to some extent, both types disrupt adaptive, dynamic regulation and response of the internal environment, and are progenitors of chronic disease. These diseases include excessive inflammation, chronic pain, diabetes, asthma, fatigue, depression, and anxiety [69,76]. Acute injuries, such as concussion, may also contribute to allostatic load development [147], and consequent disruptions to dynamic regulation. Conversely, higher levels of physical fitness are associated with not only more optimal cardiovascular health, but improved regulation as well [148].

As the health and performance consequences imparted by allostatic load develop incrementally over a career, monitoring health and fitness can be key for prevention and management. Personnel should be aware of the contributors, but also take inventory to assess their own personal situation. Which factors are the most severe or frequently present in their own situation? By identifying and evaluating key areas of potential danger personnel are better prepared to counter sources of allostatic load. Caution and awareness may be warranted during periods of acute injury or following surgery. With protective mechanisms already sent into high activity by an injury or surgery, additional sources of allostatic load, or new sources that may not have been present or impactful before the injury or surgery, may arise and require mitigation to maintain effectiveness across the tactical professional's career.

1.11 Afterword

The role of the tactical professional and their importance to society is well-defined in the current literature. Additionally, HRV has also been thoroughly explored. The theory, application, limitations, and value, especially in athletics, have been well-described. The integration of HRV monitoring into the training and operations of tactical personnel is less-thoroughly understood, however. Therefore, the objective of the next chapter of this thesis is to systematically review the extant literature exploring HRV monitoring within the context of tactical operations and training. While assessment of literature quality will also be considered, the main objective is to enhance understanding of the extent to which established HRV practices translate to the unique populations and occupational roles associated with service in a tactical profession.

Chapter 2 – Relationships between heart rate variability, occupational performance, and fitness for tactical personnel: A systematic review

2.1 Preface

This chapter summarises and critically appraises the current published literature on heart rate variability (HRV) monitoring as applied in tactical organisations. Military, fire and rescue, and law enforcement roles were considered independently, and a systematic review was conducted. Relevant gaps in the literature were identified as they arose. The review was inclusive of methodological considerations, population-specific considerations, and occupationally relevant needs.

This study has been published open access in the occupational health and safety section of Frontiers in Public Health under a Creative Commons CC-BY 4.0 license. The citation of the published article is as follows:

Tomes C, Schram B, Orr R. Relationships between heart rate variability, occupational performance, and fitness for tactical personnel: A systematic review. Frontiers in public health. 2020:729.

The full published manuscript is accessible from https://doi.org/10.3389/fpubh.2020.583336

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis. Tables and figures have been reformatted for uniformity.

2.2 Abstract

Objectives: Heart rate variability has gained substantial interest in both clinical and athletic settings as a measurement tool for quantifying autonomic nervous system activity and psychophysiological stress. However, its uses in tactical work settings, such as military, police and firefighting environments, remain controversial. Given the physical, mental, and emotional stress public safety personnel face both operationally and in training, heart rate variability measurement may be key in promoting their health, safety, and operational effectiveness.

Methods: This study identified, critically appraised, and summarised primary studies investigating relationships between heart rate variability and outcomes of interest to tactical personnel. Key literature databases were searched, and quality assessment checklists were applied to analyse retained literature. The results of the screening and assessment processes, along with key data extracted from each study were summarised and tabulated. Research gaps were also identified to improve to how tactical personnel and health or performance providers may best utilise heart rate variability to monitor or promote personnel health and performance, and thereby facilitate public safety.

Results: Twenty studies were included and were all of generally high quality. Cohort size, length of follow-up, measurement objectives, data acquisition, and data analysis all varied considerably across studies, precluding meta-analysis. However, study results correlating heart rate variability and relevant outcomes indicated that overall, heart rate variability is an effective indicator of key fitness and performance elements in the tactical work setting.

Conclusions: Heart rate variability can be an effective health and performance tool in tactical work environments. However, measurement methods must be carefully selected and applied. Further research is required to understand causal relationships. Specifically, larger cohort inclusion and the isolation and study of specific variables unique to public safety work and training may improve the effectiveness of heart rate variability measurement to provide meaningful information to end users and providers.

2.2.1 Keywords: firefighting; first responder; injury prevention and reduction; military; occupational fitness; occupational stress and mental-physical health; physiological monitoring data; police.

2.3 Introduction

Heart rate is typically described as the number of beats of the heart per minute, however, the time between beats in a healthy heart is highly variable; the heart is under constantly varying regulation modulating its activity from the two complimentary branches of the autonomic nervous system (ANS): the sympathetic (SNS) and parasympathetic (PSN) nervous systems [69,70]. The ANS is the efferent branch of the peripheral nervous system responsible for regulating most unconscious bodily activities; respiration, distribution of blood flow, digestion, pupillary response, waste excretion, arousal, and heart rate [70]. The ANS is itself composed of two complimentary pathways that typically act antagonistically to maintain homeostasis. The SNS originates from the thoracic and upper lumbar vertebrae, and governs response that require immediate action, such as the "fight or flight" response to acute stress. The PNS is characterised as a more dampening response, and governs actions that do not typically require immediate action such as sleep, digestion and tissue repair [70].

With respect to the heart specifically, the sympathetic nervous system increases heart rate, which will decrease the variation in time between beats. This is accomplished not only through direct innervation, in which the muscle is stimulated to contract more quickly and more forcefully, but also through catecholamines secreted via the adrenal glands [70]. The parasympathetic nervous system regulates the heart through the vagus nerve, slowing conduction of the sinoatrial node and contributing to respiratory sinus arrhythmia, the natural increase in heart during inspiration and decrease during expiration [73].

Disruption of the balance between sympathetic and parasympathetic influences on the cardiovascular system can lead to devastating health consequences [76,124]. These disruptions have been described as excess allostatic load [125]. Allostatic loading occurs in situations of either energy insufficiency, in which energy demand exceeds supply, and focus must be diverted wholly to survival and the maintenance of a positive energy balance, or in situations with energy abundance, but social conflict or disruption [125]. While the two types of allostatic load differ to some extent, both disrupt cardiovascular autonomic balance, and are associated with the development of chronic diseases, such as excessive inflammation, chronic pain, diabetes, asthma, fatigue, depression and anxiety

[76]. Acute injuries, such as concussion, may also contribute to elevated allostatic load [147], and consequent disruptions to cardiac autonomic balance. Conversely, higher levels of physical fitness are associated with a more optimal cardiovascular autonomic balance [148]. HRV has been identified as a valid measurement of autonomic nervous system regulation and has both time and cost advantages over other methods, such as biomarker testing, while also being non-invasive. With recent technological developments, HRV data are now available and interpretable by coaches and individual athletes, not requiring specialist appointments to read or understand results [50]. Correlations between HRV measurements and process or outcome measures are allowing for readily accessible insights to valuable health and fitness data [52,98] and have been associated with the prediction of morbidity from the chronic and acute disorders mentioned above. Individuals at high risk for the development of ANS dysregulation or allostatic loading and consequent morbidity may therefore benefit from HRV monitoring. In the athletic performance setting, HRV data has been proven useful in improving the precision of energy expenditure estimates [122]. More recently, HRV has been investigated as a means of quantifying fatigue and recovery levels, detecting overuse injuries, and calibrating training loads [52,78,149]. Research continues to emerge linking HRV domains to human performance optimisation efforts, which have themselves recently gained interest within the tactical community.

Tactical personnel, individuals who have sworn to protect and serve their communities [41], and who may place their own health and safety at risk in execution of those duties, are often faced with a multitude of unique challenges that often result in stresses to their autonomic nervous systems, [7,150] and may benefit from access to the fitness and health data HRV analyses can provide. For example, police officers and other first responders (firefighters, emergency medical responders) may be sedentary for the majority of their time on duty but could be called with little to no warning into situations of extreme danger and physiological stress [151]. The ability to monitor physiological response during these events may help protect their health. Likewise, military personnel, while often prepared in advance for deployment, are exposed to high levels of physical, mental, and emotional stress for prolonged periods of time [152], and may thus also benefit from physiological data measurement and analysis. Furthermore, tactical personnel are also regularly subjected to operations in austere environments, dysregulated sleep, and poor nutrition [137,153]. As a result of these occupational demands, literature has reported the risk of cardiovascular disease, especially in police officers, may be greater than that of the general population [133]. Conversely, many tactical personnel perform at extraordinary levels of physical performance and may seek to optimise their training, avoid overtraining and maximise the balance between training and operational demands [43].

As a result, HRV applications developed in both clinical and athletic settings may be of interest to tactical organisations seeking an inexpensive and non-invasive means of monitoring the health and fitness of their personnel, both in training and in operations. However, the unique requirements of working as a tactical professional may dictate that functional inferences derived from HRV measurements originally developed in athletic or clinical populations may not always generalise to tactical populations [41]. To date, no comprehensive, systematic reviews of the literature examining associations between occupational fitness, operator or trainee health, or occupational performance and heart rate variability analyses for tactical personnel have been conducted. Therefore, the aim of this systematic review was to identify primary studies examining relationships between HRV and relevant health and operational outcomes specifically in tactical personnel, critically appraise the methodological quality of the identified studies, and summarise the results to inform tactical professionals and those in the health and performance fields supporting tactical professionals.

2.4 Survey Methodology

2.4.1 Search Method

Prior to conducting the initial search, this study was registered with PROSPERO (ID: 153293). The PRISMA guidelines for systematic reviews were followed and the outcome of each step can be found in Figure 3 (http://www.prisma-statement.org/) [154]. A rapid search using a set of predetermined keywords was conducted to determine relevant subject heading terms and develop a sample of salient articles to guide a detailed search strategy.

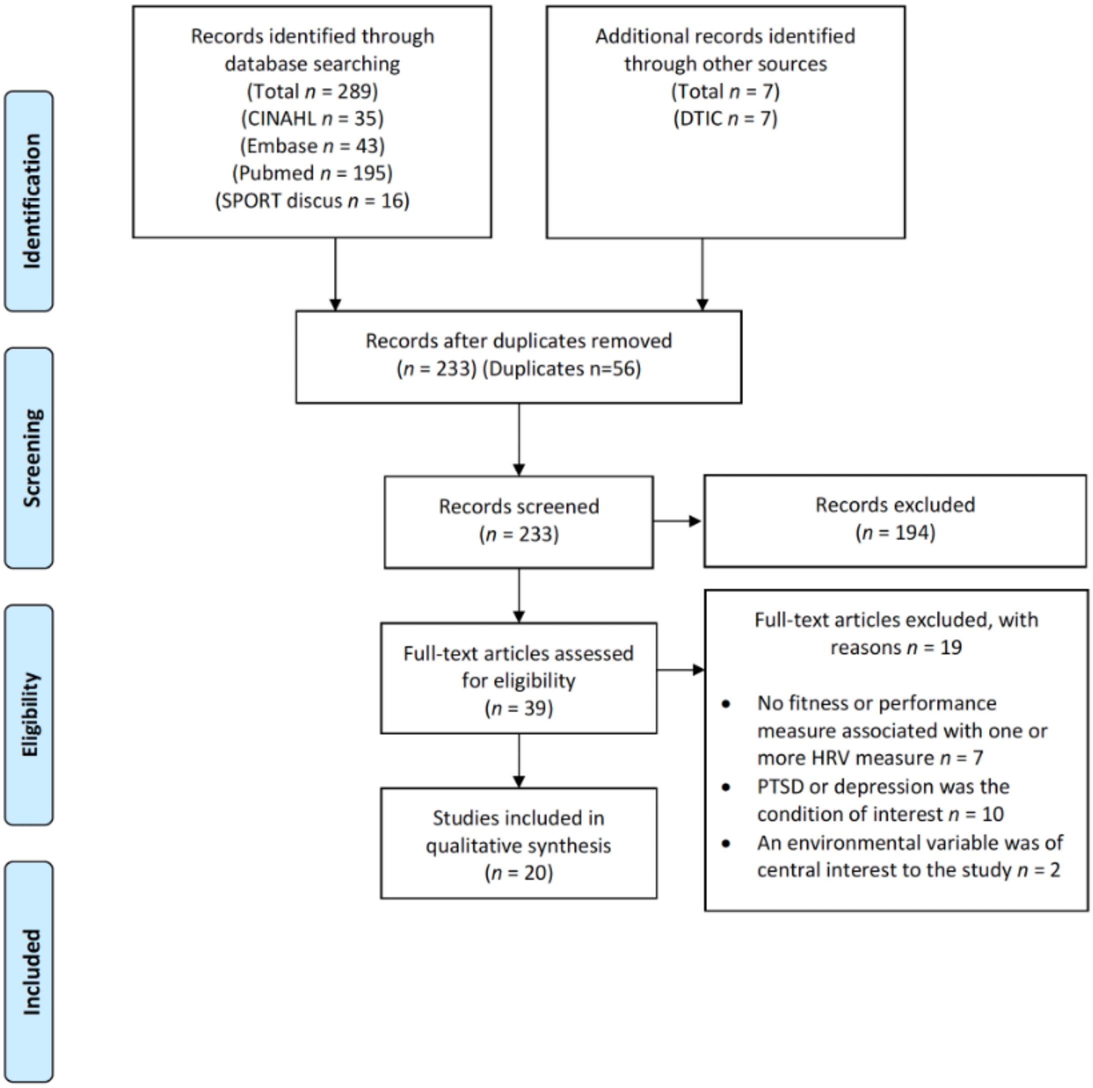

Figure 3. PRISMA Flow Diagram

The PICO strategy developed to construct the organisation and syntax of search terms was as follows: Patient(s); tactical personnel, and derivative, related, or more specific terms that would capture research conducted with public safety operators or trainees, Intervention; while no interventional studies were expected, given the observational nature of HRV analysis and the research aim, if studies compared HRV to another health or performance monitoring modality, results could be considered provided details of the HRV analysis were included. The control/comparison was not limited or specified; any comparison method could be included, provided the specific details of HRV monitoring were reported. For outcomes, a wide variety of health and occupational outcomes were considered, including physical fitness/injury, mental/emotional stress, or recovery, resilience, or job performance.

Each database (PubMed, CINAHL, Embase, and Sport Discus) was then sequentially searched by a single author (CT) using database heading terms, Boolean operators, and available filters. A second author independently verified the search results (RO). The Defence Technical Information Centre (DTIC) was also searched to capture grey literature not indexed in traditional academic databases. The DTIC was utilised as an expedient means of capturing information relevant to the research question and population of interest that was not peer-reviewed but was still likely to contribute to the aim of the study. The final search was executed and verified on 9 October 2019. Details of the finalised search strategy and initial results can be seen in Table 2. Duplicates were screened using EndNote software (Clarivate Analytics, Philadelphia, PA, USA), while additional duplicates were removed manually.

Table 2. Finalised Search Strings By Database and Results

Database	Population	Target Variable	Outcome	Results
PubMed	(("Military Personnel"[Mesh] OR "Emergency Responders"[Mesh] OR "Police"[All Fields] OR "firefighters"[All Fields] OR "Sheriff"[All Fields] OR "Patrol Officer"[All Fields] OR "Law Enforcement"[All Fields] OR "tactical athlete"[All Fields] OR "cadet"[All	("HRV"[All Fields] OR "Heart Rate Variability"[All Fields] OR "Heart Rate Interval"[All Fields] OR "RR variability"[All Fields] OR "cycle length variability"[All Fields] OR "heart period variability"[All	Exercise"[All Fields] OR "Physical Exertion"[All Fields] OR "Physical Fitness"[All Fields] OR "BMI"[All Fields] OR "Body Mass Index"[All Fields] OR "Body Constitution"[All Fields] OR "Stress"[All Fields] OR "Work	195

	Fields] OR "agent"[All Fields] OR "recruit"[All Fields] OR "FBI"[All Fields] OR "officer"[All Fields]) OR defense OR defence	Fields] OR "autonomic function"[All Fields] OR "vagal control"[All Fields]))	Performance"[All Fields] OR endurance[All Fields] OR fitness[All Fields] OR strength[All Fields] OR ("cumulative trauma disorders"[MeSH Terms] OR ("cumulative"[All Fields] AND "trauma"[All Fields] AND "disorders"[All Fields]) OR "cumulative trauma disorders"[All Fields] OR ("overuse"[All Fields] AND "injury"[All Fields]) OR "overuse injury"[All Fields]) OR (("Stress"[Journal] OR "stress"[All Fields]) AND ("wounds and injuries"[MeSH	

			Terms] OR ("wounds"[All Fields] AND "injuries"[All Fields]) OR "wounds and injuries"[All Fields] OR "injury"[All Fields])) OR recovery[All Fields] OR ("fatigue"[MeSH Terms] OR "fatigue"[All Fields]) OR readiness[All Fields] OR resilience[All Fields] OR overtraining[All Fields] OR hardiness[All Fields] OR exhaustion[All Fields])	
CINAHL	(MH "Military Personnel") OR (MH "Emergency Medical Technicians") OR (MH "Police") OR (MH	"HRV" OR (MH "Heart Rate Variability") OR "Heart Rate Interval" OR "RR	(MH “Exercise”) OR (MH “Body Mass Index”) OR (MH “Hardiness”) OR (MH “Athletic Performance”) OR (MH “Job	35

	"Firefighters") OR "Military Personnel" OR Police OR "Emergency Responder" OR "Firefighter" "Sheriff" OR "Patrol Officer" OR "Law Enforcement" OR "tactical athlete" OR "cadet" OR "agent" OR "recruit" OR "FBI" OR "officer" OR defense OR defence	variability" OR "cycle length variability" OR "heart period variability" OR "autonomic function" OR "vagal control"	Performance") OR (MH "Physical Performance") OR (MH "Physical Fitness") OR (MH "Fatigue") OR (MH "Mental Fatigue") OR (MH "Muscle Fatigue") OR (MH "Recovery") OR (MH "Recovery, Exercise") OR (MH "Stress") OR (MH "Stress Disorders, Post-traumatic") OR (MH "Stress, Occupational") OR (MH "Stress, Physiological") OR (MH "Fractures, Stress") OR (MH "Stress, Psychological") OR (MH "Overtraining Syndrome") OR strength OR endurance OR resilience OR	

			overuse OR "work performance" OR readiness OR exhaustion	
SPORTDiscus	"Military Personnel" OR "Emergency Responders" OR "Police" OR "firefighters" OR "Sheriff" OR "Patrol Officer" OR "Law Enforcement" OR "tactical athlete" OR "cadet" OR "agent" OR "recruit" OR "FBI" OR "officer" OR defense OR defence	"HRV" OR "Heart Rate Variability" OR "Heart Rate Interval" OR "RR variability" OR "cycle length variability" OR "heart period variability" OR "autonomic function" OR "vagal control"	Exercise" OR "Physical Exertion" OR "Physical Fitness" OR "BMI" OR "Body Mass Index" OR "Body Constitution" OR "Stress" OR "Work Performance" OR endurance OR fitness OR strength OR 'overuse injury' OR 'stress injury' OR recovery OR fatigue OR readiness OR resilience OR overtraining	16
Embase	'Solider'/exp OR 'rescue personnel'/exp OR 'police'/exp OR 'fire fighter'/exp "Military Personnel" OR	"HRV" OR 'Heart Rate Variability'/exp OR "Heart Rate Interval" OR "RR variability" OR	'Exercise'/exp OR 'body mass'/exp OR 'body composition'/exp OR resilience OR readiness OR hardiness OR	43

	"Emergency Responders" OR "Police" OR "firefighters" OR "Sheriff" OR "Patrol Officer" OR "Law Enforcement" OR "tactical athlete" OR "cadet" OR "FBI" OR "officer"	"cycle length variability" OR "heart period variability" OR "autonomic function" OR “vagal control”	‘fitness’/exp OR ‘stress’/exp OR ‘heat stress’/exp OR ‘job stress’/exp OR ‘muscle stress’/exp OR ‘musculoskeletal stress’/exp OR ‘mental stress’/exp OR ‘job performance’/exp OR ‘mental recovery’/exp OR ‘exercise recovery’/exp OR ‘fatigue’/exp OR ‘muscle fatigue’/exp OR ‘posttraumatic stress disorder’/exp OR endurance OR fitness OR strength OR fatigue OR readiness OR resilience OR overtraining	
DTIC	"Military Personnel" OR "Emergency	"HRV" OR "Heart Rate Variability" OR	Exercise" OR "Physical Exertion" OR	7

	Responders" OR "Police" OR "firefighters" OR "Sheriff" OR "Patrol Officer" OR "Law Enforcement" OR "tactical athlete" OR "cadet" OR "agent" OR "recruit" OR "FBI" OR "officer"	"Heart Rate Interval" OR "RR variability" OR "cycle length variability" OR "heart period variability" OR "autonomic function" OR "vagal control"	"Physical Fitness" OR "BMI" OR "Body Mass Index" OR "Body Constitution" OR "Stress" OR "Work Performance" OR endurance OR fitness OR strength OR 'overuse injury' OR 'stress injury' OR recovery OR fatigue OR readiness OR resilience OR overtraining	

2.4.2 Article Screening

Review studies, conference proceedings and other literature that was not primary, not peer-reviewed, not available in English or had no available abstract was also rejected manually if not captured by search filters. Article titles clearly irrelevant to the topic (e.g., drug intervention studies, *in vitro* studies) were also removed. Articles reporting results from animal studies, a human population that did not include active or veteran tactical personnel, and studies using HRV as an intervention rather than a measurement (e.g., biofeedback device studies) were also screened out for the purposes of this review.

2.4.2.1 Inclusion and Exclusion Criteria

Developed inclusion criteria were applied to the remaining titles: tactical personnel or trainees (well or unwell), veterans, measurement of HRV, assessment of a health/fitness/occupational outcome, use of HRV analysis findings to predict, measure or monitor a state of disease, physical or occupational performance. All study design types were considered, provided that HRV analyses were reported in relation to another factor. Article relevance to the question was first screened by CT. An additional author verified inclusions and exclusions (RO). Disagreements were adjudicated by a third author, BS.

2.4.3 Quality Assessment

The Critical Appraisal Skills Programme (CASP) toolkit (Middle Way, Oxford, UK) [155] was selected for methodological assessment of the included studies. This assessment system has been used in previous systematic reviews and allows for fair and equitable assessment of a variety of study types [156]. Three CASP checklists were ultimately necessary to evaluate the selected studies; the cohort study checklist, comprised of 13 total questions, the case-control checklist, comprised of 11 questions, and the randomised control trial checklist, also of comprised 11 questions. The randomised control trial checklist was the most suitable for quasi-experimental studies included in this review. The first two questions of each checklist screen for validity, and the following 9-11 questions guide reviewers through the assessment of study results, relevance of the results, methodology, and applicability. On the cohort study checklist, Question 7 simply asks for a summary of the results. This question was omitted, resulting in a final maximum score of 12. For each question that could be answered dichotomously, a publication was awarded with 1 point for answers of ‘yes’ and 0 points for answers of ‘no’ or ‘can’t tell’. The case-control and randomised-control trial checklists required no modification beyond score quantification. For any questions which were not answered dichotomously within the checklist, an objective parameter was fit to the question. For example, on all checklists, there is a question pertaining to the precision of the results, phrased, ‘how precise were the results?’. This question was awarded a ‘1’ (yes) if exact measurements of significance, rather than inequalities, were reported. For other questions asking for treatment effect sizes, publications were awarded ‘1’ point (yes) for including power or effect size analysis, and ‘0’ points (no) if no determination was made as to the effect size. Disagreements in CASP scoring between authors were resolved by consensus. A referee (RO) was appointed prior to initiation of scoring. Screening and quality assessment were completed 2 February 2020.

2.4.3 Results

The results of the search, screening and selection processes are summarised in the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) flow diagram (Figure 1). A total of 296 citations were captured in the finalised search, executed on 9 October 2019. At that time, all eligible results were downloaded, retained, and screened in accordance with the screening methodology. A total of 56 duplicates were removed, leaving 233 titles. Of these, 194 were identified as irrelevant to the research question. From the remaining studies, the following exclusion criteria were developed: post-traumatic stress disorder (PTSD) or depression were the condition of interest (n=10), an environmental condition was a key variable in the study (n=2), HRV was measured, but not linked to a health and fitness or occupational outcome (n=7). The remaining 20 publications were retained for this review. Further screening for quantitative review was considered, but ultimately not possible due to the heterogeneity of the included studies. The review was completed on 14 March 2020.

2.4.3.1 Critical Appraisal

The mean CASP of the quasi-experimental studies was 9.67±0.58 of 11 maximum points. The mean CASP of the case-control studies was 10.5±0.7 of 11 maximum points, and the mean CASP of the cohort studies was 10.73±0.78 of 12 maximum points.

2.4.3.2 Data Extraction

Details of all relevant data retrieved from each included study can be found in Table 3. The Author(s), title, year, participants, demographics as available, anthropometrics as available, the performance metric(s) and key results, significant or not, as well as the final CASP score are included. The HRV analysis or analyses selected, and their results are also included if succinct summarisations of the data were possible. Studies are organised first by design methodology, then alphabetically.

Table 3. Data Extraction and Summary of Selected Studies

Authors/Title	Participants	HRV Analysis	Performance Measurement	Results	CASP Score
Gamble *et al* Different profiles of decision making and physiology under varying levels of stress in trained military personnel	Male US infantry soldiers/SRT operators (n = 26) Age: 30.73±7.71	Low Frequency domain (LF) High Frequency domain (HF) LF/HF Ratio	Threat identification simulation: accuracy, sensitivity Low stress and high stress shoot conditions	Basal HF-Accuracy: positive relationship, p=0.0379 Basal HF-sensitivity: positive relationship, p=0.0379 LF/HF-stress condition: negative relationship, p=0.0379	10/11 Quasi-Experimental
Marcel-Millet *et al* Physiological responses and parasympathetic reactivation in	French Firefighters (n=28 males) Age: 37±7	SDNN LnRMSSD	Three load conditions: personal protective clothing only (PPC); PPC and the full self-contained breathing apparatus (SCBA); and with PPC	PPC-SCBA, SDNN: 27.8±14.1-21.4±9.2 (p<0.05) IFT-PPC, LnRMSSD: 2.4±0.5-2.1±0.5ms p<0.01	10/11 Quasi-Experimental

rescue interventions: The effect of the breathing apparatus	Height: 179±6 cm Weight: 76±9 kg BMI: 24±2 (n=6 females) Age: 29±3 Height: 171±4 cm Weight: 64±3 kg BMI: 22±1		and only the cylinder of the SCBA (SCBAc) One baseline unloaded condition: Intermittent Fitness Test (IFT) $VO2_{max}$: 54.3±4.9ml/kg/min	IFT-SCBAc, LnRMSSD: 2.4±0.5-2.0±0.5 $p<0.01$ IFT-SCBA, Ln RMSSD: 2.4±0.5-2.0±0.5 $p<0.01$	
Sanchez-Molina *et al* Effect of Parachute Jump in the Psychophysiolo gical Response of Soldiers in Urban Combat	Male Spanish Army Soldiers (n=19) Age: 31.9±6.2 Height: 173.6±5.3 Weight: 73.8±8.3 BMI: 24.2±2.3 Experience: 12.8±7yrs	RMSSD LF HF ΔHF power	Simulated Parachute infiltration or ground infiltration into urban combat simulation Blood lactate Blood oxygen saturation (BOS) Rate of perceived exertion (RPE)	Blood Lactate increased significantly at the end of the simulation regardless of infiltration method ($p<0.05$) RMSSD and HF domain decreased while LF increased regardless of infiltration method ($p<0.05$)	9/11 Quasi-Experimen tal

				RMSSD-ΔLactate: r=-0.504 (p=0.039) LFpost-ΔLactate: 0.589(p=0.013) HFpost-ΔLactate: r=-0.589 (p=0.013) ΔHF-BOS: r=0.493 (p=0.044)	
Porto *et al* Firefighters' basal cardiac autonomic function and its associations with cardiorespiratory fitness	Two groups of Male Brazilian Firefighters (n = 38, on-duty) Age: 41±11 BMI: 26.1±7.8 (n = 26, off-duty) Age: 40±12 BMI: 26±13	pNN50: CRF<12METs: 1.3 CRF>12METs: 3.6 RMSSD: CRF<12METs: 18.3 CRF>12METs 23.8	Maximal metabolic equivalent capacity (METs): $VO2_{max}$ (on-duty): 42.4 $VO2_{max}$ (off-duty): 40.0 Groups divided into <12METs or >12METs On duty status	Significant differences between those with METs <12 and >12: PNN50 (p=0.07) RMSSD (p=0.03) LF/HF Ratio (p=0.01) No difference between duty status	11/11 Case-Control

		LF/HF ratio: CRF<12METs: 5.2 CRF>12METs: 3.3			
Sanchez-Molina *et al* Assessment of Psychophysiological Response and Specific Fine Motor Skills in Combat Units	Two groups of male Spanish Army Soldiers (n=19 Light Infantry) Age: 30.2±5.25 Height: 176.15±8.31 Weight: 77.93±10.25 BMI: 25.00±3.11 Experience: 9.95±5.17yrs (n=12 Heavy Infantry) Age: 34.5±4.85 Height: 177.42±7.28 Weight: 79.21±9.57 BMI: 25.10±1.8	RMSSD LF HF	Simulated Urban Combat Competitive State Anxiety Inventory (CSAI-2R)	RMSSD, LF and HF values were significantly different between the light and heavy infantry groups (p<0.001): RMSSDpre: Light: 38.26±40.69 Heavy: 164.89±73.16 LFpre: Light:76.60±10.75 Heavy: 19.25±13.11 HFpre: Light: 35.10±25.51	10/11 Case-Control

	Experience: 14.58±4.87yrs			Heavy: 80.59±13.41 RMSSDpost: Light: 7.62±5.62 Heavy: 88.68±4.45 CSAI-2R correlated with all HRV measures: HFpre: r=0.382(p=0.034) LFpre: r=0.406 (p=0.24) RMSSDpre: r=0.416 (p=0.022) HFpost: r=-0.487 (p=0.006) LFpost: r=0.424(p=0.020) RMSSDpost: r=0.433 (p=0.017)	
Andrew *et al* Adiposity, muscle and	Buffalo, NY (USA) Police Officers (n=360) Age: 42.1±7.66	Low Frequency domain	Physical Activity Recall Questionnaire	Significant (p<0.05) correlation between LnPA and HRV:	11/12 Cohort

physical activity: Predictors of perturbations in hear rate variability	BMI: 29.0±4.40 Resting HR: 64.0±8.82	natural log (LnLF): 5.31±0.91 High frequency domain natural log (LnHF): 4.96±1.13	(Ln Physical Activity Index): 2.66±1.04	LnLF: r=0.071 LnHF: r=-0.035	
Andrew *et al* Police work stressors and cardiac vagal control	Buffalo, NY (USA) Police Officers (n = 259 males) Age: 41.2±6.8 (n = 87 females) Age: 40.7±5.5	Low Frequency domain natural log (LnLF) High frequency domain natural log (LnHF)	Spielberger Police Stress Survey	No significant correlations for men Significant (*p*=0.024) inverse relationship between the 'lack of support' stressor and LnHF for females	10/12 Cohort

Delgado-Moreno *et al* Combat Stress Decreases Memory of Warfighters in Action	Male Spanish Army Soldiers (n=20) Age: 35.4±6.2 Height: 179.9±7.0cm Weight: 82.38±10.5kg BMI: 25.7±2.6)	Low Frequency domain (LF), Pre: 48.3±4.2, Post: 74.8±14.4 High Frequency domain (HF), Pre: 51.7±3.1 Post: 25.1±14.3 All values in normalised units (n.u.)	Urban Combat simulation Post-mission event recall questionnaire Body Temperature, Pre: 37.8±1.2°C, Post: 37.5±1.3°C	Significant correlations between the following: LFpost, temp post: *p*=0.035, r=0.473 LFpost, correct sound recall: *p*=0.020, r= -0.516 HFpost, temp post: *p*=0.035, r=-0.474 HFpost, correct sound recall: *p*=0.019, r=0.517	10/12 Cohort
Diaz-Manzano *et al* Higher Use of Techniques Studied and	Male Spanish Army Soldiers (n=19) Age: 28.8±4.9 Height: 176.2±5.3cm	RMSSD pNN50 HF (nu) LF (nu)	Hand-to-hand combat training drill Analyses divided by higher performing half vs.	Significant pre-post differences for all HRV measures in the HPG	10/12 Cohort

performance in melee combat produce a higher psychophysiolo gical stress response	Weight: 75.1±5.3kg BMI: 24.2±1.3	HF/LF Ratio SD1 SD2	lower performing half (HPG, LPG)	Significant differences for all HRV measures in the LPG, *except* HF (p=0.880), LF (p=0.164) and HF/LF ratio (p=-.140)	
Duarte *et al* Efforts of Patrol Operation on Hydration Status and Autonomic Modulation of Heart Rate of Brazilian Peacekeepers in Haiti	Male Brazilian Army Soldiers (n =20) Age: 23.5±4.7 Height: 175.1±6.8cm Weight: 74.6±7.9kg	AVNN, Pre: 1009.1±119.3 ms Post: 862.7±136.7m s Low Frequency domain (LF) (nu) Pre: 50.5±17.1 Post: 60.6±13.9 High Frequency	Estimated Energy Expenditure (EE) Estimated $VO2_{max}$ (Cooper's Test) Estimated Hydration Status (%Body Mass Change) Pre: 74.6±7.9, Post: 72.9±7.6	EE-LF/HF ratio: r=0.49 p=0.02 $VO2_{max}$-LF/HF ratio: r=-0.42 p=0.04 %Body Mass Change: r=0.53 p=0.02	12/12 Cohort

		domain (HF) (nu) Pre: 49.5±16.9 Post: 39.3±13.8 LF/HF Ratio Pre: 1.49±1.47 Post: 2.12±1.19			
Grant *et al* The difference Between Exercise-Induced Autonomic Fitness Changes Measured After 12 and 20 weeks of medium to high intensity military training	South African Defense Force Recruits (n = 89 males) (n = 65 females) Age: 20.91±1.29 BMI: 22.85±2.78	AVNN SDNN RMSSD pNN50 LF (nu) HF (nu) LF/HF ratio SD1 SD2	Basic Military training over 12 and 20 weeks $VO2_{max}$: Basal: 49.54±8.79 12 weeks: 54.14±7.09 20 weeks: 54.15±7.16	Significant differences in Mean RRI (p=0.007), SDNN (p=0.024), RMSSD (p<0.001) and SD1 (p<0.001) between weeks 12 and 20, but no changes in LF, HF or LF/HF Ratio	10/12 Cohort

Johnsen *et al* Heart Rate Variability and cortisol responses during attentional and working memory tasks in naval cadets	Royal Norwegian Naval Academy Cadets (n= 49) Age: 23.3±8	RMSSD	California Computerised Assessment Package (Calcap) Computerised two-back test Background search task Cortisol level	Basal RMSSD-cortisol: r=-0.35, p<0.04 Basal RMSSD-post calcap: p<0.04 Basal RMSSD-post pop-out attention: p<0.04 Basal RMSSD-recovery: p<0.04	10/12 Cohort
Jouanin *et al* Analysis of heart rate variability after a ranger training course	Male French Military Academy Students (n=23) Age: 21.7±0.2 Height: 176.5±1.1 Weight: 74.0±1.3	AVNN Pre: 1008.4±33.1 Post: 1177.5±33.8 SDRR: Pre: 763.1±18.8ms Post: 837.5±20.5ms	French Ranger Training Course	Pre-Post training: Significant change in Mean RRI (p<0.001), TP (p<0.01), LF, HF and LF/HF ratio, (p<0.05)	10/12 Cohort

		LF (nu) HF (nu) LF/HF ratio Total Power (TP)			
Kaikkonen *et al* Physiological Load and Psychological Stress During a 24-hour Work Shift Among Finnish Firefighters	Professional Finnish Firefighters (n=21) Age: 38±7 Height: 178±7 Weight: 25±2 BMI: 25±2	RMSSD (ms): 24hr shift: 42±14 6-hour rescue: 38±16 6-hour Ambulance: 45±21	24-Hour shift 6-hour firefighting shift 6-hour ambulance shift	Significant Difference between shift conditions ($p<0.01$)	10/12 Cohort
Lyytikäinen *et al* Recovery of rescuers from a 24-h shift and	Professional Finnish Fire/Rescue personnel (n=14) Age: 34±9 Height: 178±7	SDNN RMSSD VLF LF	24-hour rescue shift $VO2_{max}$: 51±9ml/kg/min	Significant difference in SDNN: On shift-2nd day: $p<0.05$ On shift-third day: $p<0.001$	10/12 Cohort

its association with aerobic fitness	Weight: 80.8±11.4kg	HF LF/HF ratio Total Power		Significant difference in LF/HF ratio: on shift-2nd day: $p<0.05$ On shift-third day: $p<0.01$ No significant effect of $VO2_{max}$ on HRV during recovery	
Oliveira-Silva *et al* Physical Fitness and Dehydration Influences on the Cardiac Autonomic Control of Fighter Pilots	Male Brazilian Fighter Pilots (n=11) Age: 33.2±3.2 Weight: 76.0±8.5kg Height: 175±5cm BMI: 24.8±2.3	RMSSD: Pre: 24.2±8.2ms Post: 20.8±10.7ms SDNN: Pre: 67.0±29.1ms Post: 77.3±27.5ms SD1:	Flight training Hydration status (hematocrit) $VO2_{max}$ (Montreal University Track Test): 46.4±5.66 Bench Press: 68.7±10.8kg Pull-Down: 70.0±8.36kg Leg Press: 201.3±42.49	Flight Training day-rest day: RMSSD (p=0.036), SDNN (p=0.001), SD1 (p=0.031) Significant negative correlation between hematocrit and RMSSD, SD1: r=-0.61—0.81, p=0.044-0.002	12/12 Cohort

		17.5±5.6ms 16.4±7.8ms SD2: 79.3±18.3ms 74.7±28.1ms Sample Entropy (SampEn): Pre: 0.94±0.22 Post: 0.86±0.28 Alpha1 (fractal scaling)		Significant relationship between $VO2_{max}$-SampEn: r=0.777, p=0.001	
Rodrigues *et al* Stress among on-duty firefighters: An	Professional Portuguese Firefighters (n=15 males) (n=2 females) Age: 29.35±8.85	AVNN: 792.64±92.29 ms LF/HF ratio:	Perceived Stress Scale (PSS) Work events	Significant differences between fire, pre-hospital assistance, and accidents: LF/HF ratio (p<0.01)	11/12 Cohort

ambulatory assessment	Experience: 9.41±7.3yrs	3.82±1.76	Normative ECG values: AVNN: 930±133ms LF/HF Ratio: 3.33±3.47	Significant differences between firefighter and normative ECG values: Mean NNI (82% of firefighters lower) LF/HF ratio (71% of firefighters above)	
Rodrigues *et al* Wearable biomonitoring platform for the assessment of stress and its impact on cognitive performance of firefighters: An experimental study	Professional Portuguese Firefighters (n=19 males) (n=2 females) Age: 29.90±8.83 Experience: 8.33±8.21 years	AVNN SDNN RMSSD pNN20 pNN50 LF/HF ratio	Trier Social Stress Test (TSST) 2-choice reaction time task (CRTT)	CRTT1-Mean NNI: significant decrease, $p<0.005$ TSST-Mean NNI: significant decrease, $p<0.005$ TSST-SDNN: significant increase, $p<0.001$	12/12 Cohort

				LF/HF ratio-CRRT2: significant increase, $p<0.001$ LF/HF ratio-TSST: significant increase, $p<0.001$	
Shin *et al* Factors related to heart rate variability among firefighters	Professional Male South Korean Firefighters (n=645)	SDNN RMSSD LnLF LnHF LF/HF Ratio	Korean Occupational Stress Scale (yes or no answers to a variety of occupational variables)	Smoking-RMSSD Yes: 31.96±16.92 No: 28.69±15.31 ($p<0.05$) Smoking-LnLF Yes: 5.73±0.91 No: 5.54±0.98 ($p<0.05$) Shift work-RMSSD: Yes: 30.17±16.54 No: 25.78±11.11 ($p<0.05$) Job Demand-RMSSD: Low: 30.96±16.41	12/12 Cohort

				High: 28.04±14.97 (p<0.05)	
Souza *et al* Resting vagal control and resilience as predictors of cardiovascular allostasis in peacekeepers	Male Brazilian Army Soldiers (n=50) Age: 25.4±5.99 BMI: 23.2±4.34	AVNN RMSSD 2min RMSSD 5min	Trier Social Stress Test Ergo Resiliency Scale (ER-89)	Significant Spearman's Correlations for the following: Basal Mean RRI-speech task: r=0.50, p=0.0003 Basal Mean RRI-arithmetic task: r=0.54, p<0.0001 Basal Mean RRI-recovery (speech): r=0.45, p=0.001 Basal Mean RRI-recovery (arithmetic): r=0.53, p<0.0001 ER-89, RMSSD: r=0.28, p=0.05	11/12 Cohort

2.4.4 Research Metadata

2.4.4.1 Study Designs

Three study design methodologies were utilised in the selected studies. Quasi-experimental studies [110,157,158] and case-control studies [97,159] represented a total of four included studies. All other studies were of a cohort design. The follow-up period for the cohort studies varied from single instances of data collection activity, such as administration of a questionnaire and a single ECG trace, to as long as 20 weeks of follow-up in one study [89].

Table 4. Expansion and definition of HRV measurement acronyms

Measurement	Units	Expansion	Application	Interpretation
RMSSD	ms	Root-Mean Square of Successive Differences	Primary measurement for short-term vagally mediated changes[a]	Time-Domain Measurements generally increase with increased aerobic capacity[a,b]
pNN20	%	Percentage of adjacent intervals that differ by more than 20ms	Assessment of vagal activity[a]	
pNN50	%	Percentage of adjacent intervals that differ by more than 50ms	Thresholds of ~6.8% or lower for disease states have been posited[c,d]	
AVNN	ms	Average value N-N; mean interbeat interval	Sensitive to changes in Psychological stress[e]	
SDNN (SDRR)	Ms	Standard deviation of all interbeat intervals	Most widely acceptable HRV measurement for	

		during the sample period	assessing cardiac risk (24-hour recording only)[a]	
VLF	ms^2	Very-Low Frequency Band power (0.0033-0.04 Hz)	Intrinsically generated by the heart[a] Modulated by sympathetic activity[a]	Low VLF power has been associated with cardiac death, PTSD and inflammation[a,f]
LF	ms^2	Low Frequency Band power (0.04-0.15 Hz)	Represents baroreceptor activity during resting measurements[a]	Can be used to estimate vagal tone[a,g]
LnLF	nu	Natural log of LF	Relative frequency band measurement to total power[h]	
HF	ms^2	High Frequency Band power (0.15-0.4 Hz)	Parasympathetic and respiratory activity[a]	Low HF values are associated with high stress[e] Correlated with RMSSD[a]
LnHF	nu	Natural log of HF	Relative frequency band measurement to total power[h]	
LF/HF	%	Ratio of LF to HF power	For resting seated measurements, likely measures PNS and baroreceptor activity[a]	Highly dependent on measurement conditions[a]

TP	ms^2	Total Spectral power	Useful for determining relative power measurements[a]	Broad estimate of total autonomic activity[a]
SD1	ms	Standard Deviation from y-axis on Poincare plot	Nonlinear measurement, useful for short-term analysis without trend sensitivity[a]	Predicts RMSSD, pNN50, SDNN, and power in the LF and HF bands, and total power during 5 min recordings[a,g]
SD2	ms	Standard Deviation from x-axis on Poincare plot	Nonlinear measurement, useful for long-term analysis without trend sensitivity[a]	Correlates with LF power[a]
SampEn	-	Sample entropy or approximate entropy	Quantification of the unpredictability of a time series[a]	Useful for short recordings which may have noise[a]
Alpha1	-	Short-term detrended fluctuation analysis Extracts the correlations between successive RR intervals over different time scales	Reflects baroreflex activity[a]	Useful when longer recordings are not available[a]

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c. Chakko S, Mulingtapang RF, Huikuri HV, Kessler KM, Materson BJ, Myerburg RJ. Alterations in heart rate variability and its circadian rhythm in hypertensive patients with left ventricular hypertrophy free of coronary artery disease. American Heart Journal. 1993 Dec 1;126(6):1364-72.

d. Mietus JE, Peng CK, Henry I, Goldsmith RL, Goldberger AL. The pNNx files: re-examining a widely used heart rate variability measure. Heart. 2002 Oct 1;88(4):378-80.

e. Montano N, Porta A, Cogliati C, Costantino G, Tobaldini E, Casali KR, Iellamo F. Heart rate variability explored in the frequency domain: a tool to investigate the link between heart and behavior. Neuroscience & Biobehavioral Reviews. 2009 Feb 1;33(2):71-80.

f. Shah AJ, Lampert R, Goldberg J, Veledar E, Bremner JD, Vaccarino V. Posttraumatic stress disorder and impaired autonomic modulation in male twins. Biological psychiatry. 2013 Jun 1;73(11):1103-10.

g. Voss A, Schroeder R, Heitmann A, Peters A, Perz S. Short-term heart rate variability—influence of gender and age in healthy subjects. PloS one. 2015;10(3).

h. Kuusela T. Methodological aspects of heart rate variability analysis. Heart rate variability (HRV) signal analysis: Clinical applications. 2013:9-42.

2.4.4.2 Demographics

Selected publications included males only in 11 studies, both males and females in seven studies and the gender distribution was not reported in three studies. Seven tactical subpopulations were represented; general law enforcement officers [142,160], Army [84,94,97,110,157,161,162], Defence Force trainees [89], Naval cadets [67], Army Ranger trainees [77] firefighters/rescue personnel [5,23,91,158,159,163] and Air Force fighter pilots [164]. Specifically, the Army personnel were members of either the US, Brazilian or Spanish militaries. For the Fire/Rescue personnel, members were serving in French, Brazilian, Finnish, Portuguese, or South Korean communities. A total of nine countries were represented: USA [142,157,160], Spain [94,97,110,161], Brazil [84,159,162,164], South Africa [89], Norway [67], France [77,158], Finland [91,163], Portugal [5,165], and South Korea [23].

2.4.4.3 HRV Analyses

Analytical methods vary widely in their mathematical approach and provide different information on different autonomic processes. Table 4 describes the HRV analysis methods discussed in this review and provides an expansion of each acronym, a brief explanation of the measurement, and its clinical implications.

2.4.4.4 Frequency-Domain and Nonlinear Analyses

The low-frequency band (LF) and high frequency band (HF) spectral power were the most popular analytical methods, with 18 studies documenting these HRV characteristics. Other spectral analyses included LF/HF ratio [4,23,77,89,157,159,162,163,165], total power (TP) [77], and the very-low frequency band (VLF) [163]. The nonlinear analyses included *alpha1* (α1), a measure of signal self-similarity [164], sample entropy (SampEn)[164], SD1 and SD2 [89,161,164].

2.4.4.5 Time-Domain Analyses

The root-mean square of successive differences (RMSSD) was the most popular time-domain analysis, with 11 studies documenting this HRV characteristic. Other time-domain analyses included pNN20 [4], pNN50 [4,89,159,161], mean interbeat interval, or AVNN [4,5,77,84,89,162], or SDNN/SDRR [4,23,77,89,158,163,164].

2.4.4.6 Aerobic Fitness

A total of four studies examined the relationship between one or more HRV metrics and aerobic fitness (VO_{2max}) [159,162-164]. Three of the four were cohort study designs [162-164], and one was quasi-experimental [159]. Three [159,164], including the experimental study [162], found significant relationships between one or more HRV values and aerobic fitness, and one did not [163]. The study finding no significant relationship examined only the LF/HF ratio and SDNN HRV indices. Of the studies reporting significant relationships, LF/HF ratio [162,163], sample entropy, PNN50, and RMSSD were examined. The pooled mean VO_{2max} across all four studies was 45.4±6.2 ml/kg/min, with the lowest VO_{2max} in the cohort of off-duty male Brazilian firefighters (40.0 ml/kg/min) [159] and the highest in the cohort of male Brazilian peacekeepers (52.9 ml/kg/min) [162].

2.4.4.7 Other Fitness Measurements

Two studies [160,164] examined fitness variables that were not estimates of aerobic capacity. One recorded one-rep maximum strength measurements from Brazilian fighter pilots (bench press, pull-down and leg press) and found no significant relationships between HRV indices measured on a rest day or on a flight training day and those strength tests. The other study [160] found a significant correlation between self-reported physical activity levels and the LF and HF signal strengths.

2.4.4.8 Tactical Scenario Simulations

Six studies utilised a simulated combat scenario for participant testing [94,97,110,157,161] or observed an actual tactical engagement [162]. Of these studies, all found significant pre-event to post-event changes in HRV. Specifically, one study comparing differences between high-performing and lower-performing soldiers in hand-to-hand combat training drills found significant time-domain differences (RMSSD, PNN50, SD1, SD2) between groups, but no differences in spectral-domain analyses. In the other studies, spectral analyses correlated with weapon accuracy and threat discrimination sensitivity [157], estimated energy expenditure, and hydration status as measured by percentage of body weight change of the course of the observation period [162]. One study in this category compared a light infantry unit to a heavy unit in a simulated ground combat scenario [97]. The light infantry unit, acclimated to such events and training, showed significantly different spectral responses when compared against the heavy infantry unit.

2.4.4.9 Cognition Testing

Three studies included a measurement of cognitive performance [5,67,94]. Of these three, one found significant correlations between sound recall and the LF domain following a combat simulation (see section above) [94]. One found significant relationships between greater basal RMSSD and two computerised cognitive stress tests, as well as during recovery from those tasks [67]. The last study found a significant decrease in AVNN at the start of a two-choice critical reaction time task and a significant change in LF/HF ratio following the task [5].

2.4.4.10 Occupational Stress

Three studies [23,84,142] measured occupational stress directly through surveys or through a tactically relevant evaluation tool. Andrew et. al [36] found an inverse correlation between lnLF and the 'lack of support' stressor; meaning that greater lack of support correlated with less vagal control as measured by LF power. Shin [23], in a sample of 645 professional South Korean firefighters, found significantly reduced RMSSD values in those that reported smoking, reported 'high' vs. 'low' job demand, and those that reported shift work. Significantly higher lnLF values were also reported in smokers. Souza et. al [84] measured trait resilience in a cohort of Brazilian Army soldiers using the ER-89 scale and found a correlation between trait resilience and RMSSD.

2.4.4.11 First Response Shift Work

Three studies assessed cohorts of fire and rescue personnel working 24-hour shifts [5,91,163]. Kaikkonen et. al [91] found a significant difference in RMSSD between the 6-hour firefighting and 6-hour ambulance phases of professional Finnish firefighters' shifts, with the rescue phase of the shift resulting in a decrease of RMSSD. Lyytikäinen et. al [163], previously mentioned above, examined HRV changes during the recovery days following a 24-hour shift. They found significant differences in the SDNN and LF/HF ratio from days 2 to 3 of recovery. Rodrigues et. al [165] found significant differences in LF/HF ratio during a variety of fire and rescue tasks. Specifically, the LF/HF ratio increased most during response to accidents. They also compared their mean N-N interval data to normative healthy adult data and found the rescue personnel lower AVNN values for rescuers, as well as higher LF/HF values.

2.4.4.12 Training Events

Two studies [77,89] followed participants through a period of tactical training. One [77] measured differences in AVNN, TP, LF, HF and LF/HF ratio between the start and end of French Ranger training. They found significant changes in all measured values. Grant et. al [89] assessed the differences in aerobic capacity and HRV values at one 12 and 20 weeks during South African Defense Force initial entry training. They found that while the mean AVNN, SDNN and RMSSD continued to improve between 12 and 20 weeks, the LF/HF ratio was not significantly different over the same time period [89].

2.5 Discussion

The aim of this review was to identify primary studies examining relationships between HRV and relevant health, fitness, and operational outcomes in tactical personnel, critically appraise the methodological quality of the identified studies, and summarise the results. The quality of the 20 included studies was generally high and included a variety of observational and quasi-experimental designs over a wide range of follow-up periods. While observational research was necessary for the aims of most studies, and variations in study designs and research questions covered a variety of topic in which single instance recordings were appropriate, few of the studies included in this review were longitudinal, and larger, more comprehensive datasets describing the HRV characteristics of tactical personnel in a variety occupational fields and settings would be beneficial. Further, the CASP checklists do not account for sample sizes, which were generally small, with a few notable exceptions, so while the methodology of the included studies may have been sound, caution must be taken when interpreting the results. Qualitatively, however, the studies included in this review generally agreed, and did indicate that HRV is an effective tool for measuring psychophysiological stress across professional environments and often correlates effectively with a wide variety of outcomes of interest. The included studies indicate that HRV measurements can be effectively applied across a wide variety of tactical settings.

2.5.1 Physical Fitness

Of the four studies investigating the relationships between HRV measures and aerobic fitness, only one found no significant association, and the mean VO_{2max} of 51 ml/kg/min was higher than all but one of the other studies. This could suggest a ceiling effect, indicating that aerobic fitness above a certain capacity within a certain profession lends no additional benefits to recovery, but all considered studies used an indirect, estimated method to determine VO_{2max}. Additionally, a variety of HRV analysis methods were used, and while frequency domain values did not trend significantly with physical fitness in all studies, the study by Oliveira-Silva, et. al, examining the cohort with the highest aerobic capacity did find a significant relationship when examining sample entropy [164], suggesting that non-linear methods may be the most suitable method for these study designs.

Further research in this area might focus on directly measuring aerobic capacity of the cohort, and conducting similar research investigating VO_{2max}, HRV and recovery in different tactical professionals. Larger sample sizes may also clarify these emerging relationships. So far, only one study has examined any measurements of strength, and no measures of power have been linked to HRV indices. While no significant associations were found in a cohort of fighter pilots, it may be possible that fitness within the strength and power domains contributes to individual perception and response to stress, as well as recovery from stressful exposures in other tactical settings.

2.5.2 Tactical Scenarios

All six studies measuring HRV during simulated or actual combat situations found significant changes. While not unexpected, these results nonetheless provide a foundation on which organisations can begin to consider implementing additional psychophysiological monitoring of personnel to assist in training and deployment decisions. While these studies achieved high levels of external validity, by exposing personnel to rigorously designed and realistic simulations, questions remain as to which factors within these scenarios most significantly affected the HRV indices of operators, and therefore, which components require further validation or incorporation into regular training. For example, it is possible that load carriage, a common task for tactical personnel, may influence chest biomechanics and perceived stress, independently altering HRV. Previous research has indeed demonstrated that even experienced tactical personnel report increased exertion when carrying a load, even if physiological measures, such as estimated energy expenditure, do not significantly change [166]. Spectral and time domain analyses of HRV may be able to quantify and explain these anomalies. Furthermore, while one study has conducted a threat identification scenario, live firearms were not used, and further research into the specific effect of live firearms operation on HRV may be necessary, and may provide additional information on underlying mechanisms that contribute to the effectiveness of deliberate HRV modulation as an intervention for improving tactical decision making [123]. For field measurements and analyses of HRV in these scenarios and similar scenarios, selecting more robust analyses, such as nonlinear and fractal-scaling methods may again be the most suitable.

2.5.3 Cognition Testing

Making decisions under pressure and other cognitive work is critical to the success of many tactical operations, and a key skill for ensuring operator and public safety. While the studies examining cognitive stress and HRV values are limited to only three, which represented the military and firefighting professions, the results are promising. The value for organisations may come primarily from the ability of HRV to discriminate and quantify the severity of responses to cognitive demands without relying solely on subjective feedback. The results from one study in particular by Delgado-Moreno, et. al, which assessed recall capability and spectral HRV analysis [94], may demonstrate that personnel who adapt to stressful stimuli struggle less with higher-order tasks. This type of analysis and its integration into training, especially in law enforcement, may be beneficial for improving decision-making training and promoting improved public safety.

2.5.4 Occupational Stress

The study by Shin et. al [23] was the largest cohort studied by a considerable margin, with a total of 645 participants. The Korean Occupational Stress Scale, while a subjective tool, is a widely utilised measurement of occupational stress and was used as the primary instrument [167]. They found that the organisation system and occupational climate were correlated with lnHF changes. Time-domain changes were also found in firefighters that reported high job stress. This agrees with another large cohort of manual laborers in Korea and suggests that organisational structures and employee support can have significant changes in the allostatic load of personnel [168]. Although the study by Shin et. al did not account for physical activity outside the workplace, the study by Kang et. al did and determined that social support was an independent risk factor for adverse HRV changes. Therefore, it cannot be assumed that improvements in physical conditioning will be able to fully counteract the potential negative effects of job stress induced by organisational, job support or occupational climate concerns. As such, tactical organisations may benefit from monitoring not only external occupational stressors and hazards but may potentially benefit from assessing the effects of internal organisational and support impacts. Further research accounting for physical conditioning in tactical personnel, and enhanced qualitative methods assessing occupational organisation, support and climate may clarify some of the unique causal relationships between organisation-induced occupational stress and allostatic load in tactical operations.

Likewise, in the study by Andrew considering police work stressors and cardiac autonomic balance, a significant association between a lack of organisational support and frequency-domain changes in HRV was found, but for female officers only [142]. The authors concluded that chronic insufficient organisational support may lead to a loss of the cardioprotective effect females typically experience as a result of greater vagal control compared to men. Their results were consistent with another study that found relationships between organisational occupational stress and metabolic disorder in women, but not men [37]. Given that females will typically form a minority within a tactical organisation, specific regard to their occupational support may be especially necessary to support their health and effectiveness. One solution Andrew and his colleagues offer is for police organisations to provide for support coping opportunities, a method of stress coping more typically adopted by females. Further research may investigate the effect of occupational organisation, support methods and climate with specific regard to female operators or trainees to determine optimal strategies for maximising their performance.

2.5.5 Shift Work

While shift work is endemic to many tactical organisations, the studies in this review represented exclusively fire and rescue personnel, and the results indicated that the autonomic impacts of shift work in tactical personnel may manifest differently than in other populations. For example, two separate studies in two very different geographical locations (Finland and Portugal), both found that fire and rescue personnel who were assigned to rescue duties, which included motor vehicle accident response, experienced significantly greater HRV changes than when they worked regular fire suppression duties [5,91]. Research in healthcare workers found limited differences between physicians and nurses who worked rotating shifts and those who worked day shifts only [169], indicating that research considering longer-term HRV measurements, such as the VLF component of the frequency-domain and the nonlinear SD2, may require careful interpretation in tactical settings.

Other work in this area to aimed at using HRV indices to measure physiological strain, which may then be used when determining work/rest cycles and other scheduling concerns. Time-domain analyses were the most common across these studies, but spectral analyses were also represented and were significant. While no significant associations were found between $VO2_{max}$ and shift recovery (discussed above), it should be noted that the autonomic effects of shift work lasted up to three days [163]. Given that males may be more susceptible to adverse HRV changes induced by circadian rhythm disruptions [170], and that males comprise the majority of most tactical organisations, the effects of shift work on autonomic regulation should be investigated further in a wide variety of tactical operations to develop stronger evidence to guide policy decisions. Further studies or reanalysis efforts may also aim to apply novel indices, such as sample entropy or other signal-self similarity assessments to strengthen the relationships between HRV measurement, physiological strain, and organisational utilisation of operators. Given the differences in HRV responses to different duties even within a single unit, other populations that rely on rotating shifts, such as law enforcement and military organisations should also be considered separately to determine the unique influences present between professions and how to proceed with long-term HRV measurement interpretations.

2.5.6 Training Events

Two studies followed trainees through a period of accession training, one a Ranger training course in France, and the other basic military training in South Africa. Both found that tactical training results in HRV changes across both time and spectral domains, and one was specifically using HRV to assess for the presence of overtraining syndrome (OTS) between the 12th and 20th week of training [89], as OTS is known to contribute to injury risk [171]. A link between HRV and chronic musculoskeletal injury has been proposed in endurance athletes [78], and if proven effective, tactical organisations may be able to screen and triage trainees before clinical symptoms develop, reducing the burden of injury during training. One recent study in CrossFit™ athletes found significant associations when investigating the relationships between workload and HRV in the time domain [53]. Given the similarities between CrossFit™ and tactical conditioning activities [149], this association may prove especially valuable for tactical training programs and warrants further investigation in larger cohorts of tactical personnel. As previously stated, more robust HRV analytical methods may also be beneficial for inclusion in further studies.

2.6 Conclusions

The measurement and application of HRV indices to monitor psychological, physiological, and more specifically, autonomic stress, encountered by the tactical operator continues to be developed and has made significant strides over the past decade in terms of utilisation by a wide range of organisations, comparison to normative populations and quantification of the stress of tactical work. While strong evidence is still emerging, based on the quality and general agreement of studies included in this review, HRV monitoring appears to provide valuable insight into the psychophysiological responses of tactical personnel during occupationally relevant activities and recovery from those activities. However, substantial further research is still necessary. Specifically, the recruitment of larger cohorts and the collection of normative data specific to healthy tactical personnel should enhance result interpretation. Additionally, further isolation and analysis of specific variables relevant to the end user, such as the independent effects of load carriage, may help determine causal relationships, strengthen the reliability of applications, and ultimately provide personnel with an additional tool to maximise health and performance. Finally, HRV may prove to be highly effective for mitigation of chronic musculoskeletal injury in tactical operators and trainees as a screening tool, but such associations require further exploration, in terms of both cohort selection and recruitment and HRV analysis method(s).

2.7 Afterword

Of the 20 studies identified in this systematic review of the literature, only two evaluated HRV in the law enforcement profession; one considered a mixed cohort of military infantry and specialist police. The other study drew from populations of general duties officers. Due to the minimal representation of specialist police in the evaluated literature, this population was of chief interest. Specialist police work consists of a wide variety of duties, including search and rescue, counterterrorism, explosive ordnance disposal, high risk warrant service, policing engagements involving hostile entities with firearms, and illicit material transport interdiction. Personnel are typically employed as specialists only after accruing sufficient experience in general duties and must undergo rigorous selection courses that evaluate potential for performance in the above domains of work. Given these complexities, two research arms were devised. These addressed both the contexts of selection factors and comprehensive operational factors that require further research attention. Selection factors were considered those aspects of the individual that are screened for during selection courses. These include physical fitness, psychomotor skills, or trainability to develop psychomotor skills, and resilience under stress. Findings from this review did not consistently describe a relationship between HRV, aerobic fitness, and occupational performance. The systematic review did indicate cognitively engaging activities were closely linked with changes in HRV, but none were occupationally relevant to specialist police selection, and thus will be further explored in this thesis.

Conversely, operational factors are comprised of work-based operational demands, such as shift schedules, ongoing specialised occupational fitness assessments, and service on collateral duties, such as conducting a training exercise. The above review did note changes in HRV as a result of overnight shift work, but these appear to be heavily influenced by context, and thus merit further study in the unique population of interest. Further, Relationships between HRV and anaerobic activity were not identified in the review. Understanding these relationships is of importance given that specialist police perform tasks that are anaerobic in nature (e.g., pursuit of suspects, subduing offenders, rapid movement to clear a building or evacuate a casualty, etc.) [35,172,173]. Finally, while much literature attention is paid to trainees, those operational staff that conduct selection activities may also be subject to overstress as measured by HRV.

While this thesis will not necessarily consider solutions for each or all of these factors, the role of HRV in describing the effects of both selection and operational factors will be thoroughly explored. Given that the objectives and goals of incorporating HRV monitoring will be necessarily different in each context, selection versus operational, each will be considered in its own research arm, despite their interdependence.

2.8 Of note:

Being conducted during the COVID-19 pandemic, this review was fraught by several challenges. Not only was the primary author limited to virtual contact with the other authors, that is, the supervising team, but delays due to the pandemic resulted in some valuable literature that might have been informative to the overall findings unavailable. More recent reviews have capitalised on the gaps in the review above, and the content has been utilised and referenced as support in following chapters [75].

Chapter 3 – Defining the Problem: Insufficient Data on Specialist Police and Holistic Stress Assessment

3.1 Preface

Chapters One and Two introduced tactical personnel as a unique and critical population and the concepts of heart rate variability (HRV) monitoring while also critically appraising the current research on the topic. These chapters also assessed the current literature exploring both tactical personnel and HRV. This chapter aims to characterise the gaps in the literature and illustrate how these gaps will be addressed.

3.2 Gaps in the literature

Based on the findings in the narrative (Chapter 1) and systematic (Chapter 2) reviews, the following gaps in the literature were identified:

- No heart rate variability (HRV) research in specialist policing populations was identified.
- The relationship between aerobic fitness, HRV, heart rate (HR), fitness, and occupational performance remains unclear.
- The extent to which HRV may be utilised to predict or determine attrition in specialist police selection has not been considered.
- The effect of psychosocial stressors on HRV in specialist police selection has not been evaluated.
- While firearms performance and HRV have been researched, the literature remains scarce, does not consider live firearms or the added stress of a selection environment.
- While overnight shift work does have an established relationship with HRV, it appears to be heavily dependent on context; and has not been explored in specialist police.
- Anaerobic fitness is a key operational requirement for specialist police. Its relationship with HRV in operational context has not been considered.

- While much research attention has been given to trainees undergoing selection, demands on the operational staff conducting selection activities may also impose overstress, and have not been previously assessed.

3.3 Research Aims and Approach

The overall aim of this program of research was to determine the utility of HRV assessment as a human performance optimisation (HPO) tool and decision-making support within specialist police organisations and alert stakeholders to conditions of potential overstress and allostatic load. To address this research aim, two career stages of specialist policing will be investigated: being initial selection, and as operational personnel.

3.3.1 Selection Research Arm

To achieve this goal, research is needed at two distinct but related levels of resolution governing the operations of any tactical police team: selection and operations. At the selection level, personnel are under continuous assessment as future specialist team members with a focus on occupational suitability, team role development, team function and cohesion enhancement, and physical or executive performance development [39]. However, selection activities must mitigate potential risks of harm during events and scenarios while preserving sufficient fidelity for the training to be meaningful. Selection must also simultaneously avoid applying overstress or overtraining syndromes and personnel burnout [174]. Factors relevant to health and performance at this level that may be traceable with HRV include aerobic fitness, cognitive stress and performance, and tolerance to sleep and food deprivation, as well as environmental rigors such as heat and cold [55,90,95,97,110]. HRV data in this domain should aim to be usable without aggregation were by data for each team member should be relatively easy to obtain, interpret and analysed by the individual or by assessing staff as needed.

3.3.2 Selection - Operational Nexus

Once personnel have sufficiently progressed through selection, Directing Staff (DS: qualified officers in charge of selection) segue from assessing for trainability and begin instructing and developing candidates. In this phase, candidates begin performing realistic simulations of actual operational duties, and daily activities may be difficult to distinguish from regular ongoing training operational personnel participate in regularly. This final phase of selection provides a unique research opportunity to 'bridge' between research foci; while candidates remain under pressure to succeed and progress to operational status, their tasks are based on those undertaken by operational personnel and thus provide insight into both study arms proposed in this thesis.

3.3.3 Operational Research Arm

At the operational level, teams conduct a wide variety of missions, including high-risk warrant service, response to violent and potentially violent confrontations, and other high-risk or potentially high-risk incidents related to law enforcement and public safety [35,175]. While conducting operations, personnel must place their health and well-being at risk to achieve the mission directive and preserve public safety. Although efforts are taken to protect all individuals involved in incident response, priority is given to mission success. Apart from the effect of prolonged operational activity in austere conditions [44], factors relevant to unit-level health and performance that may be traceable with HRV include the effects of rotating shift work, intensity of ongoing unit training, and other demanding tasks (serving as a DS member on a selection course as an example). While demanding, if monitored holistically, HRV data can be used by the individual or in aggregate to unit leadership to inform personnel-related decisions such as operational schedules, shift assignments, training, and other administrative needs.

3.4 Thesis structure

As described at the end of Chapter 2, despite the robust body of literature considering the applications of HRV monitoring across a variety of tactical contexts, the specialist police population has been subject to little investigation. Specialist police as tasked with substantial occupational variety and select members from pools of already experienced law enforcement officers. Because of these complex factors in both selection and operations, two research arms were developed to address both the selection and operational contexts. These have been summarised in Figure 4 below, showing the logic flow from literature gaps to research question, and studies undertaken to evaluate these gaps and consider the questions. Figure 5 diagrams the thesis structure as well, but with consideration to the two-armed approach described above.

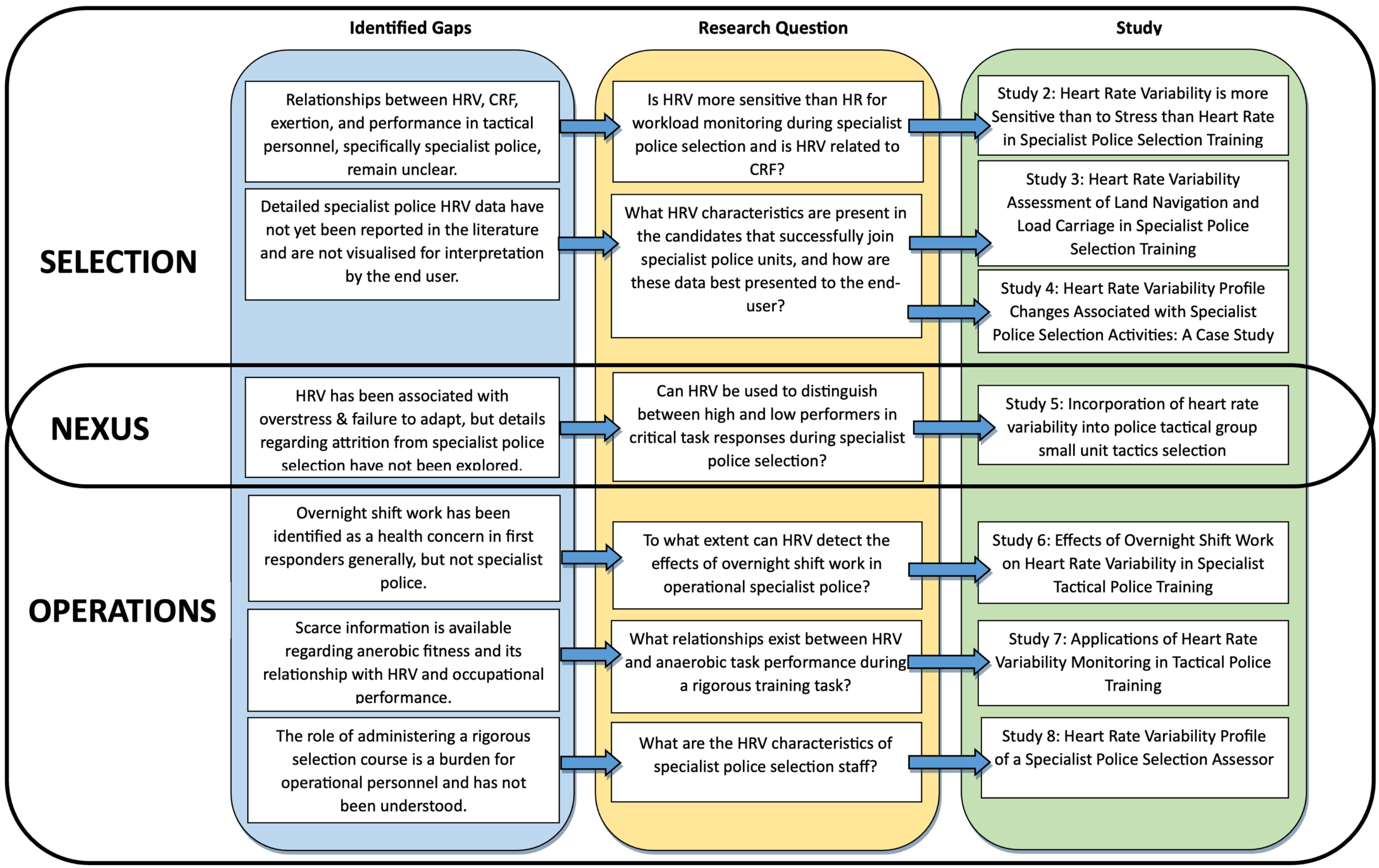


Figure 4. Thesis Structure Diagram

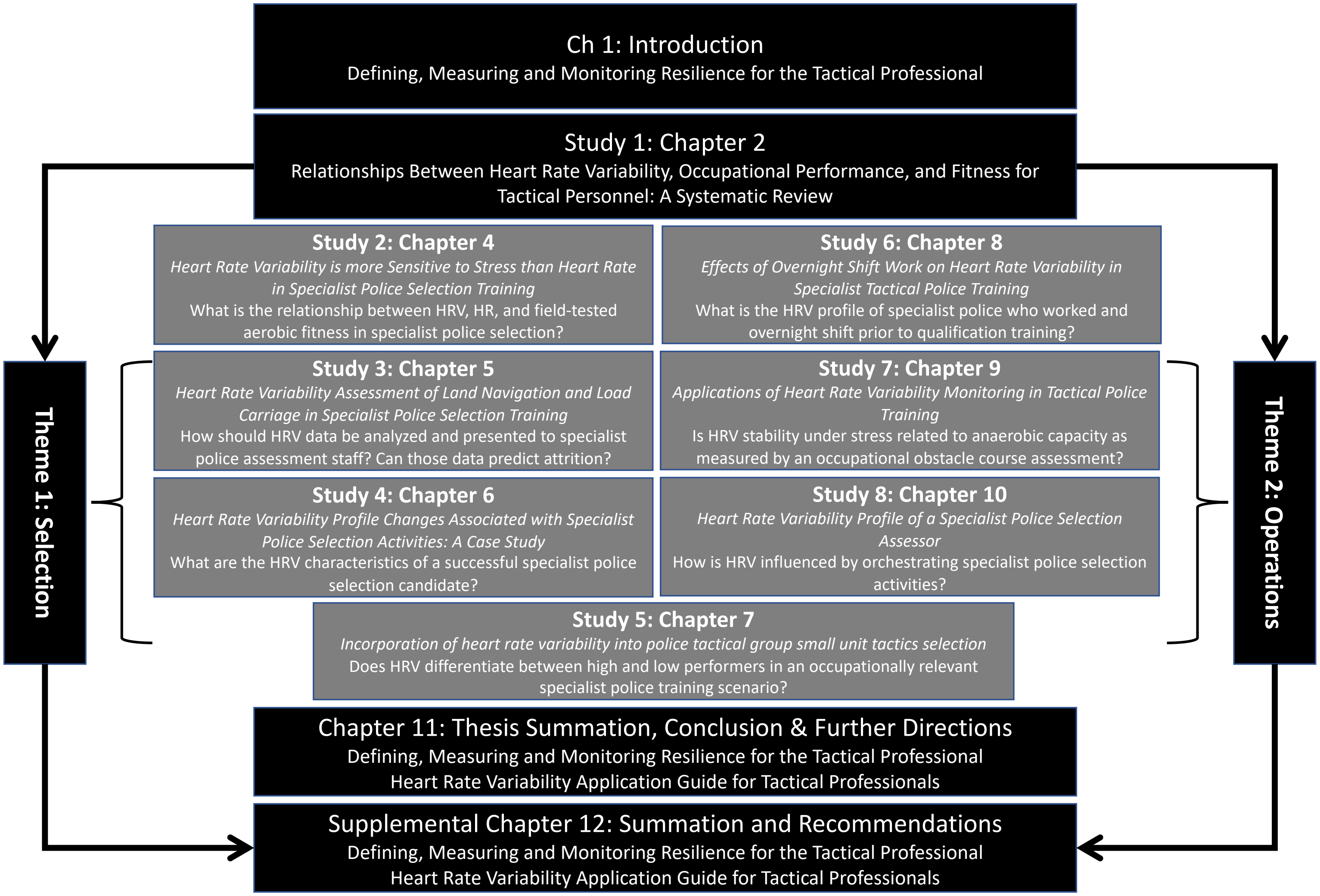


Figure 5. Thesis Flow and Structure Diagram

3.5 Afterword

As identified in this chapter, there is a lack of evidence describing the role of HRV monitoring in the specialist police population. HRV monitoring may have potential benefits across the occupational lifespan of these personnel, from initial selection through to operational performance support. While interrelated, these aims are sufficiently distinct enough that two separate research arms are indicated.

Finally, while all results may not necessarily generalise across tactical populations and teams, as many tactical environments are heavily influenced by local geography and demographics, many elements are uniformly similar across regions and disciplines [39]. Therefore, research conducted within these similar elements (e.g., selection, shift work, etc.,) may be useful to other tactical organisations. Further, as is typical with paramilitary organisations, specialist police units train and operate with traditional police elements, other first responders, and the military, an ideal nexus between professions for generalisation to other related professions exists. Indeed, previous literature has combined army personnel and military police cohorts when conducting research on HRV utility [157]. Providing data-driven and evidence-based physiological monitoring and solutions in this setting and distributing the investigative framework may improve the health and safety of tactical teams, provide a foundation for other units, and thereby facilitate enhanced community safety.

Chapter 4 – Selection Factors: Heart Rate Variability is more Sensitive to Stress than Heart Rate in Specialist Police Undergoing Selection

4.1 Preface

This chapter reports on the findings of Study 2. The systematic review (Study 1 [55] reported in Chapter 2) identified prolonged periods of exertion [84] substantially influenced heart rate variability (HRV) in tactical personnel. In the discussion regarding HRV and its relation to physical fitness during occupational tasks, the relationships remained unclear, though studies tended to agree that HRV during such tasks would generally be greater in those with greater aerobic fitness. Indeed, while in general it is accepted that greater aerobic capacity will likewise drive greater HRV [52], heart rate (HR) is typically the metric used for measuring exertion in such scenarios within tactical units [176]. However, many activities in tactical contexts also impose cognitive and psychosocial demands. As such, HRV may be more sensitive than HR to other stress sources. Therefore, investigating whether HRV would be a more sensitive measure than heart rate during tasks that have combined physical and cognitive demands would be of benefit, as may be investigating any associations with aerobic fitness. To meet this objective, relationships between HRV and HR, and load carriage performance, are of interest as not only is aerobic fitness strongly associated with load carriage performance [177], it is a strong predictor of selection success and is often integrated with tasks imparting cognitive demands (e.g., navigation) [178,179].

This study has been accepted for presentation at the Bond University Tactical Research Unit Rapid Fire Mini Congress 2023.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

4.2 Abstract

Background: Police tactical group (PTG) officers respond to the most demanding and high-risk police situations. As such, PTG personnel require exceptional physical fitness, and selection for employment often evaluates fitness both directly and indirectly. While heart rate (HR) is often used to measure physical effort, heart rate variability (HRV) may be a valuable tool for measuring stress holistically and may provide information valuable to selecting candidates. The primary aim of this research was to investigate whether HRV was more sensitive than HR at monitoring workload during key PTG selection activities. As aerobic fitness is associated with workload during these tasks, a secondary aim was to investigate relationships between HRV, HR and aerobic fitness during the same tasks.

Methods: Using a cross sectional analysis, the relationships between HRV (percentage of adjacent R-R intervals varying by 50% or more; pRR50%) and HR, as measured by ambulatory electrocardiograms obtained during a specialist police selection course, as well as aerobic fitness, as determined via total shuttles completed on the 20-meter multistage fitness test (MSFT; 'beep test'), were investigated. This study included a cohort of six male PTG candidates ($n = 6$) undergoing selection.

Results: As illustrated by a time-series plot, HR values were generally unremarkable, but HRV values were potentially depressed, and tentatively indicated overstress. The MSFT was significantly, positively, correlated with pRR50% (ρ (6) = 0.812, $p = 0.050$, Fisher's $z = 1.132$). The MSFT and HR were not significantly correlated (ρ (6) = -0.522, $p = 0.288$). When a linear regression model was applied, neither HRV nor HR were predicted by MSFT score.

Conclusions: The findings described in this study indicate that HR alone is likely not sufficiently sensitive to provide detail on the stress response of candidates undertaking essential tactical tasks that combine physical stressors with cognitive load in adverse conditions. However, HRV analysis may provide additional insights regarding candidate suitability for unit leadership and directional staff, though the causal direction of the relationship between HRV and aerobic fitness remains unclear.

4.2.1 Keywords: SWAT, biosignals, conditioning, performance, employment standards

4.3 Introduction

Police work is a physically and mentally demanding profession [8,33,145]. An officer will inevitably be required to run, jump, crawl, and balance while moving quickly, subduing suspects, climbing, lifting, and pushing or pulling significant weights in the execution of their duties; often without warning [7,8]. Additionally, the law enforcement profession requires performance of these arduous occupational tasks while carrying an external load of over 10 kg[33] and over shifts that may last in excess of 12 hours [180], exposing officers to high levels of physiological and psychological stress [35]. In order to perform these occupational tasks safely and effectively, police personnel must not only be sufficiently fit but also resilient enough to perform these tasks regularly without experiencing excessive stress across a career [39].

Police Tactical Groups (PTGs) respond to the most high-risk incidents and may utilise equipment and procedures that differ from conventional police work. As such, exceptional fitness levels are required and frequent exposure to high stress scenarios often occurs [35,39]. Therefore, selection for service in these capacities must be rigorous, challenging, and occupationally relevant [40,181]. Unit leadership and assessment personnel evaluate PTG candidates not only for physical aptitude, but also tolerance of uncertainty, teamwork, leadership, and responses to adversity [14,35]. For example, one selection exercise common in many tactical organisations is land navigation [179,182]. Land navigation exercises challenge candidates to traverse various terrains to reach grid points using only a map and compass. Not only can this be physically arduous, but effective land navigation requires computation, recollection of steps taken and cadence, as well as ability to utilise and plan routes of varying complexity with rudimentary tools [182]. Further, environmental conditions for these exercises are often deliberately adverse, conducted in regions with harsh terrain or extreme heat and/or cold and over substantial length of time. These events may also be immediately preceded with other physical and mental challenges, and personnel will often receive limited rest after their conclusion. Thus, PTG candidates are potentially at an increased risk of allostatic load sources during selection [37,56].

Assessing the loss of dynamic and adaptive regulatory responses that may signal the onset of allostatic load is therefore of critical importance. Heart rate variability (HRV), the fluctuation and oscillation across time of individual heart beats, results from a dynamic relationship between intrinsic cardioregulatory factors as well as extrinsic factors, namely the sympathetic (SNS) and parasympathetic (PNS) nervous systems [68,69] . As such this measure may be utilised as a measure for quantifying stress in tactical populations [183], particularly during rigorous training, such as PTG selection [142,157,165]. While low metabolic fitness may not be a concern in specialists, and is screened for diligently, other sources of stress that may contribute to allostatic load (e.g., cognitive demands[56,135], cannot be ignored. As HR alone may not be sufficiently sensitive to detect this load and more precise laboratory measures, such as muscle sympathetic nerve activity or functional magnetic resonance imaging (fMRI), are not practical in PTG units, HRV may be a viable measure [75].

Furthermore, while previous literature at the meta-analytical level has indicated that aerobic fitness is an effective predictor of training injury in tactical selection courses [184], the specific mechanisms remain unclear. While many factors likely contribute to the relationship between fitness and injury, one plausible explanation is that those with greater aerobic fitness can maintain a fixed workload at a lower percentage of their potential maximum relative to less fit peers [185,186]. This reduced relative load may protect a candidate from excessive physical stress. Indeed, in research in the military population, such a relationship was indicated to extend also to cognitive tasks and vigilance [187]. However, whether this is the case in PTG personnel undertaking tasks that are both physically and cognitively demanding (e.g., loaded navigation tasks under the scrutiny of staff) is not affirmed. With the review (Chapter 2) finding relationships between HRV and aerobic fitness, this was not the case in one study [163] whose participants had a VO_{2max} of 51 ml/kg/min, suggesting a potential limit in the relationship between maximal aerobic fitness and HRV as VO_{2max} approaches highly fit to elite levels. However, participants in this study by LyytikÄInen and colleagues were assessed during their recovery from a 24-hour shift as emergency response workers, and therefore their off-duty time may have imparted little cognitive requirements[163]. This is of note given that PTG personnel generally have higher fitness levels than non-specialists and the general population but may be performing tasks that are both physically and cognitively demanding [39]. Thus, HRV analysis may be an amenable strategy for describing this dynamic with detail in situ [183].

The primary aim of this research was to investigate whether HRV was more sensitive than HR at monitoring workload during key PTG selection activities. As aerobic fitness is associated with workload during these tasks, a secondary aim was to investigate relationships between HRV, HR and aerobic fitness during the same tasks. The authors hypothesised that HRV would be more sensitive to potential allostatic load responses than HR. In addition, HRV would be more strongly related to aerobic fitness than HR during selection activities, as HRV measurement may indicate holistic psychophysiological response to stressors more precisely.

4.4 Methods

This investigation was conducted at an Australian State PTG facility in Autumn of 2022. A cohort study approach was utilised, combining a combination of retrospective and prospective data. HRV was measured continuously using wearable electrocardiogram (ECG) devices for the entirety of an approximately five hour land navigation exercise. Temperature ranged from 24.2 – 34.4°C and relative humidity ranged from 60 – 75%. Aerobic fitness data were derived from candidate records, indicated as level, shuttles. All procedures were conducted in accord with the Declaration of Helsinki of 1964 and its later amendments. Candidates provided their informed written consent, and the PTG unit provided permission for publication of this work. The research protocol was approved by the Bond University Human Research Ethics Committee (2019-022 amnd 2).

An initial cohort of 18 male Australian State Police Officers were inducted into a one-day physical training selection. While female officers would have been permitted at selection and eligible for inclusion in this study, none had applied for this selection cycle. Attrition from the One-Day assessment was high, with 12 of those initially entering the course either voluntarily withdrawing or not meeting physical fitness standards. Therefore, of those 18, only six individuals were eligible to participate in the additional two-day selection course on which this study was based. All candidates eligible for the two-day selection course were eligible for inclusion in this study. There were no exclusion criteria, and all available personnel were recruited. Individual anthropometric data were not available as per a privacy agreement with the PTG, however, all candidates disclosed that they were taking no medications for cardiovascular, renal, or respiratory conditions as a requirement of participation in this study. Combined data can be found in Table 5 and includes anthropometrics, load carriage weights, and aerobic fitness data.

For this study, height was self-reported; self-reported anthropometrics have been utilised as reliable metrics in research in previous literature in law enforcement populations [188]. It should be noted that while HRV may be influenced by factors such as age, body mass, and potentially body mass index (BMI), these data limitations are not uncommon in the population of interest [189]. Further, the summarised data presented demonstrate little variance (Table 5). The aerobic fitness data were collected from the 20-m Multistage Fitness Test (MSFT) conducted approximately two weeks prior to the selection course following protocols previously described in the literature [172,190,191]. Final levels and stages were converted to total number of shuttles completed for the analysis as opposed to conversion to VO_{2max} given limitations in these predictions [192].

Table 5. Anthropometric, Load Carriage and Fitness data of Australian PTG Candidates

Value	Body Mass (Kg)	Height (cm)	Age (Years)	Land Nav Equipment Mass (Kg)	Pack March Equipment Mass (Kg)	BMI (Kg/ m^2)	MSFT (Total shuttles)
Mean	93.63	180.17	30.67	12.24	11.95	28.88	84.17
SD	8.83	5.98	2.94	0.14	1.32	2.92	7.22
Median	94.78	181.00	31.00	12.24	11.96	29.22	81.00
Range	20.50	21.08	14.00	8.00	0.20	8.47	1.9

Legend: body mass index (BMI), multistage fitness test (MSFT). Range is reported as the difference between maximum and minimum values.

The two-day selection course consisted of additional physical training activities, but also essential specialist police task training and assessment. Activities included orienteering, firearms manipulation, threat de-escalation, load carriage, and casualty evacuation. The land navigation (orienteering) exercise consisted of a sequence of navigational points candidates located and travelled to on foot utilising orienteering methods. This task was not only physically, but

cognitively demanding and is a known source of attrition for many tactical professions [44,173,177,178]. Further details of the selection activities can be found in
Table 6.

Table 6. Description of Selection Course Serials and Start Times

Serial	Description	Start Time (Duration)
Briefings and equipment issue	Candidates were briefed on expectations and role of the PTG. Standardised equipment was provided and any individual items were inspected for approval.	0705 (1:50)
Written examination	Multimodal assessment of land navigation (orienteering) principles.	0850 (0:25)
Administration	Mobilisation, review, and further explanation of expectations for the land navigation exercise.	0930 (0:35)
Land Navigation Preparation	Candidates were provided time to plan their routes and mark their maps before embarking.	1005 (0:20)
Land Navigation Exercise	Orienteering assessment of navigation over various terrain using only a supplied map, compass, and grease pencil.	1018 (5:00)
Administration	Mobilisation, hands-on assessment, and written safety/proficiency check.	1547 (2:50)
Load Carriage/Pack March	Various load carriage and transportation of stores at self-selected pace. Candidates proceeded for undisclosed time/distance.	1850 (-)

All candidates were supplied EQ02+ LifeMonitor (Equivital™, Cambridge, UK) wearable monitoring harnesses to capture ECG signals throughout the selection course. Each harness was individually fitted to each candidate to ensure electrode contact points were secured. Previous research indicates the Equivital system is comparable in terms of validity and reliability to the gold-standard Holter ECG monitor when artifact levels are low (<20%) [193]. Physiological measures were observed through accompanying software (EQ View Pro, Equivital™, Cambridge, UK, and LabChart 8 Pro, ADInstruments, Sydney, Australia). HRV measurements were assessed under both long-term and short-term ranges. For the purposes of correlation and regression analyses, the more stable, long-term value was utilised, as the task of interest was over five hours duration. The short-term analyses were compiled as consecutive 5-min samples plotted as a time series to demonstrate the most precise moment-to-moment changes in HR and HRV with acceptable validity.

For inferential analysis, HRV was assessed using percentage of adjacent R to R waves varying by at least 50ms across entire sequence of recording, as it is a candidate marker of cardiovascular disease risk [111]. While all candidates involved in this study were apparently healthy at the time of data collection, cardiovascular disease risk is known to be greater in the law enforcement profession than in the general population, as described above [133]. The ECG recording window of interest began at approximately 0730 and ended at approximately 2000 local time. This timeframe comprised the entirety of the land navigation exercise, which consisted of an average traversed distance of 9.07 km over mostly even, but hazardous terrain in environmental conditions ranging from 24.2 – 34.4°C and relative humidity ranged from 60 – 75%. Short-term analyses were conducted via the method described above.

Descriptive statistics, including the Shapiro-Wilk test for normality, were obtained, and considered prior to any inferential statistical approach. Distribution plots were also analysed visually by variable. Spearman's rho was selected for correlation analyses, as it is appropriate for non-parametric analyses [194].

4.5 Results

All collected data fell within the 'low' range for artifact presence (<20%) [193]. All six candidates successfully completed the land navigation event. Attrition events began occurring at approximately 1945 – 2000 hours, leading to the conclusion of the data collection window. Time-series plots of HR and HRV (pRR50%) are shown below in Figure 6. Visual inspection demonstrates the difference in fluctuations between HR and HRV during training. Summarised MSFT, HR, and HRV values are presented in Table 7.

Figure 6. Comparison of heart rate (HR) and HRV values by participant (P1 – P6).

Mean values are plotted and demonstrate that while HR values may appear unremarkable, HRV values can fluctuate and indicate stress and workload levels more precisely.

Table 7. Summarised MSFT, HR, and HRV Values

	MSFT (s)	**MSFT Shuttles**	**Mean HR (bpm)**	**pRR50%**	**SD1 (ms)**	**SD2 (ms)**	**HF (nu)**	**LF (nu)**	**RMSSD (ms)**
Mean	474.33	84.17	121.82	11.40	93.35	147.21	53.50	38.25	132.02
SD	24.15	7.22	19.93	6.34	42.61	53.58	13.09	17.11	60.28
Median	466.50	81.00	118.10	9.23	105.12	149.45	56.88	33.16	148.70
Range	66.00	19.00	57.09	17.53	123.21	154.55	37.07	46.40	174.30

Legend: MSFT: Multistage Fitness Test, HR: Heart Rate, bpm: beats per minute, pRR15: percentage of R-to-R intervals varying by at least 15ms, SD1: Geometric Standard Deviation 1 (X-axis), SD2: Geometric Standard Deviation 2 (Y-axis), HF: High-frequency, LF: Low-frequency, RMSSD: root-mean square of successive differences, SD: standard deviation. Range is reported as the difference between maximum and minimum values.

After conversion from raw score to total shuttles, the MSFT scores were substantially skewed. For this reason, further analysis conducted after correlation tests were conducted using a transformation of total MSFT shuttles. The transformation that best achieved tolerable skew, kurtosis, and normality was the log10 of the identity. Further details regarding this method are described by Tabachnick and Fidell [194].

Regarding the results of the correlation analysis, the percentage of pRR50 intervals was significantly and positively correlated (ρ (6) = 0.812, p = 0.050, Fisher's z = 1.132) with the MSFT (total shuttles completed without transformation). HR (ρ (6) = -0.522, p = 0.288) and other HRV metric results were not significantly correlated with the MSFT. Further details regarding the correlation analyses can be found in Figure 7.

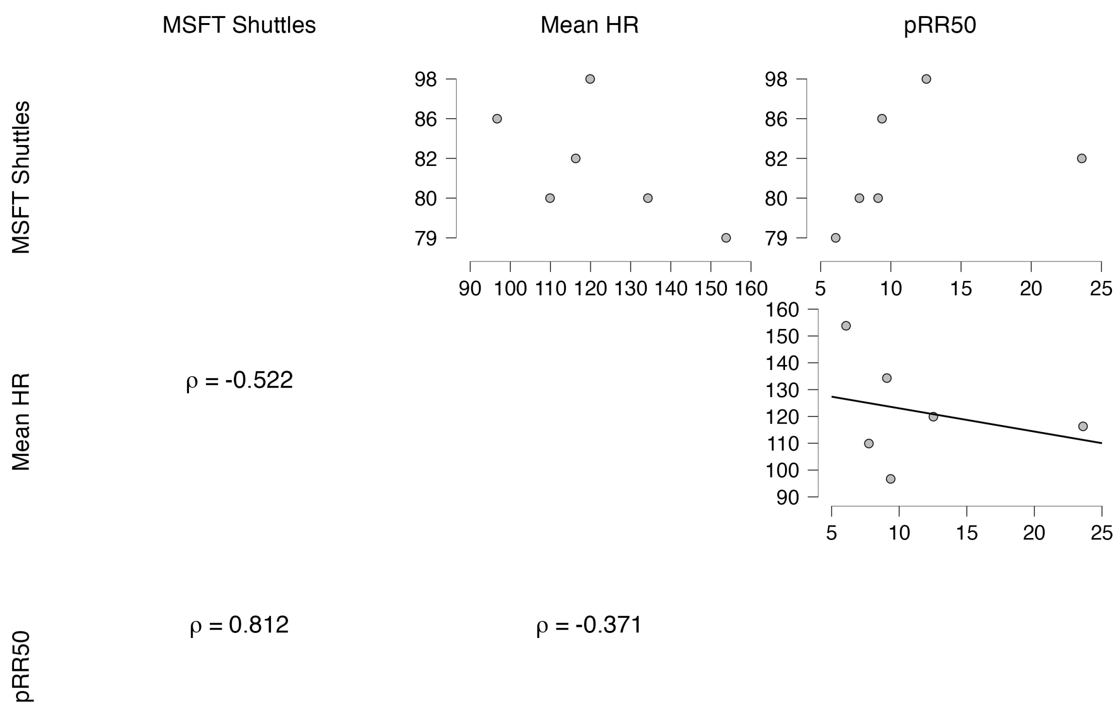


Figure 7. Spearman's Rho Correlation Scatter Plots describing the relationships between HR, HRV, and MSFT time.

The HR and HRV data did not require transformation. Results of the linear regression models can be found below:

Linear model predicting HR by Log10 MSFT score:

$$r2 = 0.113, F(1,4) = 0.512, p = 0.514$$

Linear model predicting pRR50% by Log10 MSFT score:

$$r2 = 0.027, F(1,4) = 0.112, p = 0.755$$

Neither the linear model for prediction of HRV (pRR50%) nor the model for prediction of HR reached statistical significance (p >0.05).

4.6 Discussion

The primary aim of this research was to investigate whether HRV was more sensitive than HR at monitoring workload during key PTG selection activities. As aerobic fitness is associated with workload during these tasks, a secondary aim was to investigate relationships between HRV, HR and aerobic fitness during the same tasks. The hypothesis that HRV would be more sensitive to allostatic load responses than HR was potentially confirmed. The hypothesis that HRV would be more strongly related to aerobic fitness than HR during selection activities was tentatively confirmed but could not be completely verified.

HRV, specifically the pRR50 index, demonstrated that even when physical exertion may be moderate to low, as indicated by HR (average HR: 121.82±19.93 bpm, Table 7), HRV shows a more precise picture of potential stress or workload, as HR values were generally unremarkable. HRV values, however, were generally suboptimal and suggest overstress, in that while depression of HRV, specifically pRR50 intervals will regularly drop to zero or near-zero levels during exercise (mean pRR50: 11.40±6.34%, Table 7), the literature generally describes exercise protocols of high intensity (~75% HR_{max}) producing these responses [113]. Given the low HRV observed in this study without commensurate elevation in HR suggests that either additional factors like cognitive load and uncertainty intolerance were present to drive a greater stress response than HR would indicate, and (or) a level of exhaustion was present [53,67,195]. Indeed, cognitive load likely explains why the land navigation event resulted in disparity between HR and HRV measures [12,179,182,196]. As stated, none of the candidates approached heart rates that might be considered near maximal during the navigation exercise [172]. Essentially, the submaximal physical nature, yet high overall stress induced by environmental conditions, pressure to succeed, cognitive challenge, and imposition of uncertainty could not be discriminated by HR alone. Fluctuations in HRV, however, which is sensitive to cognitive load in addition to physical load, were more effective measures to indicate potential overstress: an average HR of 138 bpm (the highest observed in this study) is not anomalous, however, pRR50% values below approximately 3% are potentially of concern [113,114]. If candidates were generally of high fitness, as the data would support, the physical load alone of the navigation exercise may not have resulted in sufficient physical strain for fitness levels to stratify HR during the event. Conversely, the cognitive load may have been more taxing for the candidates in this selection course [4].

The results show that during the PTG task battery, HRV trends with aerobic fitness, but HR does not. However, the causal relationship could not be evaluated definitively in this study. While possible that high aerobic fitness attenuates HRV depression when under stress from multiple sources, the linear regression model does not support this conclusion. As such, it is likely that aerobic fitness, while important, may be limited in its contribution to overall success in specialist police selection. Factors to which HRV is sensitive, such as cognitive load and emotional strain, should also be considered. While greater aerobic fitness may potentiate stress, there may be a ceiling above which additional aerobic capacity lends no further advantage. Indeed, findings from a recent systematic review also posit this hypothesis [55]. Namely, the study by LyytikÄInen and colleagues also did not identify a relationship between HRV recovery and aerobic fitness following a 24hr shift in a cohort of emergency services personnel [163]. However, other research does suggest aerobic fitness can support vigilance in a similar context to that described here [187]. Future studies may aim to clarify the dose-response curve with larger cohorts to characterise the point at which aerobic fitness may no longer attenuate psychosocial stress factors in tactical settings.

This research may be of interest to individuals across tactical professions interested in objective psychophysiological assessment. The findings described in this study indicate that HR alone is likely not sufficiently sensitive, especially in small cohorts, to provide detail regarding how aerobic fitness may be associated with performance during essential tactical tasks that combine physical stressors with cognitive load in adverse conditions [183]. HRV analysis may provide additional insights regarding candidate suitability to unit leadership and directional staff, as candidates were more stratified in the HRV responses than their HR responses. The approach presented in this report may provide a framework for other organisations contending with small recruit populations seeking means of stratifying individuals, even when traditional measures of fitness and exertion are not clearly delineated.

4.6.1 Limitations

The chief limitation of this study is small sample size (n = 6). Further, an objective measure of cognitive load, could not be applied in this context, given the distances and remote terrain in which the candidates were operating. Such a measure may have been valuable to substantiate the conclusions drawn in this work. While the sample size is not unusual in the population of interest, in combination with the generally high and uniform aerobic fitness testing results, the precise nature of the relationship between HRV and aerobic fitness may not have been fully characterised. Additionally, while the MSFT is known to be a reliable and valid measure of aerobic fitness, it may not have been a true measure of maximal aerobic capacity in this context. Future research may utilise lab-based measures of aerobic capacity, rather than field measurements to further refine the relationships between HRV and aerobic fitness in tactical personnel.

4.6.2 Practical applications

This research may be of interest to individuals across tactical professions interested in objective psychophysiological assessment. The findings described in this study indicate that HR alone is likely not sufficiently sensitive, especially in small cohorts, to provide detail regarding how aerobic fitness may be associated with performance during essential tactical tasks that combine physical stressors with cognitive load in adverse conditions. HRV analysis may provide additional insights regarding candidate suitability to unit leadership and directional staff. The approach presented in this report may provide a framework for other organisations contending with small recruit populations seeking means of stratifying individuals, even when traditional measures of fitness and exertion are not clearly delineated.

4.7 Conclusions

This study provides tentative, but still valuable insights into the monitoring of HR and HRV among a cohort of specialist tactical police candidates. The findings confirm the primary hypothesis that HRV exhibits a higher sensitivity to allostatic load responses compared to HR. However, the hypothesis positing a stronger relationship between HRV and aerobic fitness than between HR and aerobic fitness during selection activities was not entirely verified. The diversity of stress sources candidates encountered, including submaximal physical demands, environmental conditions, the pursuit of success, cognitive challenges, and the imposition of uncertainty underscores the limitations of HR as a standalone measure. In contrast, the nuanced fluctuations in HRV, reflecting sensitivity not only to physical load but also cognitive load, emerge as more effective indicators of potential overstress in these scenarios. In consideration of future research, the analysis of HRV holds promise in providing additional dimensions of information pertinent to evaluating candidate suitability. As the intricacies of stressors continue to shape the demands on tactical police candidates, a comprehensive assessment encompassing HRV could offer a more holistic understanding of their physiological responses. In summary, this study underscores the significance of HRV as a complementary metric alongside HR in gauging psychophysiological responses among specialist tactical police candidates. While further research is warranted, the current findings establish a more comprehensive approach to enhancing the monitoring and assessment protocols within tactical training contexts.

4.8 Afterword

This chapter explored the HRV response of PTG candidates undergoing a task that included both cognitive and physical demands. The main finding was that HRV fluctuations were potentially more sensitive than HR during a land navigation task and that HRV was tentatively associated with aerobic fitness, a known strong predictor of success in tactical training. The results of this study may be of interest to organisations considering allostatic load monitoring, as the HR data were unremarkable, whereas the HRV data demonstrated potential overstress in the candidates. While high aerobic fitness may be necessary for success in specialist police selection, it is likely that its protective effects have a ceiling, and those protective effect may not always translate across all selection events. HRV is likely a more sensitive performance indicator in specialist police selection because of its sensitivity to factors beyond physical load and fitness. However, the extent to which particular aspects of selection influence HRV has not yet been elucidated, and further, its capacity to detect overstress with material impact, such as withdrawal from selection, has not been considered in the population of interest (PTGs, specialist police). Therefore, the next chapter continues the exploration of HRV response during prolonged load carriage and navigation event in greater detail through 1) generating HRV profiles of candidates during challenging load carriage tasks, 2) summarising data in a format accessible by end-users, and 3) determining the relationships between HRV and attrition.

Chapter 5 – Selection Factors: Heart Rate Variability Assessment of Land Navigation and Load Carriage Activities in Specialist Police Selection

5.1 Preface

This chapter details the findings from Study 3. This research built upon the initial findings in study 2 which found association between heart rate variability (HRV) and aerobic fitness in candidates undergoing police tactical group (PTG) selection, but did not identify a causal link, as HRV is likely sensitive to many other sources of stress beyond those attributable to physical load and aerobic capacity. Heart rate variability (HRV) was characterised across a sustained period of specialist police selection with a particular focus on load carriage; an element of specialist selection courses known to be associates with selection failure in some [178] although not all [173] selection courses. The systematic review conducted in Study 1 [55] identified prolonged periods of exertion [84], load carriage [77], and cognitive load [67,157] all substantially influenced HRV in tactical personnel. The previous chapter demonstrated that HRV may be a more appropriate tool to monitor selection course activities than heart rate alone, which may be influenced by fewer stress sources. However, while study 2 (Chapter 4) holds exploratory value and introduces the premises on which further studies build, the material impact of overstress detected by HRV monitoring (such as attrition prediction with HRV data) was not of primary focus, nor was generating end-user accessible data visualisation. Therefore, this study sought to consider in greater detail the HRV patterns observed during the two load carriage activities conducted during the selection course (being land navigation and continuous pack march), summarise data in a format accessible by end-users, and determine the relationship between HRV and attrition.

This study has been presented at the 6th International Congress on Soldiers' Physical Performance 2023. This study has also been published open access as a full-length article in the *Healthcare* special issue "Health, Safety, and Readiness of Tactical Populations". The original published manuscript can be found via the following: Tomes CD, Canetti EFD, Schram B, Orr R. Heart Rate Variability Assessment of Land Navigation and Load Carriage Activities in Specialist Police

Selection. *Healthcare*. 2023; 11(19):2677. https://doi.org/10.3390/healthcare11192677. Made available under a Creative Commons CC BY 4.0 licence.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis. The accepted abstract provided below has been included in the original submission format.

5.2 Abstract

Police tactical group (PTG) personnel are exposed to physical, mental, and emotional stressors. Consequently, PTG selection courses (SCs) impart similar challenges, often resulting in candidate attrition. Holistic assessment may provide additional support to stakeholders given these risks. Heart Rate Variability (HRV) is an objective holistic stress measure that may be applicable in PTG SCs but has not been thoroughly researched. Therefore, this study aimed to report HRV data in an end-user accessible format and determine the relationship between HRV and attrition. A total of 18 qualified Australian State law enforcement officers completed a 1-day physical readiness assessment. Of those, six males progressed to an additional two-day course, on which this study is focused. This two-day selection consisted of additional physical challenges and occupational assessments. HRV was obtained from 2-lead ECGs and defined as the percentage of R-R intervals that varied by ≥50ms (pRR50). Data were summarised in a heat map of consecutive short-term analyses. Three candidates withdrew. A logistic regression based on heat map data found high HRV was significant for predicting attrition, x2 (6) = 8.318, p = 0.004. HRV may provide insight for PTG stakeholders monitoring attrition. While the sample size was limited and replication is needed, this study tentatively establishes value for HRV monitoring in PTG SCs.

5.3 Introduction

Police work is known to expose officers to high levels of physical, mental, and emotional stressors [8,36]. Imposed demands include response to emergencies, internal organisational demands, irregular work hours or extended shifts, and potentially service as a specialist [197,198]. In Australia, Police Tactical Groups (PTGs) are one of the most demanding specialist capacities in which an officer can elect to serve [176,181]. The specialist police who serve in PTG units are subject to additional demands beyond those encountered by general duty police officers [199,200]. As such, the PTG officer may undertake a wide scope of duties that include search and rescue, counterterrorism, explosive ordinance disposal, high-risk warrant service, and policing engagements involving hostile entities with firearms [176,201].

To ensure candidate personnel are prepared to meet these occupational demands, the selection course to join a PTG unit is physically demanding and technically challenging. Highly refined marksmanship skills, excellent physical fitness, and an exceptional ability to perform under extreme pressure are all cardinal traits for success [13,202]. The rigor of specialist selection aims to ensure future team members are not only physically, but mentally and emotionally prepared for PTG service [197]. One notable and critical requirement of PTG service is the ability to carry heavy loads over extended timespans while still performing other critical duties. Whereas general duty police officers may wear and carry loads of around 10 kg [33], specialist police officers can carry loads of around 20 kg, increasing up to 40 kg or more when additional stores (such as breaching equipment and ballistics shields) are required [203]. Consequently, PTG selection courses include often arduous load carriage events [173,204]. Further, these tasks may be required in challenging environments, such as hot and humid conditions, which can exacerbate completion difficulty, physiological demand, and subjective perception of exertion [12,205-207].

In addition to physical competency, mental fortitude to cope with psychological stressors of the professions is a desirable characteristic expected of candidates [202]. With this in mind, psychometric testing, personal interviews, and expert observation of performance are also incorporated to selection courses, creating a holistic picture of a candidate's overall suitability for the profession [12]. Often, events in the selection course will incorporate both physical and mental stressors, such as a prolonged load carriage event in a mentally challenging course under adverse conditions (e.g., a navigation exercise across various terrains). Monitoring the physiological impacts of these two types of stressors can provide decision makers additional information on the performance of personnel undergoing selection [77]. The refinement of selection courses and human performance monitoring may be especially critical as application pools continue to shrink [208], and police organisations face increasing scrutiny [209]. It may be possible that both through selection and across the career, health and human performance supports may be a valuable strategy for improving the health and safety of officers and communities [210].

Wearable technology has enhanced the capacity for health and performance support personnel to obtain physiological data from individuals in austere locations. Decreased HRV may not necessarily indicate worsened health or performance in all settings, and conversely, high HRV may not exclusively indicate high performance and optimal health [211]. However, in tactical settings where stress and sources of allostatic load are abundant and often extreme, low HRV may be more reasonably expected as an indicator of concern [56,183,211]. Examples of monitoring for depressed HRV include military basic training or advanced specialist training [77,183] as well as within firefighting units and professional rescuer teams [4,91,165]. One performance indicator obtainable from these wearables is heart rate variability (HRV). HRV generally aims to computationally describe the dynamic, interdependent, and multisystem psychophysiological responses that modulate the time between consecutive heart beats, also known as beat-to-beat or inter-beat intervals (IBI) [69]. A dynamic relationship between intrinsic cardioregulatory factors, as well as factors external to the heart responding to the environment, namely the sympathetic (SNS) and parasympathetic (PNS) nervous systems [68,69], drive fluctuations in IBI. Therefore, the use of HRV assessment is considered a viable measure for quantifying stress holistically in many career fields but may be particularly beneficial in tactical settings, as stress in tactical populations may be particularly intense and multifactorial [142,157,165]. When other strategies for evaluating autonomic regulation or stress response are inaccessible due to the nature of tactical work, HRV shows promise as a deployable measurement tool for identifying stress responses [23,36]. For these reasons, HRV monitoring has been utilised with increasing frequency in military [183], fire [5], and rescue populations [163]. However, its application in the specific context of PTG selection remains subject to limited inquiry [90]. Therefore, the aim of this study was to (1) pragmatically implement wearable HRV monitoring during prolonged load carriage events conducted during PTG selection, (2) provide data in an easily accessible format, and (3) determine if the data could be used to assess candidate attrition. The research question was as follows: can HRV data obtained during specialist police selection load carriage activities be processed into an accessible format for end-users and can those data predict attrition? The authors hypothesised that HRV would be practical, presentable in an efficient manner to key stakeholders, and that HRV would be sufficiently sensitive to distinguish candidates that withdrew from those that did not.

5.4 Methods

This study was a prospective cohort study of six male PTG candidates undergoing specialist selection at an Australian State PTG facility in Autumn of 2022. Female candidates were eligible both for selection and inclusion in this study, but none had applied for the selection cycle on which this report is based. Table 8 contains mean descriptive data for those anthropometrics and fitness data that could be released; further detail regarding these variables could not be published as per a privacy agreement with the sponsoring organisation. For this study, height was self-reported; self-reported anthropometrics have been utilised as reliable metrics in research in the previous literature in law enforcement populations [188].

Table 8. Anthropometric, Load Carriage and Fitness data of Australian PTG Candidates

Value	Body Mass (Kg)	Height (cm)	Age (Years)	Land Nav Equipment Mass (Kg)	Pack March Equipment Mass (Kg)	BMI (Kg/ m^2)	MSFT (Total shuttles)
Mean	93.63	180.17	30.67	12.24	11.95	28.88	84.17
SD	8.83	5.98	2.94	0.14	1.32	2.92	7.22
Median	94.78	181.00	31.00	12.24	11.96	29.22	81.00
Range	20.50	21.08	14.00	8.00	0.20	8.47	1.9

Legend: body mass index (BMI), multistage fitness test (MSFT). Range is reported as the difference between maximum and minimum values.

Candidates were supplied with an Equivital™ EQ02+ LifeMonitor (Equivital, Hidalgo, UK) wearable monitoring harness sampling at 256 Hz to capture ECG activity from the start of the selection course until the candidate was withdrawn or the selection course ended. Each harness was individually fitted to the level of each candidate's xiphoid process to ensure electrode contact points were secured. Previous research indicates the Equivital system is comparable in terms of validity and reliability to the gold-standard Holter ECG monitor [193]. ECG data were captured with Equivital software (EQ View Pro, Hidalgo, UK) and processed with LabChart version 8 (ADInstruments, Sydney, Australia). Visual ECG examination was performed in combination with automated detection of signal noise provided by the LabChart Software. ECG complexity was set between 1.0 and 1.5. Acceptable R-R intervals were established as those beats that fell between 272 and 1600 ms. This is equivalent to a heart rate between 220 bpm and 37.5 bpm. Any identified beats falling outside this range were checked manually and either included or excluded based on the visual features of the ECG. HRV was defined as the percentage of R-R intervals that varied by more than 50 ms (pRR50). Results were summarised in a heat map format consisting of 153 consecutive short-term analyses, each lasting 5 min. This reporting strategy allowed for the greatest resolution of HRV changes between tasks, without sacrificing validity, given potential for signal noise in this context. The total time span was from 0700 to 2000 h on the initial day of a two-day selection course. The end point of 2000 h was identified as the threshold time for suspending analysis, as three of the six candidates were medically withdrawn at approximately that time.

5.4.1 The Selection Course and Load Carriage Events

The initial cohort was comprised of 18 male police officers who were inducted into a 1-day physical training selection assessment. Of those 18, six individuals were eligible to participate in an additional two-day selection course. The one-day course primarily screened for physical fitness and workload tolerance. Attrition was high, resulting in six of those 18 progressing to participate in an additional two-day selection course, which is the focus of this study. There were no exclusion criteria; all personnel eligible for the two-day assessment were eligible for study inclusion and recruited. In general, the two-day selection course consisted of additional physical training activities, but also essential specialist police task training and assessment activities. These included orienteering, firearms manipulation, threat de-escalation, load carriage, and casualty evacuation. Specifically for this study, HRV response to prolonged load carriage (~12 kg) was of chief interest as load carriage tasks are a fundamental requirement for these personnel [35] and may be associated with selection failure [173,178]. As such, the 13 h of continuous load carriage activities that took place during the overall selection and assessment process formed the focus of this work. These load carriage events included a land navigation exercise in which candidates were tasked with locating various landmarks from longitude and latitude only, utilising simple tools such as a paper map, pencil, and compass. The land navigation load configuration consisted of self-selected combinations of standardised web belts, uniforms, modular pouches, and chest harnesses on which candidates mounted water, the land navigation equipment, and other tactical stores. The land navigation exercise took place in an undeveloped area with mostly level terrain. Environmental temperatures ranged from 24.2–34.4 °C and the relative humidity ranged from 60–75% (Australian Bureau of Meteorology). Landmarks were approximately 1–3 km apart from both the starting area and each other. Candidates were not told how many landmarks needed to be reached successfully to achieve a passing outcome. The other load carriage event consisted of a pack march on a level, paved road surface. Participants continued marching with no knowledge of the required time or distance.

5.4.2 HRV Outcome Measures

The pRR50 metric was chosen specifically because it has been identified as a clinically important feature when assessing for risk of cardiovascular disease (CVD). CVD is known to affect police officers to a greater extent than the general population [113,114,133]. This metric is also less volatile and more amendable to use in short-term recordings than frequency-domain measures [101]. While lower values of HRV are not exclusively indicative of worsened health or performance, and high values are not exclusively indicative of high performance and optimal health, in tactical settings where stress and sources of allostatic load are abundant and often extreme, low HRV may be more reasonably expected as an indicator of concern [56,183,211]. Specifically, a lower pRR50 value indicates less variation in IBI for the analysis period, and therefore decreased responsiveness to dynamic external and internal environmental fluctuations. Insufficient responsiveness to stimuli may in turn signal excessive physical or psychophysiological stress [68,127]. Consecutive 5 min short-term blocks, rather than one single long-term (13 h) analysis, was performed to allow for the greatest resolution of changes possible during the selection course without sacrificing validity. Heat map shading was informed by the work by Hopkins and Buchheit [212,213], using the mean and standard deviation (SD) of each participant's pRR50 values. This controls for the highly individual nature of HRV and its volatility while still permitting meaningful analysis of the entire cohort [214].

Values in each short-term block above ½SD of the participant's mean (for all blocks) were shaded green, within ±½SD of the participant's mean were shaded yellow. Values below ½SD of the participant's mean were shaded red.

5.4.3 Participants

Candidates were briefed by the research team to inform them that their decision to participate would in no way influence their selection result. This briefing was reiterated by the assessment selection staff. After agreeing to participate, all candidates disclosed that they were taking no medications for cardiovascular, renal, or respiratory conditions as a requirement of participation in this study. During selection activities, all candidates were provided uniform rations by the assessing organisation. Water was provided ad libitum, but all other beverages, including caffeine, were restricted. All candidates provided their informed written consent, and the unit commander provided permission for publication of this work. The research protocol was approved by the Bond University Human Research Ethics Committee (BUHREC) (Protocol 2019-022 amnd 2) and all procedures were conducted in accordance with the Declaration of Helsinki of 1964 and its later amendments [215].

5.4.4 Statistical analysis

Descriptive analytics were derived from the heat map. Visual inspection of histograms was conducted for each participant to ascertain distribution, skew, and kurtosis. These can be found in Figure 22. These included count data tabulations of total time and longest consecutive time span in each of the shaded colour zones of the heat map. Given the small sample size, Mann–Whitney U tests were planned for direct comparison of raw HRV and heat map count data between those candidates that withdrew during the pack march and those that did not. Logistic regression analyses were also performed to determine if attrition could be predicted. The dichotomous variable for each model was selection success or failure (1 or 0). For continuous variables, models were attempted using raw HRV values and count data from the heat map analysis. Model iterations utilising heat map count data were drawn from the beginning of the selection course (0700) to the end of the first load carriage activity, being land navigation (1430), and included the total quantity of shaded 5 min intervals with either 'green' shading representing >½SD from the mean value, 'red' shading <½SD from the mean value, or 'yellow' shading (the intermediary 1SD surrounding the mean). The time range was chosen to determine if HRV response during the first event would be predictive of attrition that occurred in the second event. All statistics were calculated using JASP 0.17.1 (JASP Project, University of Amsterdam, Amsterdam, The Netherlands). Sensitivity and specificity were calculated from successful ($p < 0.05$) models using the regression package found in JASP.

5.5 Results

All collected data fell within the 'low' range for artifact presence (<20%) [193]. Three candidates withdrew during the pack march event. Two candidates withdrew the following day, with only one candidate ultimately completing the entire two-day course. During the data capture period considered in this study, temperatures ranged from 24.2–34.4 °C and relative humidity ranged from 60–75%. For every five minutes of recording, HRV was measured as the percentage of R-R intervals varying by at least 50 ms, yielding 153 consecutive short-term HRV analyses. The integration of these data into the finalised shaded heat map can be found in Figure 1. The column furthest right in Figure 1 provides information regarding the activity being completed at the time of HRV recording. Time of day is also provided for context in the column furthest left in Figure 8.

Table 9 and Table 10 describe count data derived from the heat map (Figure 8) analysis. The quantitative values of interest from the heat map include the total amount of time each candidate had shaded for red and green, respectively, as well as the longest consecutive time period without change in shaded colour, representing prolonged high (green) or low (red) HRV for the epoch.
Regarding the Mann–Whitney U-tests, there were no statistically significant results from any variables (raw HRV data, count data totals, and count data consecutive sequences). Of the logistic regression analyses performed, only one was successful. The regression model that was statistically significant (χ^2 (6) = 8.318, $p = 0.004$) was for count data of 5 min blocks with pRR50 intervals above ½SD from the mean value during the beginning of the selection through to the end of the land navigation exercise (0700–1430). That model correctly identified 100% of candidates

that passed the pack march and 100% of candidates that failed the pack march. The resultant sensitivity of high HRV predicting that a candidate would pass the pack march event that followed was 1.0, and the specificity was also 1.0.

Table 9. Count Data: Total and longest consecutive time of HRV (pRR50) registered below ½SD of the participant's mean.

	Total Time (min)	**Consecutive Minutes**
Finished Pack March (n = 3)	326.67 ± 5.77	56.67 ± 25.17
Did not Finish (DNF) Pack March (n = 3)	363.33 ± 57.95	116.67 ± 70.06

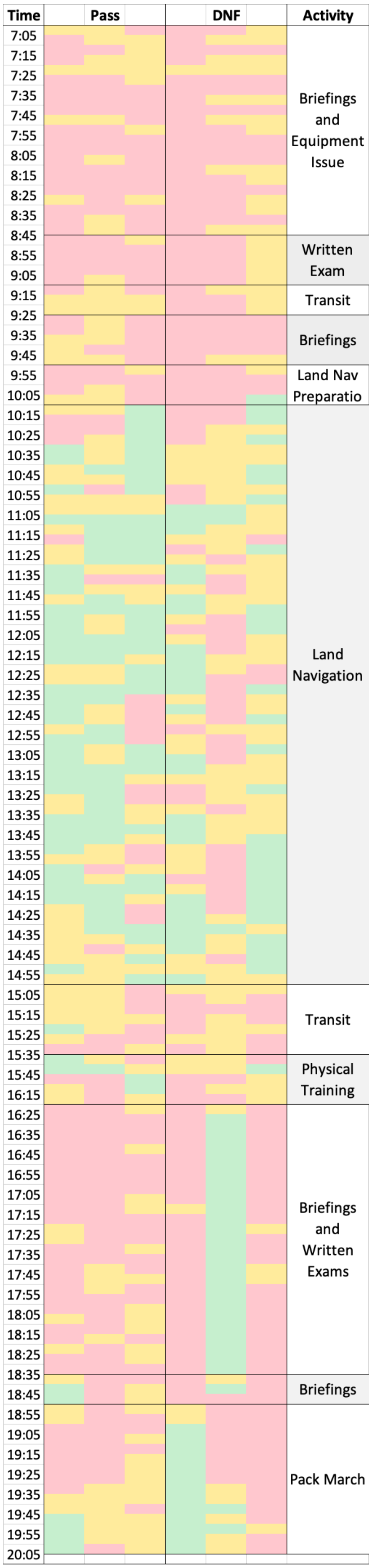
All values are presented as mean ± standard deviation.

Table 10. Count Data: Total and longest consecutive time of HRV (pRR50) registered above ½SD of the participant's mean.

	Total Time (min)	**Consecutive Minutes**
Finished Pack March (n = 3)	173.33 ± 30.14	38.33 ± 7.64
Did not Finish (DNF) Pack March (n = 3)	165.00 ± 22.91	80.00 ± 44.44

All values are presented as mean ± standard deviation.

The heat map visualisation of candidate's pRR50 values illustrates the fluctuations in HRV during 13 hours of load carriage activities (Figure 8). In a qualitative consideration of the heat map, all candidates demonstrated an initial period of minimal variability and values below ½SD of their individual mean values (areas shaded red). This lasted approximately three hours (07:05 – 10:05). Some recovery is noted once the candidates were underway and commencing the first land navigation activity, beginning at approximately 10:05 (areas shaded yellow and green). Values generally deteriorated again as the first load carriage activity ended. Participants then proceeded to another period of briefing and exams indicated at 18:50.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20:05
Briefings and Equipment Issue
Written Exam
Transit
Briefings
Land Nav Preparatio
Land Navigation
Transit
Physical Training
Briefings and Written Exams
Briefings
Pack March

Figure 8. Heat map visualisation of candidate pRR50 values

Legend: Heat map visualisation of candidate pRR50 values in 5-min short-term blocks**.** PTG Candidates, n = 6. Red regions indicate values below ½SD of the participant's mean, yellow regions indicate values within ± ½SD of the participant's mean and green regions indicate values above ½SD from each participant's mean. The furthest right column indicates activities and changes in activities throughout the recording period.

5.6 Discussion

The primary aim of this study was to determine if HRV data obtained during specialist police selection load carriage activities could be processed into an accessible format for end-users, and if the data could predict attrition. The capture, processing, and description of the data of an initial six-member cohort was completed to provide useful individualised feedback to unit selection course staff and leadership. Specifically, a logistic regression model was able to predict those that would complete the first day of selection from those that would not. In even a small cohort, with less HRV data than the extant literature would suggest is necessary [75], this model was statistically significant and could be utilised in future selection cohorts to identify at-risk candidates before their risk of elimination from selection. The captured data, their description, and presentation were analysed and interpreted to provide the greatest practical value to selection staff personnel and key stakeholders within the tactical police profession. The novel heat map approach (Figure 8) to visualise HRV data potentially demonstrates the levels of physical and psychophysiological stress each individual candidate experienced during selection course events and allowed concurrent monitoring of all candidates. While these results are certainly promising, this report may best be interpreted as an effective proof of concept but with a need for replication with a larger sample size.

Overall, the heat map approach to HRV interpretation identified the components of assessment that were the most taxing, as indicated by lengthy periods of low HRV, particularly those periods of pRR50 below ½SD of each candidate's mean value. This process also allowed for the most powerful regression model to be developed for predicting attrition; the raw HRV data were not statistically significantly predictive, nor was low HRV. The initial observed period of diminished variability may have been due to several factors (namely circadian rhythm influences) [100,111,216]. However, the most likely reasons can be postulated to be latent exercise-induced sympathetic dominance from aerobic endurance testing occurring prior to the start of the presented data [217], or anticipatory stress [52,68]. Environmental considerations should also be contemplated, as previous research has determined that, even in highly trained individuals, high heat and humidity exposure may reduce parasympathetic and (or) enhance sympathetic modulations [206], likely also decreasing the pRR50 percentage in this sample. Regarding anticipatory stress, incomplete information and uncertainty were deliberately imposed by the selection staff as an important element of trainability assessment. A body of relevant literature is emerging, assessing relationships between stress, HRV, and uncertainty in which stress imposed by uncertainty acts to impair the physiological mechanisms that promote higher HRV [132,218,219]. While one investigation specific to the law enforcement profession did not find significant relationships between intolerance of uncertainty and physiological response as measured specifically by mean heart rate [195], HRV was not specifically analysed; only HR was reported in the referenced work, and therefore the greater sensitivity provided by HRV may be crucial in this assessment strategy. Indeed, HRV analysis, potentially including heat map interpretations, may yield more information than HR alone [90].

The establishment of this plausible relationship between uncertainty intolerance and its downstream effects on HRV may be of high value to selection staff and unit leadership. Selection course staff may aim to preferentially select candidates with either minimal psychophysiological response to uncertainty, or an ability to continue functioning effectively despite an elevated psychophysiological response. In the present reported data, all candidates, except for one candidate that did not finish the pack march, demonstrated prolonged decreased HRV during the written examination and briefing period following the land navigation exercise. This may highlight the impact of cognitive load on HRV, decreasing values and potentially impairing recovery. For this candidate, it is possible that the transition from a hot outdoor environment to a cooled indoor environment contributed to this elevation in HRV to a greater extent than the other candidates due to the greater stress experienced during the land navigation event, as evidence by greater periods below ½SD of mean long-term pRR50 relative to peers. It is also possible that this participant entered a hyperparasympthetic state due to overstress. Indeed, a U-shape distribution for describing HRV and disease risk has been proposed in the psychiatric literature [211]. The sports performance literature also supports high HRV in a context in which it is not expected (e.g., not a resting or post-prandial state) indicating performance deterioration as well [220].

Regarding the load carriage events, all candidates with the except of one that did not complete the pack march exhibited minimal impact from the pack march event relative to the previous exercises, and even improved in values during this time. This may indicate some capacity for recovery despite continued selection activities. The potential recovery period noted once the first load carriage task commenced may reflect a natural response to resolution of uncertainty; the candidates knew, once underway, the parameters of their task and were familiarised with it. This premise is supported by the recent psychiatric literature that determined depressed HRV to be indicative of high stress and anxiety states [211]. Indeed, as typical in these specialist populations [173], the candidates were of generally high aerobic fitness (mean MSFT Score: 84.2 ± 7.2 shuttles or approximately level 10.1), and the physical component alone may not have been a substantially taxing factor for this assessment. The re-emergence of uncertainty intolerance may have influenced the decreased HRV values, in combination with fatigue, noted during the initiation of second load carriage event [68,219]; the candidates were not informed the time or distance needed for success. Further research in this domain may provide more certainty regarding how these relationships manifest in this unique population. Finally, the first candidate to withdraw did not appear to have a similar increase in pRR50 percentage with the commencement of the second load carriage navigation event, indicating little recovery or return of dynamic adaptive regulation. This can be seen as continued regions of red and yellow in the one region of the DNF column in Figure 1, contrasting with the data trends observed in the other candidates beginning at approximately 1855. Another period of potential additional anticipatory stress may have occurred as the next load carriage event began.

While there were no statistically significant differences in the total number of short-term analyses below ½SD of mean long-term pRR50 threshold between the candidates who completed the final load carriage event and those who failed to complete the event (or continue after the event), the candidate that had the shortest *consecutive* sequence of pRR50 values below ½SD of mean was candidate 4, who did pass the pack march. This distinction is important because optimal HRV is characterised by dynamic adaptive response—prolonged instances of limited variation of either atypically high or low values potentially indicate suboptimal stress response [69,75]. While low HRV did not appear to necessarily be indicative of success, time spent with high HRV was predictive of at least progressing into the second selection day, as demonstrated by the outcome of the logistic regression model.

Visible, outward demonstrations of difficulty with task completion may not necessarily be reflected by the individual's external environment. For example, while a candidate may not present as struggling by outward appearance, they may nonetheless be subject to high stress. This is of importance to selection staff who are assessing how each individual manages stress in a given situation. As such, individualised heat maps of candidate stress may provide highly valuable information to selection staff and unit leadership. In addition, identifying those candidates who are failing to recover may allow for adjustments in the activity to be made if needed, thereby helping to prevent the high selection failure rate described in this study and elsewhere [12,178,221].

5.6.1 Limitations

This study was not without its limitations. As discussed above, while the sample size was not unusual for the population of interest, it nonetheless may diminish the generalisability of the reported findings. The approach provided here may not prove effective outside of the organisation within which this study was conducted. Further investigations with either multiple cohorts or larger cohorts are warranted to verify if modelling HRV data in the manner reported is sufficiently robust for wider application. Additionally, while the heat map visualisation provided additional insight for unit leadership, the data could not be obtained, aggregated, interpreted, and visualised before attrition events occurred. Future studies or selection course operators may consider utilising real-time HRV monitoring, or more frequent data processing to acquire this valuable data ahead of attrition occurrences. The data reported here demonstrate the potential of HRV as a robust biomarker that may hold value, but the time from data acquisition to reporting requires additional expediency.

5.7 Conclusions

The assessment and heat mapping of HRV can provide additional insight to selection staff and unit leadership during selection courses where the performance of each individual is critically analysed. The processing of HRV data using this approach allowed for a statistically significant regression model predicting attrition to be generated that was not possible with raw HRV values alone. This monitoring and data processing approach can be used to identify poorly performing candidates, and with future research may allow for intervention before medical attention is necessary. These data and approach may also support the objective identification of exceptional performers. Further, those who continue to demonstrate competence despite potential psychophysiological overstress as measured by HRV can also be identified. As the ability to suppress discomfort and function as part of a team is essential for the specialist police occupation, this additional information that can be provided within selection courses allows decision makers additional detail and objective, rather than subjective, means of holistic candidate analysis. While further research is needed to verify the objective relationships between HRV profile, performance, withdrawal from training, and other outcomes, this study demonstrates the unique utility of HRV and heat map generation of biosignals in specialist police selection.

5.8 Afterword

In this study, a novel approach to HRV data analysis and presentation that may provide unit leadership with an additional tool for assessing candidates was profiled. The findings of this study support the conclusion from Study 2 (Chapter 4), in that HRV likely provides additional sensitivity to the breadth of stressors experienced in the specialist police selection course. The refinement of HRV data into an end-user accessible format (heat map) and the application of that data into a model that could be associated with, or even predict attrition, without baseline or other comparative HRV measures, further supports HRV integration into specialist police units. One weakness of note though, is that while HRV identified 100% of candidates that withdrew, it was less effective at identifying the most successful candidates. Therefore, further investigation into what aspects may potentially differentiate successful candidates from those that were not successful may provide additional information for selection purposes. This additional detail may demonstrate greater utility of HRV monitoring to unit leadership. In addition, whereas Study 2 (Chapter 4) and Study 3 (This chapter) included selection activities that had a highly physical component, the utility of using HRV as a monitoring tool in less physical but still highly stressful activities (like a fear of heights assessment) also require detailed investigation.

Chapter 6 – Selection Factors: Heart Rate Variability Profile Changes Associated with Sleep, Less-lethal Explosive Device Exposure, and Fear of Heights Training in Specialist Police Selection

6.1 Preface

The previous field studies (2 and 3) initially demonstrated the enhanced sensitivity of heart rate variability (HRV) versus heart rate (HR) monitoring during specialist police selection events, as specialist police selection applied multifactorial stressors. These stress sources include physical, psychological, and emotional demands to which HRV is sensitive, but to which HR may not be. These observations are not purely limited to the theoretical: HRV data can be processed and formatted to be made accessible to the end-user and the data can be utilised to predict attrition, which is a known concern in these settings. However, while the attrition prediction model utilising HRV data in Study 3 effectively identified 100% of candidates that were not successful, the identification of the most successful candidates was less definitive. Further, additional tasks beyond load carriage such as exposure to explosive devices, threat de-escalation, and exposure to high heights that may cause a stress response must also be evaluated within a selection course. As demonstrated in Study 2, HRV may be a more sensitive measure for these multifaceted stressors than HR alone, while still being deployable in austere conditions and providing objective data. Therefore, the aim of this next study was to 1) develop a more precise profile of the most successful candidate from Studies 2 and 3; and 2) investigate HRV outcomes during events imparting psychophysiological stressors.

This study was presented at the 4th International Physical Employment Standards Conference 2023 and has been accepted in the journal *WORK: A Journal of Prevention, Assessment & Rehabilitation*.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis. The requested revisions from the *WORK* peer reviewer team have been integrated.

6.2 Abstract

BACKGROUND: Police Tactical Groups (PTGs) are specialist police units tasked with rigorous physical and psychosocial duties. Consequently, selection courses (SCs) for service in these units must also be rigorous. Given the intensity of SCs, holistic monitoring for potential overstress may be beneficial. Heart Rate Variability (HRV) is one holistic stress measure that can be obtained in austere environments. OBJECTIVE: The purpose of this study was to profile HRV during a PTG SC. Six (n=6) qualified male police officers attempted a 36-hour PTG selection course held at an Australian state facility. METHODS: HRV was obtained from Equivital™ EQ02+ LifeMonitor bioharnesses. The selection course consisted of physically demanding events with minimal sleep (approx. 45 mins). Only one candidate completed the full selection course; whose results are reported here. RESULTS: A visual time-series of 384 consecutive 5-min HRV analyses was generated. Contextual analysis was applied to appreciate HRV changes between SC serials. HRV decline occurred during the planning of a navigation exercise and a pack march. Increases in HRV were observed throughout the pack march exercise and rest period. CONCLUSIONS: This case study demonstrates the potential utility for selection personnel to obtain additional insight into candidate responses to various occupational challenges throughout an SC. Information provided by HRV monitoring may support leadership decisions when evaluating personnel holistically. For example, the ability to continue occupational task execution even while experiencing potential overstress (as measured by HRV) and after food and sleep deprivation is desirable. HRV may potentially inform stakeholders regarding overstress in PTG candidates.

6.3 Introduction

In Australia, Police Tactical Groups (PTG) are specialist units within State services tasked with a wide scope of duties that include search and rescue, counterterrorism, explosive ordnance disposal, high risk warrant service, response to active shooters, and illicit material transport interdiction [35]. Because of the breadth and intensity of occupational tasks, the selection courses (SCs) that screen individuals for service in PTG units must be commensurately rigorous. These SCs integrate as many relevant occupationally derived challenges as possible to rapidly ensure selected personnel can be prepared for the realities of PTG service [173,199]. While necessarily physically demanding, other key competencies, such as the ability to perform effectively under states of intense pressure or fear and perform despite sleep or food deprivation, possibly in combination with extreme climate exposure (e.g., heat and humidity), are also evaluated [35,222]. Because these qualities are not necessarily exclusive to domains of physical performance or fitness, consideration of metrics sensitive to psychosocial influences may provide additional value to selection staff interested in holistic assessment of candidates [75,77]. Heart Rate Variability (HRV), the computational analysis of moment-to-moment changes in heart activity imposed primarily by autonomic nervous system (ANS) activity, has been demonstrated as a useful technology in the assessment of tactical personnel for assessing cognitive load and demand faced in high-stress environments [55,67,90,110]. Wearable technologies have allowed for high-fidelity electrocardiogram (ECG) monitoring of ambulatory personnel in a wide variety of occupational contexts, including tactical environments [56,75]. Further, the provision of an objective holistic monitoring framework, potentially including HRV, may reduce bias in the selection of candidates. Some of these devices, such as the Equivital system utilised in this study, also demonstrate adequate comparability to the 'gold standard' Holter monitor for ECG, achieving low (<20%) to medium artefact percentages (<50%) [193].

The purpose of this case study was to illustrate the psychophysiological data (HRV) of a PTG SC candidate obtained from the aforementioned 2-Lead ECG wearable device. This case study includes consideration of the detailed HRV interpretation of the only individual (out of 18 candidates) to successfully complete a PTG selection course from two common HRV indices. Further consideration is given to the process by which personnel supporting tactical units with HRV analysis may transform data into approachable and actionable information for decision makers.

6.4 Methods

This study was conducted at a State PTG facility in Australia in Autumn of 2022. Environmental temperatures ranged from 24.2 – 34.4°C and the relative humidity ranged from 60 – 75%. An initial cohort of 18 personnel were inducted into a one-day physical training selection process. This one-day course was primarily a screening for physical fitness and capacity. Attrition was high, resulting in only six of those 18 progressing to participate in an additional two-day selection course. All personnel eligible for the two-day selection course were eligible for participation in this study and were successfully recruited. There were no exclusion criteria. The two-day course consisted of multiple physical training and physically demanding activities, as well as essential specialist police task training and assessment. Activities included variations of circuit training, orienteering, firearms manipulation, threat de-escalation, load carriage, and casualty evacuation. Further details of the SC serials can be found in Table 12. The timing of changes in serials was documented to the nearest tenth of a second, then rounded to the nearest whole minute utilising an Apple watch (Apple, California, USA) and paired smartphone (iPhone 13, Apple, California, USA). Only one candidate, the present reported case, completed the entirety of the two-day selection course and was approved to proceed to the next stage of selection. The ECG data presented in this report began at approximately 0700 and ended at the completion of the selection event at approximately 1530 the next day. All candidates were involved in training activities from approximately 0600 the first day and continuously through the night into the final day of selection. The missing data period from approximately 0600 to approximately 0700 was due to signal noise; this section was discarded to improve fidelity of the HRV measurements.

6.4.1 Subjects

Candidates were briefed first by the research team and then again by the assessment staff regarding the voluntary nature of participation; candidates were informed that participation was for the benefit of their organisation, and that no compensation was to be provided for participation. Further, no penalties or influence on the outcome of their selection would be imparted by the decision to participate in this research. All procedures were conducted in accord with the Declaration of Helsinki of 1964 and its later amendments [215]. Candidates provided their informed written consent, and the PTG unit provided permission for publication of this work. The research protocol was approved by the Bond University Human Research Ethics Committee (BS02165 amendment 1). Individual anthropometric data are not available as per a privacy agreement with the host organisation. However, the summarised data for all six candidates enrolled in the study can be found in Table 2. This table includes anthropometric data that could be provided, load carriage data, and aerobic fitness data. The aerobic fitness data (multistage fitness test; MSFT) was obtained during the 1-day selection assessment. For this study, height was self-reported; self-reported anthropometrics have been found to be reliable in research in previous literature in law enforcement populations [188]. All anthropometric values for the present reported case fall within the described ranges found in Table 11 to provide context.

Table 11. Anthropometric, Load Carriage and Fitness data of Australian PTG Candidates

Value	Body Mass (Kg)	Height (cm)	Age (Years)	Land Nav Equipment Mass (Kg)	Pack March Equipment Mass (Kg)	BMI (Kg/ m^2)	MSFT (Total shuttles)
Mean	93.63	180.17	30.67	12.24	11.95	28.88	84.17
SD	8.83	5.98	2.94	0.14	1.32	2.92	7.22
Median	94.78	181.00	31.00	12.24	11.96	29.22	81.00
Range	20.50	21.08	14.00	8.00	0.20	8.47	1.9

Legend: body mass index (BMI), multistage fitness test (MSFT). Range is reported as the difference between maximum and minimum values.

6.4.2 Procedures

All candidates were supplied Equivital™ EQ02+ LifeMonitor (Equivital, Hidalgo, UK) wearable monitoring harnesses to capture ECG data throughout the selection course. Each harness was individually fitted to the level of each candidate's xiphoid process. This fitment ensured ECG contact points were secured to the candidate in the correct position. Physiological measures were observed through accompanying software (EQ View Pro, Hidalgo, UK, and LabChart 8 Pro, ADInstruments, Sydney, Australia). Data were obtained from the harness after the conclusion of the SC. HRV measurements were considered 'short-term' in this investigation, utilising 5-minute traces analysed every 5-minutes for the duration of the course. This process allowed for the greatest possible resolution (i.e., the most detail on changes from series to serial) without sacrificing validity. While shorter (as low as 30s) HRV measurements have been utilised in previous research, the traditional 5-min window was utilised for this study given the austere conditions in which data was collected and potential for signal artifacts [101,193]. The wearable device utilised in this study correlates well with the 'gold standard' Holter ECG, but only when artifact levels are low (<20%)

[193]. Therefore, additional signal length to reduce the likelihood of excessive artifact presence was opted for *a priori*. While many HRV metrics are reported in the literature, this investigation primarily considered the time-domain metrics of pRR15 (percentage of adjacent R-R intervals varying by at 15ms) and root-mean square of successive differences (RMSSD). Time domain metrics are easily approachable by end-users, such as an on-site exercise physiologists or strength and conditioning professionals, as well as the candidate assessment team.

6.4.3 Analyses

As the current report is of only a single longitudinal case, descriptive statistics only regarding HR, pRR15, and RMSSD values throughout the event were generated; no inferential analyses were appropriate. Both HR and HRV were assessed every five minutes yielding 384 consecutive short-term HR/HRV values. These values were plotted by time, generating a visual HR and HRV time-series. Contextual analysis was applied to the time-series. Specifically, the selection course events and subjectively observed disposition of the candidate were documented periodically throughout the duration of the course by the lead author. Focus was given to key points in the recording timeline that might provide additional insight and information regarding the interpretation of individual HRV data. The contextual analysis process began by visually identifying deviations in the expected oscillating HRV pattern without information on which serials were conducted at those time points to minimise bias in the analysis. Large magnitude fluctuations in HRV potentially signal overstress or excessive exertion if no commensurate increase in HR is seen, as occurs with exercise [75]. Next, these anomalous HRV regions were compared against the SC serial and subjective observations of the candidate, as well as the assessment staff opinion of the candidate at the time of the disruption in HRV. Finally, any training activities or subjective observations not yet considered were included and the final visual HRV description was generated. The composite of these three steps is presented in Figure 9 and Figure 10, and again, further detail of the individual serials can be found in Table 12.

Table 12. Description of Selection Course Serials, Start Time, and RMSSD descriptive data.

Serial	Description	Start Time (Duration)	Mean HR (bpm)	pRR15 (%)	RMSSD (mean±SD)
Briefings and equipment issue	Candidates were briefed on expectations and role of the PTG. Standardised equipment was provided and any individual items were inspected for approval.	0705 (1:50)	103±12	27.28±11.12	44.7±38.9 ms
Written examination	Multimodal assessment of land navigation (orienteering) principles.	0850 (0:25)	94±3	28.85±5.34	30.99±22.50
Administration	Mobilisation, review, and further explanation of expectations for the land navigation exercise	0930 (0:35)	104±14	30.71±10.42	91.36±42.66
Land Navigation Preparation	Candidates were provided time to plan their routes and mark their maps before embarking	1005 (0:20)	116±13	18.44±4.68	166.88±58.56

Land Navigation Exercise	Orienteering assessment of navigation over various terrain using only a supplied map, compass, and grease pencil	1018 (5:00)	117±13	28.99±11.67	91.34±49.70
Administration	Mobilisation, hands-on assessment, and written safety/proficiency check	1547 (2:50)	92±5	38.06±16.26	138.56±131.82
Load Carriage/Pack March	Various load carriage and transportation of stores at self-selected pace. Candidates proceeded for undisclosed time/distance.	1850 (10:30)	112±16	39.67±30.21	144.22±98.56
Rest	Candidates were permitted to eat, sleep and change clothing/equipment as needed.	0520 (Day 2) (0:40)	78±8	52.31±9.18	87.45±44.78
Less-lethal device deployment	Less than lethal device that produces bright light and sound was activated adjacent to the sleeping area	0606 (Day 2)	109±3	25.53±13.26	140.41±44.28

Physical Training	Circuit training consisting of various weightlifting, calisthenics, and plyometric activities	0626 (Day 2) (1:35)	115±7	50.31±15.94	247.56±85.99
Fear of heights evaluation	Perform various activities at various heights, up to several stories above ground	0800 (Day 2) (1:20)	121±11	33.51±17.56	195.07±79.74
Physical Training	Candidates engaged in additional physical challenges	0922 (Day 2) (1:40)	119±10	52.16±23.22	248.15±81.84
Threat de-escalation simulation	Candidates were given an operational scenario	1105 (Day 2) (0:10)	111±2	36.82±0.70	95.12±1.08
Tactical police occupational scenario	Candidates were tasked with scouting a region on foot	1246 (Day 2) (1:40)	100±9	38.99±13.90	125.32±52.67
Tactical police occupational scenario	Candidates were given an operational scenario	1521 (Day 2) (0:20)	128±16	44.07±22.10	242.12±49.84

Legend: HR: Heart rate, bpm: beats per minute, pRR15: percentage of R-to-R intervals varying by at least 15ms, RMSSD: root-mean square of successive differences, SD: standard deviation

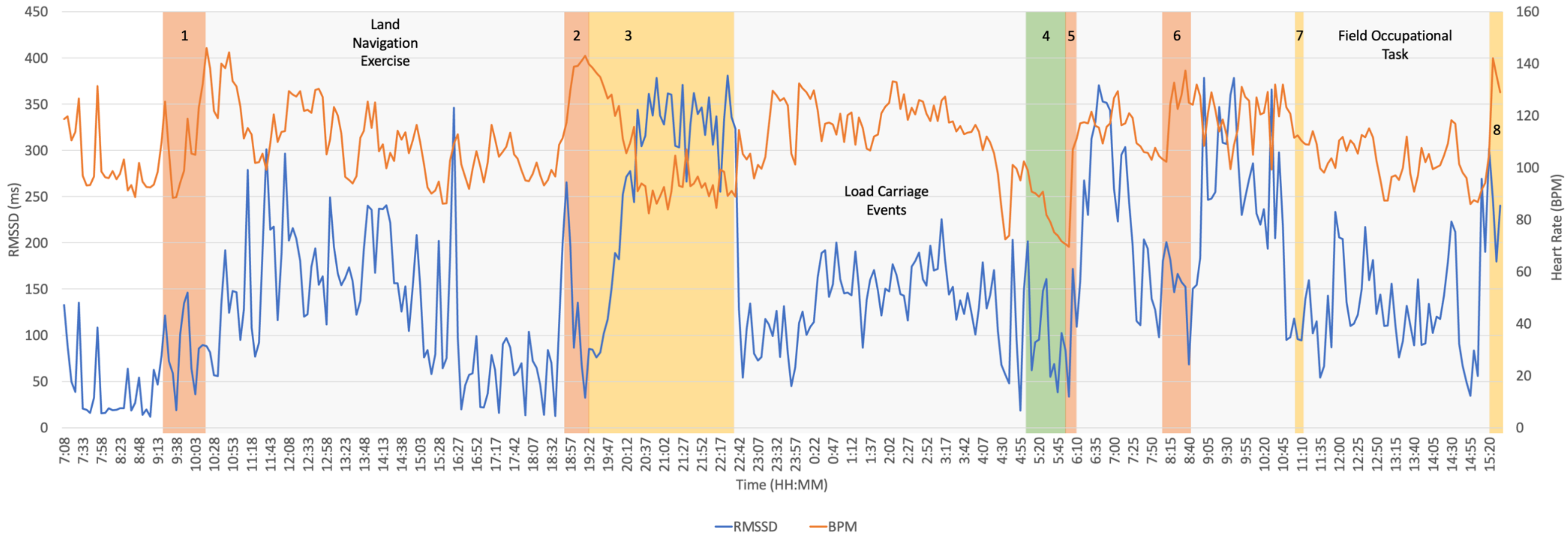


Figure 9. RMSSD HRV and HR Illustration, Male PTG Candidate Case Study

Legend: 1. Travel to and planning of navigation exercise; 2. Pack march planning; 3. Pack march exercise; 4. Rest period; 5. Less-lethal device deployment; 6. Fear of heights evaluation; 7. Occupational Scenario; 8. Tactical Police Occupational Scenario. Events within the shaded light grey areas are described within the figure.

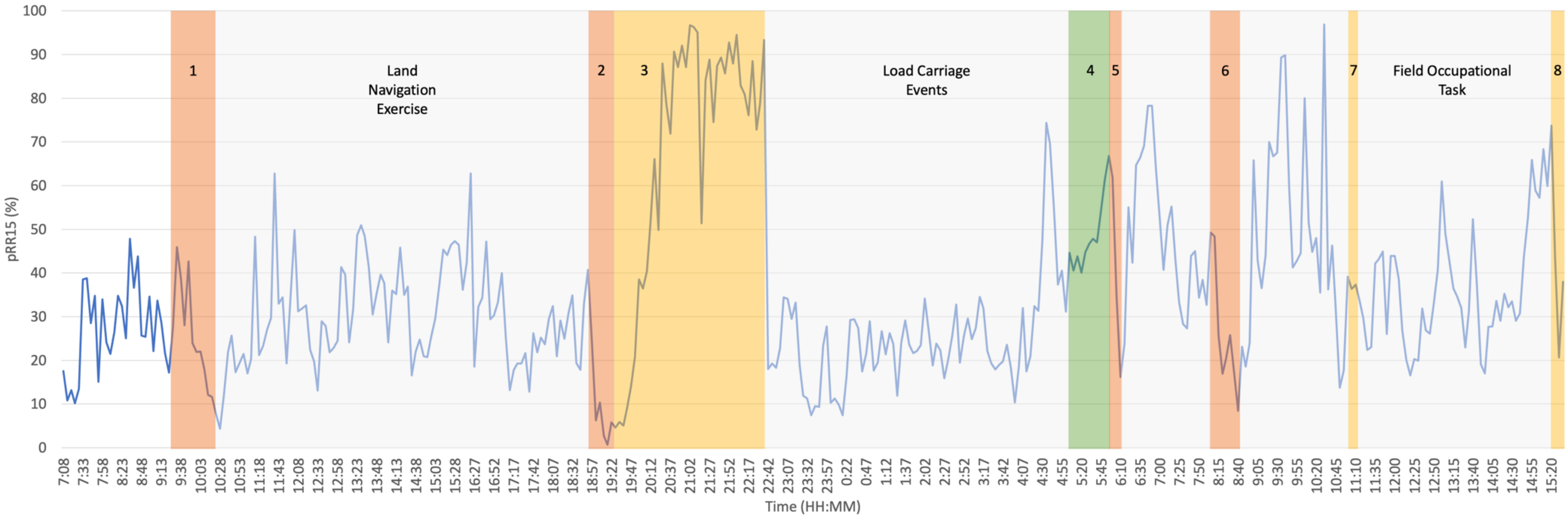


Figure 10. pRR50 HRV Illustration, Male PTG Candidate Case Study

Legend: 1. Travel to and planning of navigation exercise; 2. Pack march planning; 3. Pack march exercise; 4. Rest period; 5. Less-lethal device deployment; 6. Fear of heights evaluation; 7. De-escalation simulation; 8. Tactical Police Occupational Scenario. Events within the shaded light grey areas are described within the figure.

6.5 Results

Figure 9 and Figure 10 illustrate the finalised graphical descriptions of the fluctuations in HR and HRV throughout the entirety of the selection course. Table 1 contains the details of each selection course serial, the start time of the serial, and the mean and standard deviation of pRR15 and RMSSD for that event. Regarding HR (Figure 9), while some fluctuation is noted, values generally ranged between 70 beats per minute (bpm) and 150 bpm, or the equivalent of moderately intense exercise and rest [223]. Specific details can be found in Figure 9.

Regarding HRV, an initial decrease and low trough in values is noted at approximately 0938 through 1023 (lowest mean RMSSD; written examinations; 30.99±22.50). During this time, the candidate was travelling to, planning, and then commenced a land navigation field exercise (Figure 9, shaded region 1). A second decrease and trough is noted from approximately 1842 – 1912 hours. The candidate was again preparing for and initiating activity, at this point a sustained pack march (Figure 9, shaded region 2, RMSSD = 91.36±42.66). The change in RMSSD and pRR15 values throughout day were of particular interest as the only opportunity for rest in the 36-hour course commenced at approximately 0520 hours and lasted until approximately 0600 hours (highlighted in green on, Figures 1 and 2, shaded region 4, RMSSD = 87.45±44.78). A modest increase in the percentage of pRR15 intervals and RMSSD can be seen during the rest period, along with a commensurate decrease in HR. A less-lethal explosive device producing a bright flash and loud sound was deployed adjacent to the candidate's sleeping area at approximately 0600 hours (Figure 10, shaded region 5). A severe and immediate decrease in percentage pRR15 intervals is noted at about that time, highlighted in the orange (shaded region 5, Figure 10). However, RMSSD did not also exhibit this change (Figure 9). The candidate appeared to recover from this stressor and proceeded with physical training activities until approximately 0800 hours, when a fear-of-heights test was conducted (Figure 9 and Figure 10, Shaded region 6). This event involved tactical police manoeuvres at various heights, up to several stories above ground. This again resulted in decreased HRV. The specific values of minimum and maximum percentage of pRR15 intervals, along with other descriptive statistics, can be found in Table 13.

Table 13. Descriptive Values of HRV and HR

	Recording Duration	Mean	Median	SD	Maximum	Minimum
Heart Rate (beats per minute; bpm)	32:27:56 (hr:min:sec)	109.54	109.42	14.78	146.00	69.57
pRR15 Value (Percentage)	32:27:56 (hr:min:sec)	36.04	31.78	20.71	96.83	0.71
RMSSD Value (ms)	32:27:56 (hr:min:sec)	154.53	142.88	91.17	380.98	11.78

Legend: SD: standard deviation, pRR15: percentage of R-to-R intervals varying by at least 15ms, RMSSD: root-mean square of successive differences

6.6 Discussion

The aim of this case study was to illustrate the outcome of HRV monitoring during PTG selection. PTGs select for personnel that are highly physically competent, but also resilient to cognitive and emotional stressors, sleep, and food deprivation. Further, PTGs are also select for those who work effectively as a team in austere conditions. Based on the results described in this study, HRV monitoring may support PTG selection by providing objective information on overstress and adaptation to an otherwise subjective process.

In general, lower percentage of pRR15 and lower RMSSD both indicate less variation in heart rate for the assessed time window, and therefore decreased adaptive external and internal environmental responses. This may in turn signal excessive psychophysiological stress [68]. Overall, the HRV profile indicates potential overstress periods, but also the ability to recover or continue functioning despite potential exhaustion. The candidate was able to proceed through each selection serial without succumbing to fear or exhaustion. Important to note when reviewing these findings is the potential pitfall in HRV interpretation of viewing values dichotomously; that is, the implication that a result is either ‘high’ or ‘low’ and therefore either ‘good’ or ‘bad’ [224]. The reality that is visually demonstrated by this case is that HRV is necessarily oscillatory [83,225]. Indeed, this case potentially agrees with the ‘U-shape’ distribution of illness risk for HRV values described in the psychiatric literature [211]. Essentially, prolonged values at either extreme of any HRV metric are potential indications of failure to adapt and respond dynamically to external and internal environments. This is especially true if those environments are subject to abrupt and frequent change [75,211], such as tactical police selection. Indeed, the objective is to expose personnel to as many varieties and intensities of stressors as can be permitted within the bounds of safety. A portion of the load carriage activity, spanning much of the evening on Day One (approximately 5 hours from 1900 – 0000, shaded region 3), is a prime example. An interpretation of pRR15 or RMSSD values without sufficient nuance would lead to the conclusion that the candidate was in optimal health and performance status during this window – pRR15 values remain between 70 and 90% during this time (RMSSD = 242.21±17.49). However, the reality is that the candidate was undergoing a highly rigorous task, initiated with minimal rest, minimal calorie intake, and the added psychological stress of an unknown end point for the task. Therefore, this potentially excessive variability may best be viewed in the context of research on both cognitive load and progressive exercise testing. These findings generally report overactivity of the parasympathetic nervous system during periods of heightened exertion, which would be consistent with highly elevated pRR15 values [220,226]. This finding from the present data is further supported by the HR data, in which the HR is not elevated, but rather depressed during this time window, when an elevated HR would be expected. Depressed HR during exertional tasks potentially also signals exhaustion (Figure 1). Therefore, the end-user should interpret this section carefully and with understanding of the relevant context. If this individual was indeed reaching exhaustion, the extent to which it manifested externally was limited. As such, the objective HRV data coordinated with subjective observation indicate a strong capacity to suppress discomfort and achieve the occupational aim, a highly desirable quality in PTG personnel.

The particularly depressed HRV values during the preparatory phases of the land navigation field exercise (Figures 1 and 2, shaded region 1) and pack march (Figures 1 and 2, shaded region 2) are also of interest as little physical activity was occurring, supported by both the HR data and observation of the candidates. Therefore, anticipatory stress may have contributed to the decrease in values. Additionally, the trough noted during fear of heights training (approximately 08:10-08:45 on Day Two) indicates that despite the other rigorous and challenging events conducted later that day, the candidate's strongest psychophysiological response as measured by pRR15, and perhaps period of greatest sympathetic activity, was during the fear-of-heights test (Figure 2, shaded region 6). However, again, the candidate was subjectively not demonstrating any externally visible signs of distress. The value of the objective HRV measurement that does indicate high stress further supports this candidate as an individual that is able to overcome the 'fight or flight' response and continue functioning. Other notable examples of high stress events that did not elicit such strong responses as measured by HRV include threat de-escalation simulations (approximately 11:05-11:10, Figure 2, shaded region 7) and tactical police scenario manoeuvres (15:21-15:35, Figure 2, shaded region 8), indicating that potentially no excessive stress response occurred despite the intention of the instructing staff to do so. This feedback may also be beneficial for the design of future selection courses. The possible exception to this conclusion can be found at the period highlighted in orange from approximately 18:42 through to approximately 19:12 on the initial day of the selection course. This period was the only point of the entire selection course where the participant dropped to near zero pRR15 (min value 0.71%) and may be as a result of combined fatigue from earlier events during the first training day and the above-mentioned anticipatory stress surrounding the load carriage event (18:50-23:23 on Day One) which was known to have a high attrition rate.

6.6.1 Limitations

The data captured for this case study were not without noise. While the recording window was sufficiently long enough to eliminate the effects of ectopic and erroneous potential R-R intervals, the potential for confounding cannot be ignored. The region with the most noise was the discarded section of data from 0600-0700 on Day One, which may have provided additional information on this candidate's response to heavy exercise before fatigue onset occurred. Future studies may consider real-time monitoring to intervene when excessive noise events occur. Additionally, the serials were not of equal length, and therefore the mean and standard deviation values of pRR15 and RMSSD are difficult to compare. Finally, the collection of baseline data before the beginning of the SC in a controlled environment (such as an air-conditioned indoor space), and of the candidate's recovery following the SC, would provide further value and context.

6.7 Conclusions

This case study demonstrates the potential utility for selection personnel to obtain additional insight from HRV data into candidate responses to various occupationally relevant challenges throughout a selection course. This information may support leadership decisions when evaluating personnel holistically for service in extremely demanding professions such as PTG units. The ability for personnel to recover quickly with limited rest, continue performing even under potential overstress (such as when afraid of heights) and continue to display adaptive response after food and sleep deprivation are valuable traits in specialist police. Provision of visual aids for the interpretation of HRV data may also be useful for stakeholders using HRV data for decision making. While additional studies are needed that assess multiple cohorts of personnel, both successful and unsuccessful, the consideration for HRV as an element in the personnel selection matrix to assess the overall suitability of a candidate for service in PTG units is warranted.

6.8 Afterword

In this chapter, a case study was presented describing the HRV profile of a successful specialist police candidate over a continuous selection course with a specific focus on psychophysiological stress. This chapter visually associated psychophysiological stress events and tasks during the selection course with HRV responses and demonstrated a potential indictor of resilience; the candidate, by all outwardly visible measures, demonstrated the ability to recover with brief rest, overcame a fear of heights, and was not rendered ineffective by the integrative stress response that was illustrated by the HRV signal. However, success in training is distinct from performance once operational. Therefore, the following chapter does discuss further aspects of selection, aiming to answer the following dedicated research question, can HRV analysis as captured by wearable technology, from a three-member cohort effectively discriminate between high and low performing individuals in specialist police selection? In addition, the next study (Study 5) also bridged the research arms of this program of research with a focus shift towards the application of HRV monitoring at an operational level.

6.8.1 Future Directions

Case studies may be limited in their utility outside their specific research context. While HRV obtained by wearable monitoring is generally reliable and supported as generally equivalent to gold standard Holter monitoring, the unpredictability and rigor of tactical environments cannot be discounted. Indeed, segments of data loss due to noise or signal disruption did occur in the above case, and resulted in some missing information that may have been of further value. While careful consideration must be made when comparing HRV data across individuals, evaluating the HRV responses of multiple individuals to a given stressor likely provides more information.

Chapter 7 – Selection Factors: Incorporation of Heart Rate Variability into Police Tactical Group Tactical Skills Assessment

7.1 Preface

In the previous Chapters, 2, 4, 5, and 6, literature gaps were identified and systematically approached, focusing on specialist police selection courses to inform unit leadership and stakeholders with objective psychophysiological responses of candidates undergoing selection. In study 2, heart rate variability (HRV) was demonstrated as a more sensitive measure to potential overstress than heart rate (HR). Study 3 built on this finding by refining data visualisation and developing an attrition prediction model for HRV during load carriage events. Study 4 accomplished two aims: 1) the development of a more precise profile of the most successful candidate from Studies 2 and 3; and 2) the investigation of HRV outcomes during events imparting psychophysiological stressors. These stressors and HRV measures were observed during a 2-day selection course. Any candidates succeeding in an attempt of the 2-day course were permitted to participate in a further 5-day selection course. The purpose of this additional course was to focus on assessment of additional skills and attributes beyond those chiefly considered in the 2-day course. While physical acumen and resilience are necessary, and thoroughly evaluated in the 2-day course, these are not the only prerequisites for success in specialist police selection or operations. Fluid psychomotor skills, such as firearms safety, and the ability to retain effectiveness of those skills while under duress are also critical. These skills are not only limited to function as an individual, but also the ability to lead and follow as part of a team. These are essential and non-modifiable components of work as a specialist police officer. Therefore, in this next study, study 5, two aims were approached: 1) to answer the research question: can HRV analysis as captured by wearable technology, from a three-member cohort effectively discriminate between high and low performing individuals in specialist police selection? The second aim was to 2) link between the selection and operational research perspectives. Specifically, attention to those factors that are endemic to specialist police work outside of selection courses will be of chief interest in the following chapters. These factors include firearms proficiency and teamwork, overnight shift work, operational marksmanship requalification, and service as a directional staff cadre member, assessing the next generation of specialist police personnel. Addressed first in the following chapter (Chapter 7) is the exploration of HRV monitoring as a psychophysiological stress measurement in specialist police selection when realistic scenarios, such as a simulated active shooter event, are introduced.

This study was originally developed and produced as an internal white paper for the sponsoring organisation. It has been adapted and presented at the American Physiology Summit 2023. The full citation is as follows:

APS Tomes C, Schram B, Canetti E, Orr R. Incorporation of heart rate variability into police tactical group small unit tactics selection. Physiology. 2023 May 23;38(S1):5763348. https://doi.org/10.1152/physiol.2023.38.S1.5763348. Available from https://journals.physiology.org/doi/abs/10.1152/physiol.2023.38.S1.5763348

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

7.2 Abstract

Background: Police work is known to expose officers to high levels of physical, mental, and emotional stressors. As such, personnel selection must ensure future team members are not only physically, but mentally and emotionally prepared for duty. Thus, to assess personnel for suitability requires a complex and holistic approach, which can be augmented using wearable technologies. Heart rate variability (HRV), one metric obtainable from wearable technology, has been used with increasing frequency, but its application in police selection has been subject to little investigation. Therefore, the purpose of this study was to identify if HRV analysis can effectively discriminate between high and low performing individuals in specialist police selection.
Methods: This study was a prospective cross-sectional study of three male PTG candidates. HRV was analysed by time-domain, nonlinear, and frequency-domain measures. Long-term (5 hour) and consecutive hourly measures were obtained. For the long-term analyses, measures of central

tendency were generated; the maximum, minimum, and standard deviation were reported for each HRV measure.

Results: The maximum values (highest HRV) for RMSSD, pRR50, SD1, and SD2 were all noted in one participant. That same participant also held the lowest maximum heart rate and lowest mean heart rate as compared to the other two candidates. This participant was also the highest performer as rated by the observing selection directional staff.

Conclusion: Given the discriminatory capacity of HRV in this context, HRV may be a valuable metric in tactical police training.

7.3 Introduction

Police work is known to expose officers to high levels of physical, mental, and emotional stressors and high levels of fatigue [36,142]. Imposed stressors and fatigue sources include response to emergencies, internal organisational demands, irregular work hours, prolonged shifts, and collateral duties [39]. Exertion in challenging or dangerous environments is expected, and personnel must be able to perform without becoming a liability themselves due to exhaustion or other potential failures so as to maintain task proficiency [35,39]. While this is true of all sworn officers, specialist police, such as those in Police Tactical Groups (PTGs), may be expected to perform duties unconventional for law enforcement under even more extreme circumstances [227]. These PTG tasks may include search and rescue, counterterrorism, explosive ordnance disposal, high risk warrant service, and policing engagements involving hostile entities with firearms [13,35,199]. For this reason, selection for PTG service is usually physically, mentally, and technically challenging, requiring highly refined marksmanship, excellent physical fitness and an exceptional ability to perform under extreme pressure and over prolonged durations that aim to induce high levels of fatigue [39]. Future team members must not only be physically, but mentally and emotionally prepared for duty and, as such, performing under cognitive duress over extended timeframes is a vital assessment component for PTG candidate suitability [95,97,110].

To effectively assess personnel for suitability requires a complex and holistic framework that includes a battery of physical fitness tests, psychometric testing, interviews, and expert observation of performance. Specifically, these observations are often of tactical skills, such as room entry appreciation, ability to decide and execute use of force escalation, and other psychomotor tasks [228]. Wearable technologies can provide decision makers additional information on the performance of personnel undergoing selection [75,77]. One metric obtainable from wearable technology is heart rate variability (HRV). HRV may generally be thought of as one or more computational descriptions the complex, integrated, and holistic psychophysiological responses that occur when the time between consecutive heart beats, also known as beat-to-beat or inter-beat-intervals (IBI) is modulated simultaneously by a variety of influencing factors [69]. The fluctuation and oscillation of individual heart beats across time results from a dynamic relationship between intrinsic cardioregulatory factors as well as factors extrinsic to the cardiovascular system, namely the sympathetic (SNS) and parasympathetic (PNS) branches of the autonomic nervous system [68,69]. HRV is therefore a viable measure of quantifying stress holistically in tactical populations and may even signal the emergence of allostatic load in these populations [56,142,157,165]. When other measurement tools with which autonomic regulation or stress response may be quantified are unavailable, due to impracticality of application in tactical contexts outside of a laboratory, HRV shows promise as a field-based measurement for identifying maladaptive stress responses, including those induced by fatigue over extended duty periods [23,36,183].

While HRV monitoring has been employed with increasing frequency in military, fire, and rescue populations [55], the law enforcement population has received less research attention. Specifically, the application of HRV as a tool for identifying and stratifying performance in specialist police, particularly during assessment of those skills key for operational performance, still remains the subject of little investigation [90]. Therefore, the purpose of this study was to identify if HRV analysis, captured by wearable technology, from a three-member cohort can effectively discriminate between high and low performing individuals undergoing Police Tactical Group Small Unit Tactical Skills Assessment.

7.4 Methods

7.4.1 Participants

This study was a prospective cross-sectional study of male PTG candidates (n = 3) undergoing specialist selection at an Australian State PTG facility in 2022. Females were eligible both for selection and participation in this study, but none had applied for the selection cycle on which this research is based. All three available selection candidates were eligible for inclusion, and were recruited, but high attrition rates (>90%) in previous selection activities precluded a larger sample size. This is a known concern in elite tactical units [13,39,178]. Anthropometric data are not available as per a privacy agreement with the host organisation, however, all candidates disclosed that they were taking no medications for cardiovascular, renal, or respiratory conditions as a requirement of participation in this study. During the duty day (0700 – 1700) food intake was uniform and closely regulated; all candidates were provided ration packs and only permitted to eat at designated times. Caffeine was restricted for two hours prior to data collection. All candidates provided their informed written consent, and the unit commander provided permission for publication of this work. The research protocol was approved by the Bond University Human Research Ethics Committee (BUHREC), Protocol BS02165 amnd 1.

7.4.2 Procedures

Ambulatory 2-lead electrocardiograms (ECGs) were recorded for 5 hours during a single continuous training session, between 13:00 and 18:00. Participants were supplied with body worn Equivital™ EQ02+LifeMonitor (Equivital, Hidalgo, UK) harnesses to measure heart rate and HRV. The Equivital system has been reported in the literature as reliable and comparable to the gold-standard Holter ECG monitor [193]. Each participant was provided an appropriately sized harness and one of the senior researchers fitted and donned each participant. Participants did not doff the equipment until data collection concluded. Each harness was individually fitted to the level of each officer's xiphoid process to maximise electrode contact with the skin and minimise noise or artifact generation, as per manufacturer guidelines. ECG data were processed with

Equivital Manager (Equivital, Hidalgo, UK) and LabChart 8 Pro (ADInstruments, Sydney, Australia).

Participants were introduced to a building purposely designed for room clearance training; the purpose being to methodically check rooms for any threats and mitigate them. The rooms comprised of various resident and commercial specification rooms and hallways. Incomplete information and uncertainty were deliberately imposed by the selection staff as an important element of trainability and resilience assessment. Scaled room clearance training scenarios were performed first as individual candidates, then in pairs whereby a demonstration was provided by directional staff and which the participant was instructed to imitate. Basic door appreciation techniques, through to more advanced techniques were taught, practiced then assessed over a five-hour period [228]. Participants utilised a primary M4 weapon on a three-point sling (Colt Defence, Connecticut, United States of America) and a secondary 9mm handgun (Glock Ges.m.b.H, Deutsch-Wagram, Austria) holstered on the hip with simulated paint ammunition (Simmunition, Avon, Connecticut, USA). Candidates were permitted to wear their own tactical boots, webbing, plate carrier and ballistic plate, and were provided a gas mask and combat helmet. Targets ranged from paper silhouettes to role players. For live role-player scenarios, simulated ammunition was supplied. The role players engaged candidates as active shooters. The duration of the selection events ranged from a few seconds to clear a single room, through to more elaborate, multiple room clearances operating in pairs which lasted several minutes. Participants were assessed for their safety, movement technique, tactical reloads, and transition from primary to second weapons where required. Both verbal and non-verbal communication were assessed, as was weapons safety and overall outcome of each scenario by the primary instructor. Input was also provided by the simulated assailant (if present) and other staff (n=2-3) observing from an elevated observation deck.

7.4.3 Analyses

The author conducting the analyses was blinded to the overall selection process result (i.e., whether each participant passed or failed selection) until after the initial internal document containing HR and HRV data were provided to the selection staff. The following HR descriptive data were explored: minimum heart rate, maximum heart rate, and mean heart rate during the recording window. The minimum heart rate was considered the lowest heart rate that occurred for each individual over the five hours of data recording and training while maximum heart rate was considered the highest heart rate that occurred for each individual over the duration. HRV was analysed via the following metrics: for the time-domain, root-mean square of successive differences (RMSSD) and percentage of adjacent R to R wave (RR) ECG intervals varying by at least 50ms (pRR50) were determined. Nonlinear short-term variability (SD1), and long-term variability (SD2), as well as the ratio of long-term to short-term variability (SD2:SD1) were also measured. Finally, for the frequency domain, natural logarithm (Ln) measures of high frequency (HF), low frequency (LF), and very-low frequency (VLF) were considered. pRR50% was defined as the percentage that are at least 50ms different from their preceding neighbouring IBI [51,69]. The paired indices SD1 (Poincare plot x-axis) and SD2 (Poincare plot y-axis) were reported in milliseconds but generated geometrically by plotting the differences in time of a heartbeat to its preceding neighbouring beat [51,69] to form a Poincare plot. SD1 represents short-term oscillations, and is closely related to RMSSD, discussed above. SD2 represents long-term oscillations and is closely related to LF frequency-domain HRV, discussed further below [69,75]. The frequency-domain of HRV was obtained by the transformation of a time-series into its component frequencies[51]. The accepted frequencies in HRV measurement are high frequency (HF), low frequency (LF), and very-low frequency (VLF)[69]. Each frequency corresponds to a biological oscillatory mechanism[229], such as the baroreflex[230], respiratory sinus arrythmia[73], and circadian rhythm[169], though other influences, such as cognitive load and exercise can also exert influences on frequency-domain HRV[4,226]. In this study, the natural logarithm of the raw fast-Fourier transform value in milliseconds for each frequency range is reported, as this is a commonly reported metric in the literature[69].

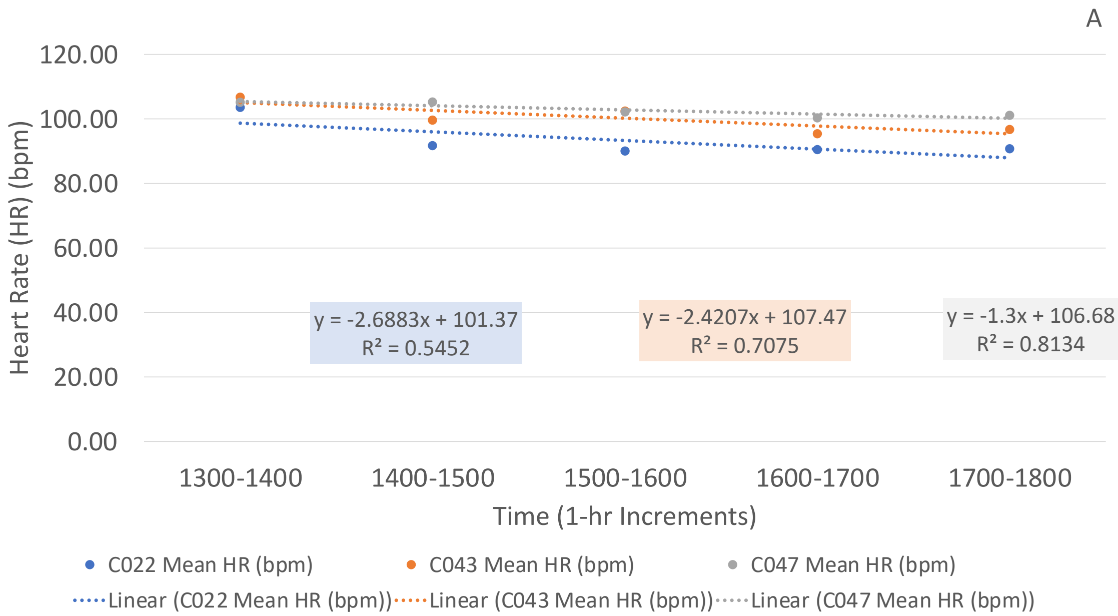
Measures were calculated for both the entire five-hour recording window and individual hourly blocks. While short term recordings can be obtained with validity over as little as three to five minutes [101], the longer time segment was utilised in this study to account for data noise due to tactical load carriage equipment. This yielded a single long-term value and five hourly HRV data points per participant, per HRV measurement. For statistical analysis, measures of slope and correlation coefficients (HR or HRV by time) were determined for each participant's HR or HRV data points across the time series. As the sample size was small, these data were compared qualitatively and by descriptive statistics.

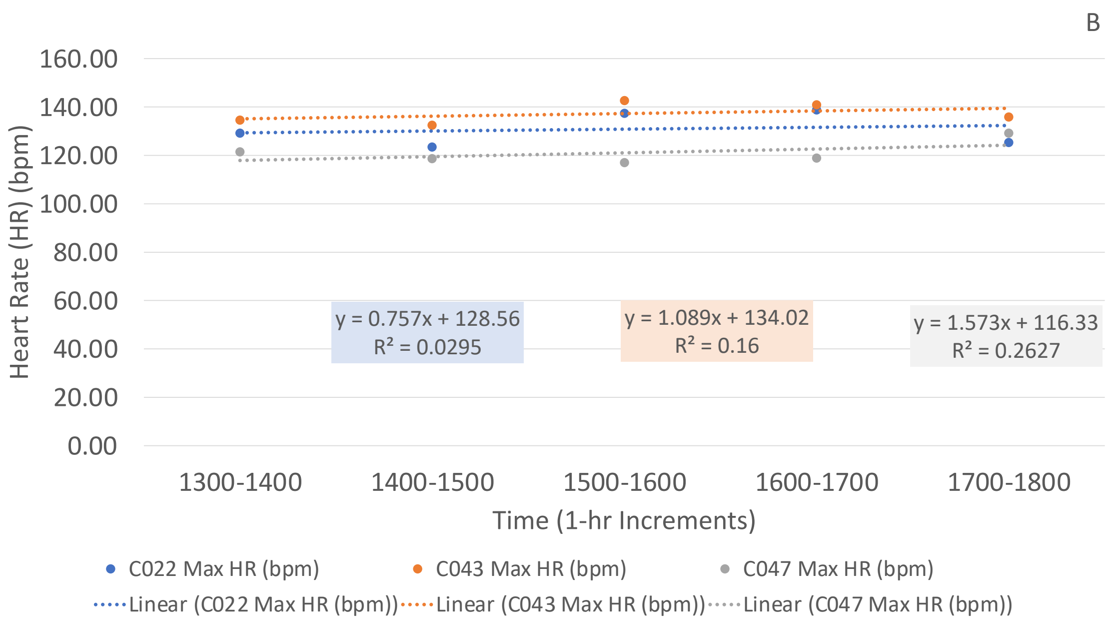
7.5 Results

All three candidates successfully completed the selection procedures, but only one participant (C022) was approved to progress beyond the present reported stage of selection. While participants C043 and C047 were not selected to progress, C043 was performing to a higher degree than C047.

7.5.1 Mean RR Value and Mean HR

Across all participants, the mean HR value was 96±9 bpm. The difference between mean and minimum values was 11 bpm, outside the standard deviation by 2 bpm. The maximum value was separated from the mean by 7 bpm. In terms of slope and correlation, the participants were difficult to distinguish from the HR data alone. This can be seen in Figure 11.


A
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Heart Rate (HR) (bpm)
y = -2.6883x + 101.37
R² = 0.5452
y = -2.4207x + 107.47
R² = 0.7075
y = -1.3x + 106.68
R² = 0.8134
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 Mean HR (bpm)
C043 Mean HR (bpm)
C047 Mean HR (bpm)
Linear (C022 Mean HR (bpm))
Linear (C043 Mean HR (bpm))
Linear (C047 Mean HR (bpm))


B
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Heart Rate (HR) (bpm)
y = 0.757x + 128.56
R² = 0.0295
y = 1.089x + 134.02
R² = 0.16
y = 1.573x + 116.33
R² = 0.2627
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 Max HR (bpm)
C043 Max HR (bpm)
C047 Max HR (bpm)
Linear (C022 Max HR (bpm))
Linear (C043 Max HR (bpm))
Linear (C047 Max HR (bpm))

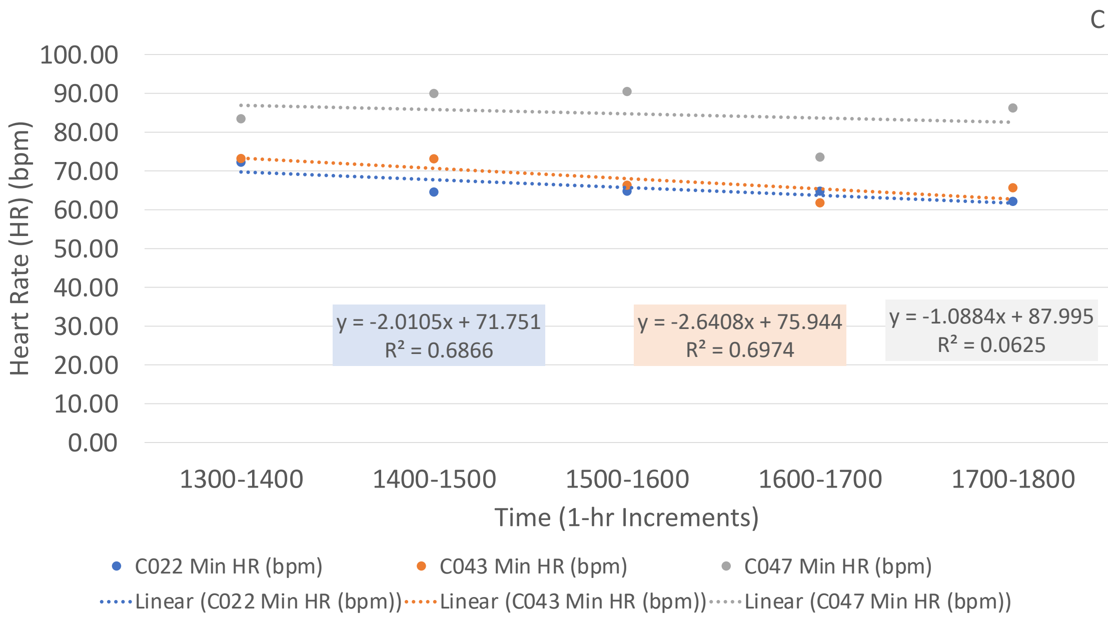
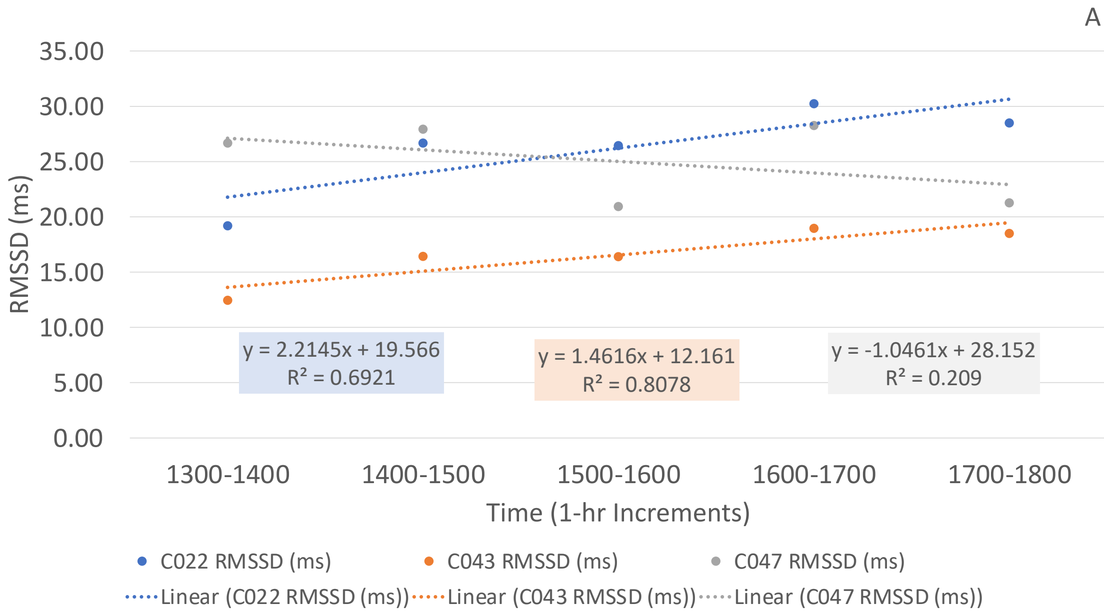


Figure 11. Hourly time-series heart rate value plot with trendlines

n = 3 male PTG candidates. Plots illustrate hourly time-series data for A) Mean HR, B) Max HR, and C) Min HR. Slope and correlation coefficient for the linear trend are reported for each candidate in the corresponding colour.

7.5.2 Time Domain HRV Data

The root-mean square of successive differences (RMSSD) is a time-domain analysis of HRV describing relative fluctuations in R-R intervals between adjacent beats and is reported in milliseconds. Regarding long-term RMSSD HRV, the mean value was 26.8±13.4ms. The difference between mean and minimum values was 8.0ms, within the standard deviation by 5.43ms. The max value was separated from the mean by 15.5ms. The percentage of RR intervals varying by at least 50ms (pRR50) generates a percentage value. The long-term minimum value of 2.0% fell within the standard deviation of the long-term mean value of 5.8±5.8%. However, the long-term maximum value was outside this range at 6.7% greater than the long-term mean. Regarding the consecutive hourly HRV values as seen in Figure 12, there is a clear difference between two of the participants (C022, C043) from another (C047).



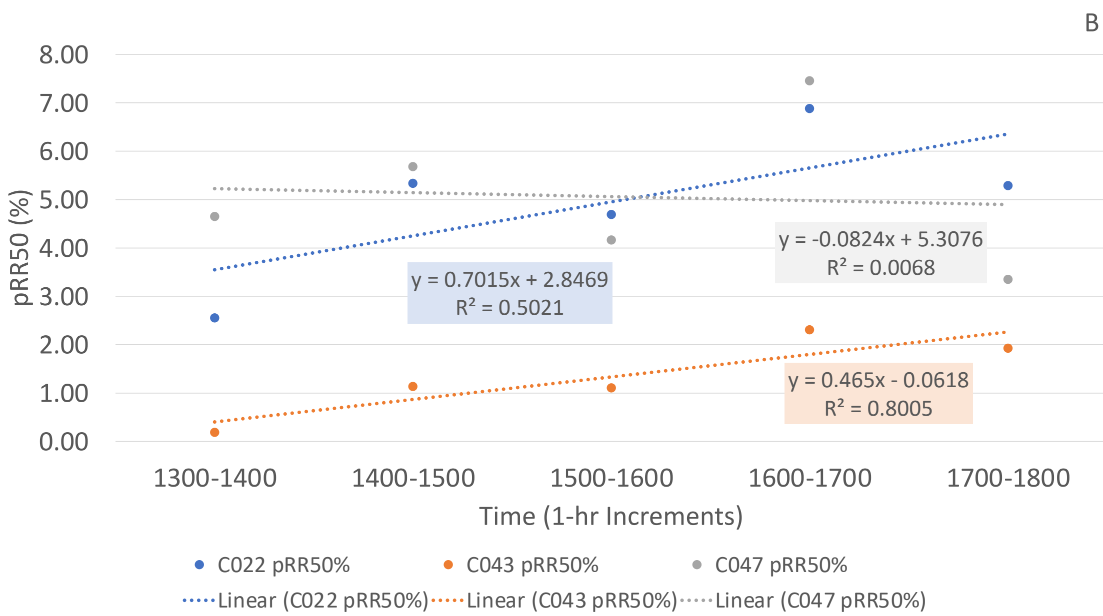
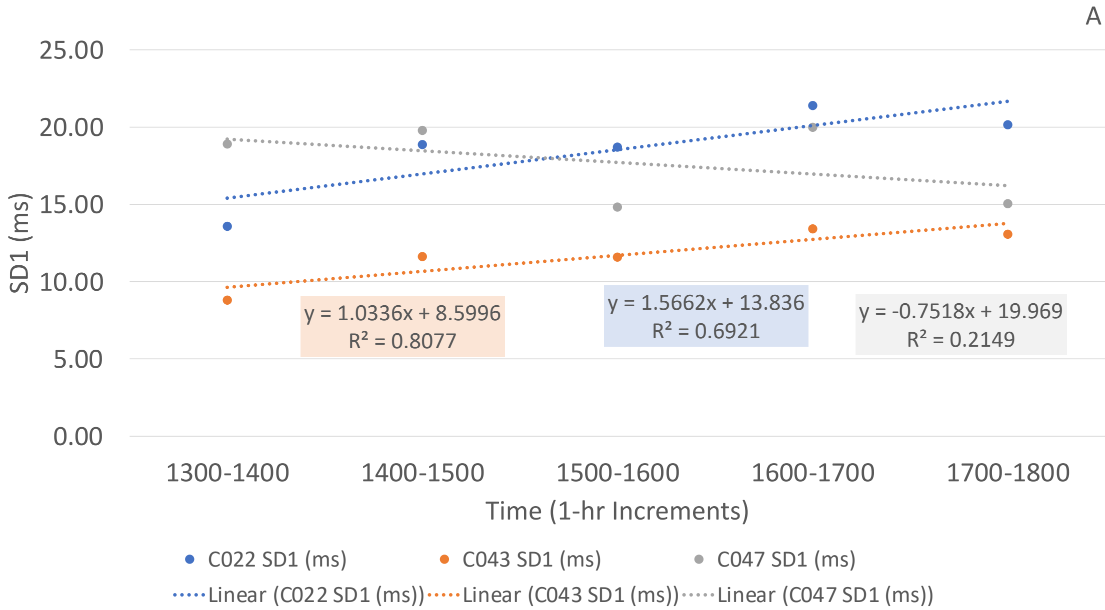


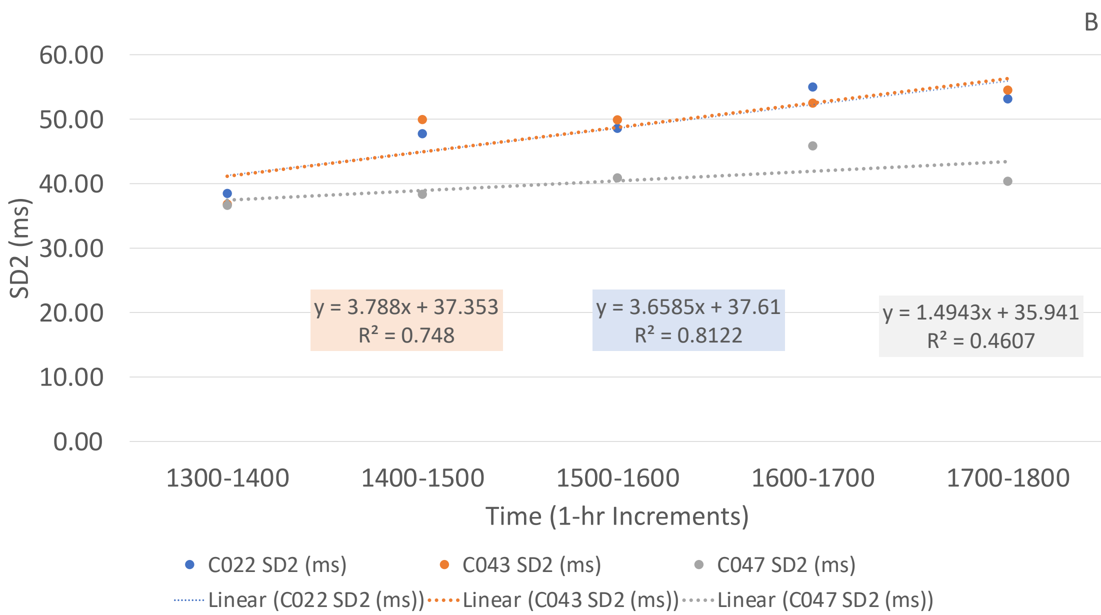
Figure 12. Hourly time-series time domain HRV value plot with trendlines

n = 3 male PTG candidates. Plots illustrate hourly time-series data for A) RMSSD and B) pRR50 (%). Slope and correlation coefficient for the linear trend are reported for each candidate in the corresponding colour.

7.5.3 Nonlinear HRV Data

In consideration of SD1 HRV across the entire data collection period, the mean value was 18.9±9.5ms. The difference between mean and minimum values was 5.6ms, within the standard deviation by 0.5ms. The maximum value was separated from the mean by 11.0ms. Regarding SD2 HRV across the entire data collection period, the mean value was 50.0±12.0ms. The difference between mean and minimum values was 12.5ms, outside the standard deviation by 5.43ms. The maximum value was separated from the mean by 11.6ms. As for the time-series nonlinear HRV data, specifically SD1, participant C047 displays a negative trendline, whereas the other candidates did not. This indicates potential failure to adapt, as the values deteriorated throughout the training shift. While SD2 values were generally similar between participants C022 and C047, there are differences in HRV magnitude, fit, and slope in SD1 and SD1:SD2 ratio values. These can be seen in Figure 13.


A
25.00
20.00
15.00
10.00
5.00
0.00
SD1 (ms)
y = 1.0336x + 8.5996
R² = 0.8077
y = 1.5662x + 13.836
R² = 0.6921
y = -0.7518x + 19.969
R² = 0.2149
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 SD1 (ms)
C043 SD1 (ms)
C047 SD1 (ms)
Linear (C022 SD1 (ms))
Linear (C043 SD1 (ms))
Linear (C047 SD1 (ms))


B
60.00
50.00
40.00
30.00
20.00
10.00
0.00
SD2 (ms)
y = 3.788x + 37.353
R² = 0.748
y = 3.6585x + 37.61
R² = 0.8122
y = 1.4943x + 35.941
R² = 0.4607
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 SD2 (ms)
C043 SD2 (ms)
C047 SD2 (ms)
Linear (C022 SD2 (ms))
Linear (C043 SD2 (ms))
Linear (C047 SD2 (ms))

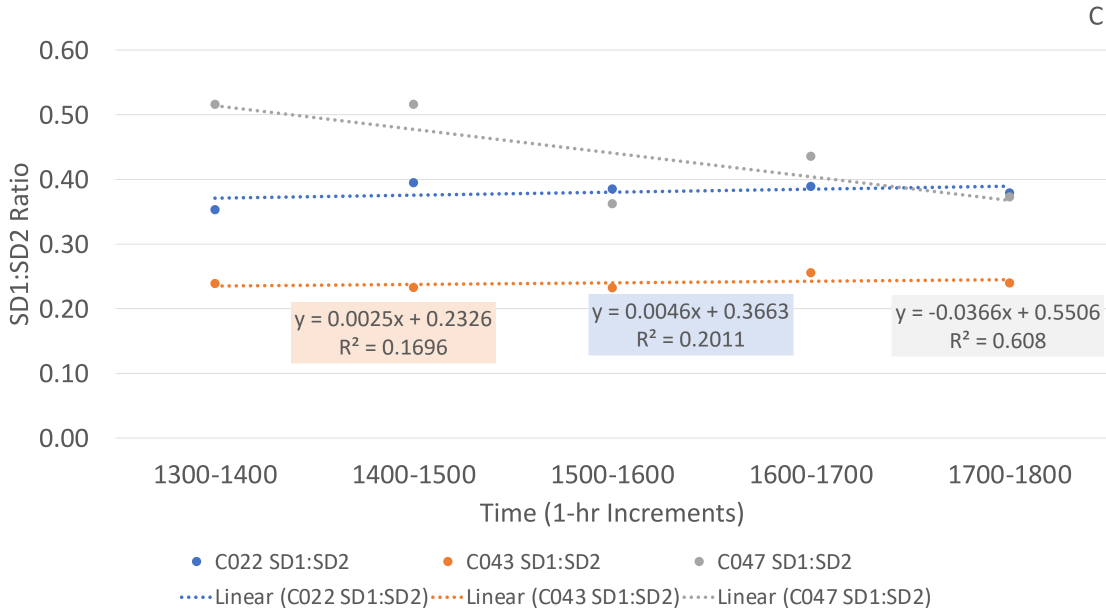
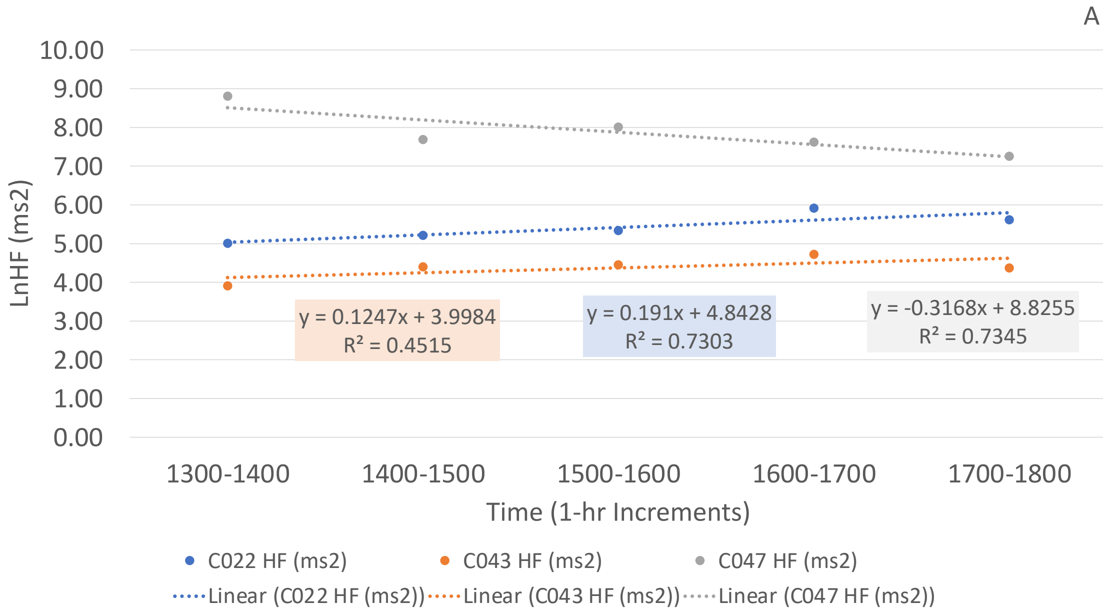


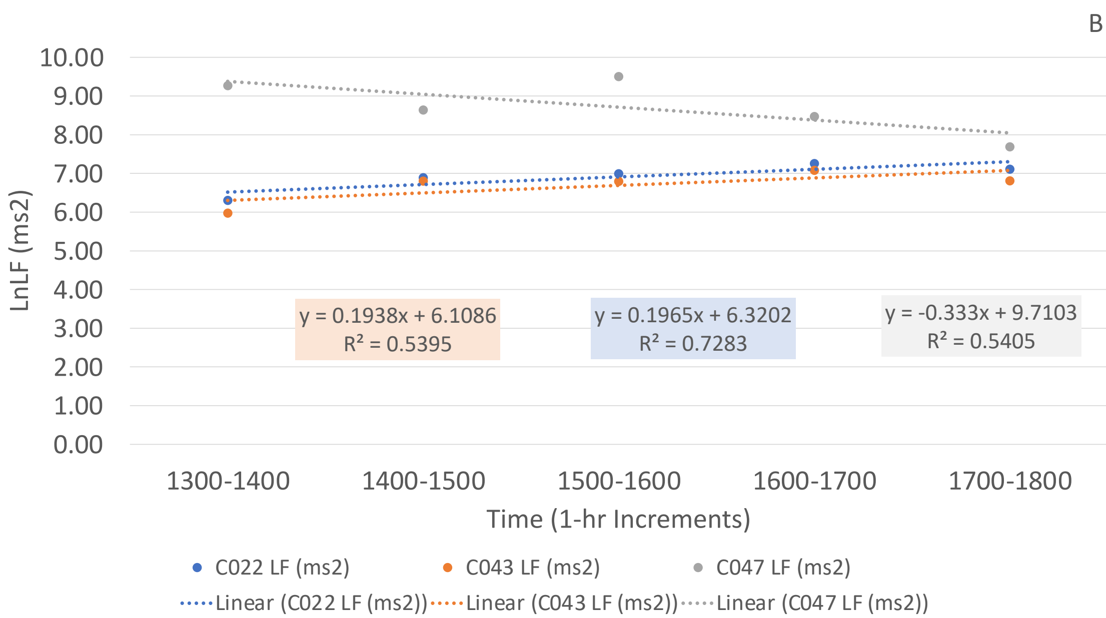
Figure 13. Hourly time-series nonlinear HRV value plot with trendlines

n = 3 male PTG candidates. Plots illustrate hourly time-series data for A) SD1, B) SD2, and C) SD1:SD2 ratio. Slope and correlation coefficient for the linear trend are reported for each candidate in the corresponding colour.

7.5.4 Frequency Domain HRV Data

Regarding long-term HF HRV, the mean value was 6.6±1.7ms. The difference between mean and minimum values was 1.6ms, within the standard deviation by 0.1ms. The maximum value was separated from the mean by 1.84ms. Regarding LF HRV, the mean value was 7.7±1.2ms. The difference between mean and minimum values was 1.0ms, within the standard deviation by 0.2ms. The maximum value differed from the mean by 1.28ms. Regarding long-term VLF HRV, the mean value was 5.1±0.6ms. The difference between the mean and minimum values was 0.6ms, approximately equivalent to the standard deviation. The maximum value was separated from the mean by 0.1ms. In terms of the hourly time-series (Figure 14), the most effective discrimination between the participant that passed selection and the two that did not is seen in VLF HRV; participant C022 demonstrates a positive slope, indicating recovery throughout the selection shift, whereas the other two participants deteriorated in terms of VLF HRV. While participant C047 again demonstrates a markedly different time-series HRV profile from the other candidates, the other frequency-domain measures do not appear to substantially differentiate participants C022 and C047, beyond somewhat greater HF magnitude in participant C022.


A
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
LnHF (ms2)
y = 0.1247x + 3.9984
R² = 0.4515
y = 0.191x + 4.8428
R² = 0.7303
y = -0.3168x + 8.8255
R² = 0.7345
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 HF (ms2)
C043 HF (ms2)
C047 HF (ms2)
Linear (C022 HF (ms2))
Linear (C043 HF (ms2))
Linear (C047 HF (ms2))


B
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
LnLF (ms2)
y = 0.1938x + 6.1086
R² = 0.5395
y = 0.1965x + 6.3202
R² = 0.7283
y = -0.333x + 9.7103
R² = 0.5405
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
Time (1-hr Increments)
C022 LF (ms2)
C043 LF (ms2)
C047 LF (ms2)
Linear (C022 LF (ms2))
Linear (C043 LF (ms2))
Linear (C047 LF (ms2))

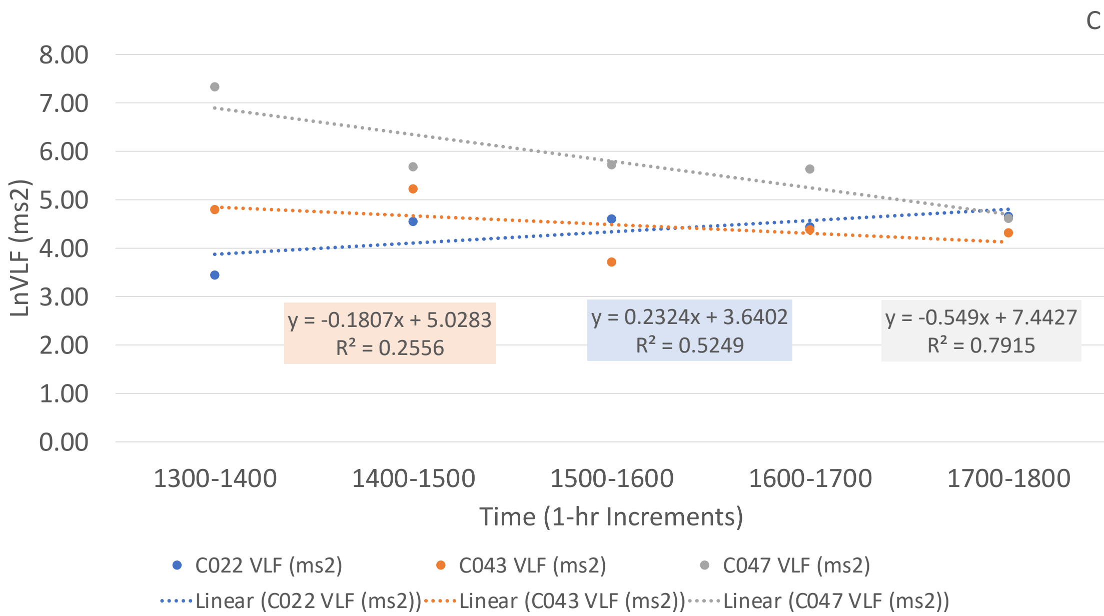


Figure 14. Hourly time-series frequency domain value plot with trendlines

n = 3 male PTG candidates. Plots illustrate hourly time-series data for A) LnHF, B) LnLF, and C) LnVLF. Slope and correlation coefficient for the linear trend are reported for each candidate in the corresponding colour.

7.6 Discussion

The primary aim of this study was to identify if HRV analysis, as captured by wearable technology from an initial three-member cohort, can effectively discriminate between high and low performing individuals in specialist police selection. Overall, HR data alone provided little additional information to the selection process, but HRV data were able, in some instances, to differentiate the highest and lowest performing candidate.

7.6.1 HR Data

The participant (C047) with the highest maximum heart rate, 168bpm, presented as equivalent to a healthy 30-year-old male exercising at approximately 88% of their age predicted maximum heart rate, or an intense level of work that generally cannot be maintained beyond 30-60 minutes [223]. The lowest minimum heart rate, 138bpm, would be equivalent to a healthy 30-year-old male exercising at approximately 73% of their age predicted maximum heart rate. This workload can be maintained beyond 60 minutes without excessive fatigue [223]. The participant with the lowest minimum heart rate, 62bpm, approaches the generally accepted resting HR range for athletic bradycardia (60bpm) [231]. In general, higher mean R-R interval values will indicate a lower heart rate [69] and potentially less exertion, though R-R interval values and derived heart rates provide less nuanced consideration of the influences of dynamic adaptive regulatory responses during potentially stressful exposures than more sophisticated HRV analyses, such as the time- frequency- and nonlinear-domains [69].

7.6.2 Time Domain HRV Data

The RMSSD is one of the most widely reported HRV metrics [69], and is frequently utilised in athletics [54,232] as many technologies can produce this computationally simple metric. The RMSSD is reported in milliseconds and describes to what extent on average each heartbeat differed in time from its preceding neighbouring beat [51,69]. During periods of stress, maintaining higher RMSSD likely indicates less 'fight or flight' response during the event [69,75], though relative contributions of sympathetic to parasympathetic nervous system contribution should not be inferred [72,214]. The mean value reported in this study of 26.8ms is similar to another previous study of operational specialist police personnel undergoing a firearms-related stress training event (20.7±13.7) [90], potentially indicating a level of generalisability in HRV metrics in this population. Notably, one participant's values were substantially different (participant C022) to his peers, potentially indicating greater dynamic internal regulatory capacity during the five-hour training event. The hourly time series also revealed an upward trend in HRV for the successful participant, indicating potential recovery as the training and selection activities progressed. This may be related to resolution of uncertainty [132,219], as information was deliberately withheld from participants as an aspect of the selection process.

In consideration of the pRR50%, there was a clear difference between C047 and the other candidates. This candidate (C047) was not approved to proceed further in the selection process.

Regarding C043 and C022, while similar, there are differences in terms of correlation across each of the five HRV data points. The participant that passed (C022) demonstrates a lower correlation coefficient relative to participant C047. While this analysis is informal, it does suggest that there was greater oscillation in the HRV characteristics of participant C022, and less dynamic cardioregulatory activity present over the reported period in participant C047. The pRR50 metric is known to be negatively influenced by sleep deprivation[90], and the relationship between sleep, fatigue, and HRV while under stressful conditions merits further exploration[90].

7.6.3 Nonlinear HRV Data

The nonlinear methods of determining HRV, such as SD1 and SD2 can be particularly useful in tactical settings, as these approaches are less vulnerable to data collection errors such as noise [55]. As another advantage of their robustness, nonlinear HRV measures can generate meaningful results with short recording timeframes [101]. SD1 reflects short-term variations and correlates strongly with time domain measures such as RMSSD and other components that capture respiratory sinus arrythmia, hence its association with parasympathetic activity [103]. SD2 reflects long-term variations, like the circadian rhythm [69]. Depressed SD1 and SD1:SD2 ratio values are also indicators of failure to adapt, excessive stress, or fatigue [69,75]. Participant C022 demonstrated greater magnitude of in this measure, a greater slope, and less correlation than the other candidates, though this is true of only SD1, and not the SD1:SD2 ratio. In general, especially during stress events, higher values of SD1 may indicate less 'fight or flight' response [75]. The mean SD1 value of 18.9ms reported here is similar to another previous study of operational specialist police personnel undergoing a stress training event (14.7±9.7ms) [90]. Higher SD2 values, conversely, may indicate failure to adapt to training when measured over repeated time frames [75]. The mean value of 49.87ms is again similar to another previous study of operational specialist police personnel undergoing a stress training event (52.8±33.6) [90]. In the hourly time series, participant C047 again demonstrated a different profile from C022 and C043. However, in contrast to the generally supported premise in the literature of lower SD2 indicating more effective adaptive response, the most highly performing participant (C022) demonstrated the greatest SD2 values. In the psychiatric literature examining HRV as a disease risk indicator, a U-shape distribution is proposed, where HRV values at either extreme may indicate suboptimal cardioregulatory function

[211] . This hypothesis may be relevant in the specialist police setting as rapid changes in perception of threat or danger are not uncommon [233]. For example, a scenario may begin with reports of an armed and dangerous individual, but on actual entry to the room with the alleged threat, a child is playing with a toy. Conversely, a benign interaction with a bystander may suddenly turn violent. Therefore, generalisations of HRV links with health or disease drawn from the civilian population, may not always apply in the present occupational context.

7.6.4 Frequency Domain HRV Data

The most notable finding in the frequency domain findings is the VLF component. This component represents the longest-term biological oscillations measurable by HRV and includes the circadian rhythm and is thus likely suggestive of fatigue levels in the participants [69,75]. Circadian rhythm disruption is a known concern in rotating shift workers [170], such as specialist police, and may be related to allostatic load accumulation in police officers more generally, and cardiovascular disease risk more specifically [56]. The VLF component is also known to be disrupted with high cognitive load and is also sensitive to metabolic fitness [52,234]. In this study, the only participant that demonstrated improvement in VLF throughout selection was the successful participant (C022). Given the volatile nature of frequency-domain HRV measurements, it may be this longer-term measurement that proves to be the most useful for integration into performance assessments in this population, though certainly the sample size and limited window of measurement remain important limitations to consider. Rather, this finding may serve to direct more focused attention into the HRV metrics that show promise and their sources, measurement, and documentation.

The successful participant (C022) had additional experience in the small unit tactics procedures assessed during this phase of selection, which may be reflected in the present HRV analysis findings, potentially due to less uncertainty or anticipatory stress throughout the selection process [95,235]. These HRV findings are also in agreement with directional staff assessments of performance. The candidate with the most notably different HRV results was also the candidate that struggled the most with the selection activities (C047). While it was more difficult to distinguish the candidate that ultimately passed (C022) from the other eliminated candidate (C043), the successful candidate did generally demonstrate more optimal values of HRV. Particularly, the nonlinear metrics and VLF HRV assessments. The levels of agreement between the HRV values observed in this study and previous specialist police candidate studies are also of note. While HRV is known to be a volatile biosignal [72,214], there appears to be some tentative degree of stability in this particular context. This is likely due in large part to volunteer bias and aspects of self-selection; the individuals likely to volunteer for specialist policing duties likely share many physical characteristics responsible for determining HRV [13,35,199]. Indeed, in previous research with this population, aerobic fitness was high, and all six participants were within approximately seven shuttles of each other, as measured by the multistage fitness test (MSFT). While causal research has not yet determined the predominant influences, previously studies investigating characteristics influencing HRV such as age, physical fitness, training history, cognitive and emotional disposition are candidate factors of interest for future research that may validate the similarities noted here across cohorts in specialist police [157,199].

7.6.5 Limitations

There are several limitations to this study. Beyond the small sample size, which is not unusual in specialist police research [90,236], the primary limitation to this study was that the moments in which the candidates were actually progress through the selection activities were not able to be identified specifically. Therefore, while this study provides an overall picture into the HRV responses of specialist police candidates when engaging in high-stress training, the time-series still provides limited resolution. Also, because of this it was not possible to distinguish between anticipatory stress, physical stress, and other potential stress sources, such as emotional stress encountered during the simulated active shooter events. While the top performer was clearly differentiated in consideration of the HRV analysis, there was no clear indicator, as measured by HRV, which of the other two candidates was the lowest performer. This may be because of the volatile and individualised nature of HRV but may also be due to the limited sample size or a potential floor effect. The influence of sleep deprivation has been explored in the limitations of this chapter and the discussions of previous chapters, but no attempt at inferencing the effect of sleep on HRV in multiple individuals has yet been considered.

7.7 Conclusions

The findings in this study indicate that HRV, specifically LnVLF, may be a valuable metric for quantifying load holistically in tactical police training. For LnVLF, the successful participant trended positively, whereas the others trended negatively in that domain. More generally, the individual with the highest rated performance by the directional staff also demonstrated the most optimal HRV values across multiple instances. HRV can be collected and measured in instances where leadership can immediately utilise the data as a component of their decision-making matrix, rather than exclusively in laboratory environments. With further study, organisations training personnel for service in specialist policing units may be able to enhance their selection processes with HRV data, considering it in context of task performance and behaviour of personnel undergoing selection.

7.8 Afterword

This study investigated HRV responses during small unit tactics training and selection, determining that previous small unit tactics experience may be a critical element to maintain HRV index stability during high stress events that also demand psychomotor capacity. This chapter also explored how complex cooperative tasks, such as small unit tactical manoeuvres result in psychophysiological stress measurable by HRV. While teamwork is an essential component of specialist police work, it is not the only non-modifiable factor that must be considered once personnel are operational. The effect of overnight shifts, while incorporated into elements of specialist police selection to an extent, have not yet been independently explored, and as such, form the basis of the following chapter.

Chapter 8 – Operations: Field Monitoring the Effects of Overnight Shift Work on Specialist Tactical Police Training with Heart Rate Variability Analysis

8.1 Preface

In previous chapters, namely Chapter 6, the presence of sleep deprivation was acknowledged as a factor that likely contributed to HRV fluctuations but was not explored in depth. The aim of Chapter 8 is to focus more specifically on sleep deprivation, and specifically overnight shift work in operational specialist police, as rotating shift work is an essential component of the job. However, rotating shifts have been identified in the literature, described in greater detail in Study 1 (Chapter 2), as an independent risk factor for chronic disease, and potentially a source of allostatic load. Operationally, specialist police are expected to maintain high work tempos across careers that may last decades, and so sources of chronic disease and allostatic load, even if minor, must be considered to support the long-term health of the personnel. As such, the outcomes of interest for this study were HRV profile differences between operational personnel who attended an annual firearms requalification and a subsequent firearms training exercise either after an off-duty period, or directly following a shift. This practice is a common and essential competency for specialist police units.

This study has been published open-access as a communication in *Sustainability* under a CC-BY 4.0 creative commons license. The original published manuscript can be found via the following: Tomes C, Schram B, Orr R. Field monitoring the effects of overnight shift work on specialist tactical police training with heart rate variability analysis. Sustainability. 2021 Jul 15;13(14):7895. https://doi.org/10.3390/su13147895 Made available under a Creative Commons CC BY 4.0 licence.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

8.2 Abstract

Police work exposes officers to high levels of stress. Special emergency response team (SERT) service exposes personnel to additional demands. Specifically, the circadian rhythms of SERT operators may be subject to disruption, resulting in decreased capacity to compensate in response to changing demands. Adaptive regulation loss can be measured through heart rate variability (HRV) analysis. While HRV trends with health and performance indicators, few studies have assessed the effect of overnight shift work on HRV in specialist police. Therefore, this study aimed to determine what effects overnight shift work may have on HRV in specialist police. HRV was analysed in 11 SERT officers and a significant ($p=0.037$) difference was found in pRR50 levels across the training day (percentage of R-R intervals varying by >50ms) between those who were off-duty and those who worked the night prior. HRV may be a valuable metric for quantifying load holistically and could be incorporated into health and fitness monitoring and personnel allocation decision making.

8.3 Introduction

Police work is known to expose officers to high levels of physical, mental, and emotional stress. These stressors can come in the form of challenging physical tasks, ranging from pursuing offenders on foot or performing first response to a natural disaster [237], to challenging cognitive and emotional tasks such as those encountered when performing life saving measures for a casualty. Not only are these demanding events often encountered with little to no warning, opportunities for recovery between response calls may be scarce, and the daily duties of a police officer are often compounded by the need to perform with external load carriage, take action under environmental stress such as extreme heat or cold, and endure social stressors associated with critical incident response [34].

In addition to these external demands imposed by response to emergencies, personnel are also subject to internal organisational demands, such as irregular work hours, prolonged shifts, and collateral duties [35,39]. In the United States, the special emergency response team (SERT) is an especially highly demanding collateral duty. Selection is usually physically and technically challenging, requiring highly refined marksmanship skills, excellent physical fitness and an exceptional ability to perform and make decisions under extreme pressure [13,35]. Furthermore, even once accepted onto a team, personnel must devote additional time to training, accept additional on-duty hours, and respond to the most high-risk scenarios within the region served by the organisation [14,35]. As such, the circadian cycle of SERT operators is subject to frequent disruption [14,35].

Circadian cycle disruption in and of itself is known to contribute to risk of illness and injury in tactical personnel, and the neurophysiological effects of working an overnight shift can manifest for as long as three days after the shift, even when no further work is required [163,238]. Shift work may also contribute to allostatic load, the decompensation of adequate response following prolonged exposure beyond tolerable levels of stress [124,125].

The allostasis model, first proposed by Bruce McEwen et. al., describes increased susceptibility to deterioration and dysregulation as an individual is exposed to increasing stress levels beyond their tolerance [125,126]. Essentially, allostatic load occurs when an individual's efforts to compensate for and regulate in response to uncertainty fail. As neuroendocrine, cardiovascular, and emotional responses become persistently overactive in attempts to compensate for the imposed stressors, blood flow turbulences in crucial regions of the body, namely the heart and brain, develop along with hypertension, cognitive dysfunction, and depressed mood. Any one of these processes can be debilitating, but all can occur in combination and accelerate disease acquisition and progression. Allostatic load can result in permanently altered brain architecture and systemic pathophysiology [132] while also minimising an individual's ability to further cope with and reduce additional uncertainty.

While the relationship between allostasis and shift work in tactical populations is still emerging, shift work appears to be a significant contributing factor to cardioregulatory changes that may contribute to allostasis in tactical personnel [91], and the nature of tactical work appears to have effects on healthy dynamic regulatory responses that other professions working overnight shifts do not experience to the same extent [55]. In other words, it is possible that overnight shift work and nature of stress in tactical environments act synergistically to impart extraordinary levels of physiological and psychosocial demand [55]. These stressors, if manifesting as allostatic load, may explain, at least in part, the known elevated incidence of heart disease among first responders [28,133].

Assessing the loss of dynamic and adaptive regulatory responses that may signal the onset of allostatic load is therefore of crucial importance, especially in tactical personnel who are not only at a potentially increased risk of allostatic load, but who also carry out tasks vital for the safety of the communities they serve. Heart rate variability (HRV), the fluctuation and oscillation across time of individual heart beats, results from a dynamic relationship between intrinsic cardioregulatory factors as well as extrinsic factors, namely the sympathetic (SNS) and parasympathetic (PNS) nervous systems [68,69] and is therefore utilised as a measure for quantifying stress in tactical populations [5,142,157]. In the absence of other measurement tools with which autonomic regulation or stress response may be quantified (due to impracticality of application in tactical contexts outside of a laboratory), HRV shows promise as a viable field measurement for determining maladaptive stress responses [23,36]. Other high-intensity settings, largely in elite athletics, have demonstrated the utility of HRV in calibrating training loads [53,54] with measures potentially used to augment injury risk predictions as well [78,89]. Additionally, correlations between HRV and cardiorespiratory fitness [148] and psychological stress [80,157] have been described. However, no known studies have been conducted assessing the specific effect of overnight shift work on the HRV, and potentially therefore, stress levels, in specialist police. Therefore, the purpose of this study was to determine what effects working an overnight shift may have on the HRV of specialist police during firearms qualification and training events, and to investigate if the utilisation of HRV monitoring may be viable in the field with tactical police organisations. It was hypothesised that officers who recently completed a work shift would have higher baseline pRR50 levels than previously off-duty officers and that following a shift officers would experience greater fluctuation in pRR50 levels.

This study was a prospective investigation of 11 male specialist police officers with an average of 5.2±4.4 years of experience as SERT members. All team members present for a regularly scheduled training exercise were eligible for inclusion. Operators prescribed cardioactive medications, medications for a renal, respiratory, or neurological condition, or who disclosed an injury or illness were excluded. All participants were recruited, consented, and followed for data collection on a single day of training. All data were collected during a regularly scheduled training event at the team's training grounds. No further descriptive data were available as per a privacy agreement with the team, which has occurred in other published studies investigating similar populations [189].

For the purposes of this study, off-duty operators (n=6) were defined as those who were able to sleep *ad libitum* and had no scheduled duties for 10 hours preceding training. On-duty officers (n=5) were those who were ending an overnight 10-hour shift immediately prior to reporting for training. All team members provided their informed written consent, and the unit commander provided permission for publication of this work. The research protocol was approved by the Messiah University Institutional review board (2019-022) and the Bond University Human Research Ethics Committee (2019-022 amnd 2).

Three-lead seated electrocardiographs (ECGs) were recorded for five minutes prior to the start of training, between 8:00 and 8:30am, and again immediately after the completion of yearly firearms qualification. While being recorded, participants were asked to sit quietly, refrain from moving so as to maintain the integrity of the trace and avoid using cell phones or talking. ECG recordings were obtained with an ADInstruments Powerlab (ADInstruments, Sydney, Australia) with leads placed on both wrists over the distal/lateral radius as close to the where the radial artery is typically palpated. The final lead was placed on the left ankle, just above the medial malleolus. Leads were not placed on the chest so as to facilitate measurement without requiring participants to remove their protective gear. Labchart (v7, ADInstruments, Syndey, Australia) software was used to capture and record all ECG traces and was set at a sampling frequency of 40KHz.

The qualification event consisted of static standing handgun engagement (Glock 22 firing .40 calibre S&W ammunition) at 3, 5, 7, 10, 15, and 25m. Rifle qualification (M4 rifle firing 5.56 mm ammunition) was also required and consisted of target engagements 50, 25, and 15m with walking shots delivered down to 5m. Operators were required to wear all standard issue gear (boots, uniform, plate carrier vest, helmet) and accurately place shots on all targets at all distances. The assessment was pass/fail, with 100% accuracy required to pass; failure resulted in elimination from the team and passing represented a significant yearly milestone for team members. All operators completed the qualification event within four hours of the initial baseline recording, reporting for their second measurement immediately after their completion of the event and notification of passing or failing. See Figure 15 for additional details on the timeline of operator events and data acquisition.

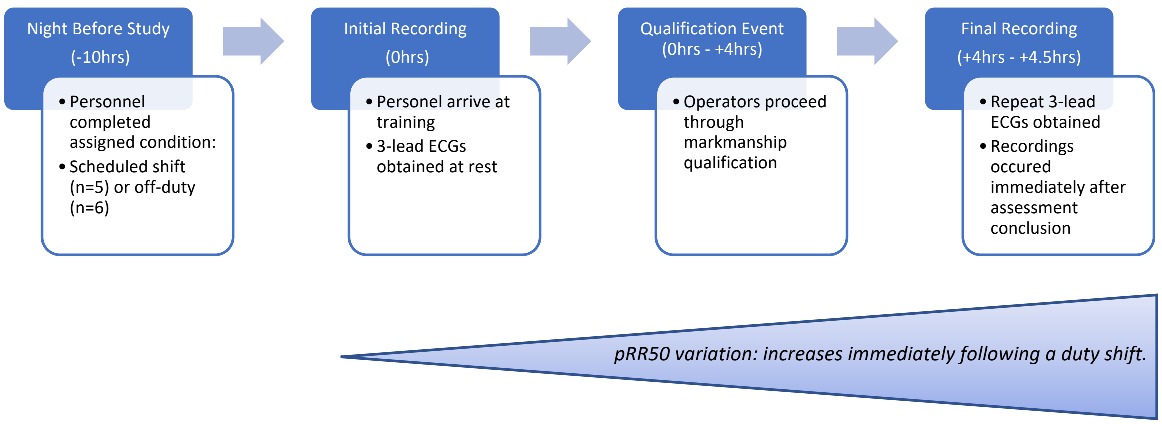


Figure 15. Sequence of Participant Duties and Data Acquisition

The triangle below the event sequence represents the hypothesis of the present study, suggesting greater variation as the training day progressed.

ECG data were processed with a LabChart v8 student license (ADInstruments, Sydney, Australia). Visual ECG examination was performed in combination with visual analysis of R-R plots to exclude outlier and ectopic beats. HRV was defined as the percentage of R-R intervals that varied by more than 50ms (pRR50). Results from officers who worked the night prior to training (n=5) were compared against those who were off duty (n=6) by determining if significant differences existed in the change between pre- and post-qualification pRR50 values. The pRR50 metric was chosen specifically because it has been identified as a clinically important feature when assessing for risk of cardiovascular disease [111] and is also less volatile and more amendable to use in short-term recordings than frequency-domain measures [69]. The change in pRR50 values across the training day was of particular interest in this study as the stress of attempting qualification could substantially perturb adaptive regulatory responses that would affect cardioregulation and therefore the HRV profile.

For statistical analysis, Shapiro-Wilk tests for normality were undertaken to determine whether parametric inferences would be suitable. Further testing via the Levene test was conducted to ensure equivalence of variance between sample groups. Independent-samples *t*-tests were used to determine significant differences, with alpha levels set at 0.05. SPSS Statistics (SPSS v26, IBM, Armonk, NY) was used for all analyses.

This All operators successfully passed qualification. Shapiro-Wilk test results confirmed normality of the data (p=0.598 for the non-rested group, p=0.581 for the rested group), and the Levene test showed equal variance between sample groups (p=0.257), allowing for independent-samples t-tests between groups. While no statistically significant differences existed when the baseline and final HRV measurements were assessed between the on-duty and off-duty groups, there was a significant difference between the *change* in pRR50 between groups; the mean difference between groups was 3.73% (95% CI: 0.29-7.18%, p=0.037). Previous research has described a threshold of 3% or lower for cardiovascular disease risk [111,114]. Rested operators remained above this level for all recordings. Non-rested operators fell below this threshold. Detailed HRV results can be found in Table 14.

Table 14. HRV Characteristics by Duty Status

	Off-duty operators (n=6)	**On-duty operators (n=5)**
Mean pRR50 at baseline	16.71±21.60	4.99±4.61
Mean pRR50 post-qualification	18.00±21.94	2.52±2.37
Mean change in pRR50	1.27±2.03*	-2.47±3.01*

** p<0.05: pRR50, percentage of R-R intervals varying by >50ms. All values are reported as percentages (%)*

8.4 Discussion

The purpose of this study was to determine what effects overnight shift work may have on the HRV of specialist police during firearms qualification and training events. While tentative, the results of this study indicated that off-duty operators, defined in this study as those with no scheduled duties during the 10 hours preceding data collection and training, experienced less cardioregulatory stress response during the training day; those who worked the previous night experienced a greater fluctuation in their regulatory capacity when exposed to the stress of the qualification event. This main finding agrees with previous research investigating the effects of shift work on stress regulation in tactical personnel, in which the authors found significant changes in HRV not only when personnel were required to work overnight, but between shifts that required different job tasks and duties [165]. The relationships between overnight shift work, specific job tasks unique to tactical professionals, and stress regulation are in need of further investigation, as previous work in healthcare workers found only limited changes in HRV during overnight shifts [169], whereas the effects in tactical personnel seem to be more pronounced [55].

While no significant differences were observed at baseline or on final measurement, this was likely due to the small sample size of this study relative to the volatility of HRV measurements; despite all operators available on the day of training volunteering to participate, the sample size still limited statistical power. Further, the standard deviation of the off-duty group was very high (greater than the mean for all recordings), and despite the substantial difference between rested and non-rested operators after qualification, this variability likely precluded the differences from reaching significance.

It should also be noted that while off-duty operators saw their mean pRR50 increase across the course of the day, as might be expected with the psychological relief of success following a substantial challenge (passing annual qualification, for which a single missed shot means elimination from the team), the mean pRR50 of the operators who worked overnight decreased even further. This result may indicate that the psychophysiological strain of working overnight was exacerbated as the day continued, and even resolution of the challenging event (firearms qualification) was not sufficient to fully attenuate the stress response reaction in those officers. This finding also agrees with previous literature in tactical personnel that found the effects of working overnight could be detected with HRV analysis for as long as three days following the shift [91,163]. This residual disruption in HRV following overnight shift work may also contribute to the high variance observed in the off-duty sample but may suggest that the most substantial effects can be resolved by a single night off-duty.

Additionally, while no operators reported a state of ill health or injury, previous research has posited that a resting pRR50 of 3% or less may be linked to cardiovascular disease [111,114,216]. The operators in this study that were off-duty the night before training were, on average, well above this threshold at ~17%, whereas operators who worked overnight were below or near the threshold at ~2.5-5%. While this result must be interpreted with caution, given the small sample size and short-term, rather than 24-hour, recordings, there is cause for further investigation, given that law enforcement personnel are known to be at elevated risk of cardiovascular disease beyond the general population [133]. It could be construed from these findings that overnight shift work contributes to depressed HRV and represents a risk factor in the development of cardiovascular disease. This would agree with previous research investigating the potential harms of working overnight shifts [239].

This findings reported in this study align with previous research linking allostatic load, disrupted sleep, and chronic disease risk [124]. These relationships in tactical personnel are complex; allostatic load may be induced through both type I and type II mechanisms [125]. Type I allostatic loads relate to an energy deficit imparted by physically demanding work or training in addition to limited resource availability (i.e., poor nutritional intake). Type II mechanisms include energy abundance, social stress, and are also not uncommon in first responders; suboptimal food choices, organisational demands, and shift work can contribute to insufficient recovery, all of which may contribute to chronic diseases, including heart disease, diabetes or insulin resistance, obesity, and pathological inflammation [23,38,124]. Further research with more sensitive R-R variability cut-off values closer to 12 or 20ms [111], additional screening for cardiovascular disease risk factors, longer HRV recordings that assess operators over multiple shifts, and include larger sample sizes may clarify this relationship.

Overall, the data presented in the study agree with previous literature assessing HRV in tactical personnel [55]. Specifically, two previous studies with similar methodological approaches in two very different geographical locations (Finland and Portugal), both found that first responder teams assigned to rescue duties overnight, which included tasks such as motor vehicle accident response, experienced significantly different HRV changes when the same teams were assigned to more typical fire suppression duties [5,91]. Contrastingly, research in healthcare workers found much more limited differences in HRV in groups of physicians and nurses who worked rotating shifts when compared to those who worked day shifts only [169]. In the present study, the effects of overnight shift work on cardioregulation in tactical police were noticeable when assessed by HRV, even in a small sample, establishing precedent for further investigation. Beyond this though, the need for the investigation into causal links is warranted; the specific tasks undertaken during night shifts and the psychophysiological response to those tasks may critically influence an officer's cardioregulatory profile and adaptive capacity during the period following an overnight shift. Mixed-methods studies that capture both the qualitative and quantitative elements of overnight shift work in tactical professions may begin to uncover the discrepancies between HRV profiles in first responders and professionals in other strenuous settings, such as hospitals.

8.5 Conclusions

The findings in this study indicate that HRV may be a valuable metric for quantifying load holistically in tactical police organisations, and that HRV can be collected and measured in instances where leadership can immediately utilise the data as a component of their decision-making matrix, rather than exclusively in laboratory environments. With further study, organisations employing collateral duty specialist police may be able to more effectively calibrate shift lengths and scheduling as related to training or other operational considerations to optimise operator health. Additional further research may also consider using HRV to determine the dose-response curve for sleep and improved stability of HRV measures across a challenging training day. Further, mixed-methods approaches may be able to inductively approach the qualitative elements that may distinguish cardioregulatory responses to work in tactical professions from other strenuous overnight work environments. Finally, the incorporation of a human performance optimisation expert to manage and apply these data may also benefit organisations by allowing for more regular monitoring, additional relevant data analysis, and health or fitness solutions to mitigate adverse health or fitness conditions.

8.6 Afterword

This chapter identified clear differences in HRV profiles during annual firearms qualification and a subsequent firearms training exercise in operational specialist between those who worked an overnight shift previously and those who were off duty with performance decreasing following the overnight shift. While the effects of rotating shift work are of concern for organisations, as indicated not only by this report, but additional research (noted in review: Chapter 2), load carriage and physical fitness are also important considerations at the organisational level. This is because, like rotating shifts, the carriage of heavy loads and the necessary base of fitness to support load carriage are intractable elements of service within specialist police units. As such, these serve as the focus of the next chapter, from an operational, rather than selection-based context.

Chapter 9 – Operations: Applications of Heart Rate Variability Monitoring in Tactical Police Anaerobic-based Tasks and Training

9.1 Preface

The previous chapter (Chapter 8), reporting the findings of Study 6, explored the influence of overnight shift work, an important occupational requirement, on heart rate variability (HRV) during a stressful task (firearms qualification and training) within an operational specialist police unit. Of additional interest in the stability of the noted changes in HRV from pre- to post-qualification is the role of anaerobic fitness and capacity. As determined in Study 2 (Chapter 4), aerobic fitness was limited in its capacity to affect HRV during stressful specialist police tasks. While there is likely a role of aerobic fitness in mitigating HRV depression during stressful events, particularly those stressors that are of a more physical than psychosocial source, it may not be the most causal factor. Conversely, not only is anaerobic fitness a vital operation capacity for a specialist police officer to develop [173,191], but it also is regularly evaluated in an operationally contextualised test battery [240]. As such, the relationship between anaerobic fitness and HRV modulation under stress in specialist police personnel requires investigation. Therefore, the study reported in this chapter investigated how performance on a generally anaerobic occupational obstacle course related to HRV changes during the same annual firearms requalification and subsequent firearms training exercise as per the study reported in Chapter 8.

This study has been presented at the National Strength and Conditioning Association (NSCA) National Conference (2021). The official published abstract for the NSCA conference is provided below:

9.2 Abstract

Purpose: Police work is known to be a physically, mentally, and emotionally demanding profession. Special Emergency Response Teams (SERTs) are tasked with responding to the most high-risk scenarios. Further, many SERT operators serve on teams as a collateral duty beyond their regularly scheduled police work. As such, these personnel often attain very high levels of physical fitness but may be vulnerable to accumulating excessive chronic stress. Heart rate variability (HRV), the analysis of the difference in time between individual beats of the heart, shows promise as a field measurement of holistic load because of its sensitivity to the dynamic regulatory patterns that both intrinsically and extrinsically regulate cardiac activity. However, little HRV research has been conducted to date among SERT personnel. Methods: The aim of this study was to identify potential relationships between a measure of physical fitness (occupational obstacle course completion time) and time-domain HRV (pRR50) in a pilot cohort of SERT personnel. This research was conducted in compliance with the Declarations of Helsinki and with IRB approval. Prospective 3-lead ECGs were captured from 8 male SERT operators prior to and following a firearms training event. HRV was assessed as the within-operator change from baseline to post-training of the percentage R-R intervals varying by 50 ms (ΔpRR50). Results: Obstacle course time correlated significantly with ΔpRR50 $r(8) = 0.712$, $p = 0.048$. More fit operators (as measured by obstacle course time) were more resilient to HRV changes during training. Conclusions: These results indicate the HRV monitoring is feasible in the field environment and can provide human performance optimisation personnel with an additional meaningful tool for the objective measurement of stress in a tactical police environment. Organisations should promote fitness in personnel and may especially consider anaerobic capacity and recovery as a means of mitigating stress vulnerability based on the results of this study. Practical Applications: These results establish precedent for further investigations into HRV monitoring utilisation in tactical police units. The findings of this study also indicate that more fit operators were more physiologically resilient to demands imposed by the training exercise. Specifically, anaerobic capacity and recovery may be key performance indicators within this population and warrant further investigation. TSAC practitioners may consider utilising HRV measurement to support human performance optimisation efforts within their organisations.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

9.3 Introduction

Police officers are frequently and regularly exposed to high levels of physical, cognitive, psychological, and social stress on the job and at home [35,241]. In addition to the external demands imposed by responding to emergencies, personnel are also subject to internal organisational demands, such as irregular work hours, prolonged shifts, and the wearing and carrying of occupational loads [39,90]. Employment as a specialist police officer can further intensify these demands. Initial selection courses to join specialist police units are physically and technically challenging demanding highly refined marksmanship, excellent physical fitness and an exceptional ability to perform under extreme pressure [14,39,44,191]. Once trained, these personnel are called upon to respond to the most high-risk scenarios within the region served by the organisation [35]. When responding to these high-risk emergencies, specialist police must often perform tasks beyond the scope of traditional law enforcement units [242], including the management and de-escalation of potentially high-intensity conflicts and exposure to atypical physical threats [172] while wearing loads that exceed 20 kg [32,35,175]. Specifically, these duties may range from counterterrorism operations, hostage rescue, environmentally extreme search and rescue, crowd control, high risk prisoner escort, personnel security details, and court protection [243-245]. During such mission taskings, specialist police are expected to sustain optimal performance without compromise and within potentially hostile environments [172,242,246]. In addition, in some jurisdictions these officers often volunteer to join specialist teams as a collateral duty in addition to their regular police work, further extending their time on duty, loads carried, time spent in training, and administrative work [199]. The compounding effect of these stressors may manifest as allostatic load, potentially contributing in part to the elevated risk of heart disease that has been identified among first responders [28,133].

Assessing the patterns of regulatory responses that may signal the onset of allostatic load may therefore be of value to specialist police organisations. Given the complexity and diversity of stressors encountered by these teams, holistic and integrative objective measures may benefit individual operators and unit leadership. The application of heart rate variability (HRV) analysis is one increasingly popular monitoring tool applied for this purpose with widespread usage in athletes, and the military as it can be utilised to obtain detailed assessments of an individual's psychological and physiological responses to physical training [52,78,183]. This is because HRV results from a dynamic relationship between both intrinsic cardioregulatory factors and extrinsic factors, including, but not limited to the sympathetic (SNS) and parasympathetic (PNS) nervous system branches of the autonomic nervous system (ANS) [68,69]. Relationships between HRV indices and several outcomes of interest to tactical organisations, including cardiorespiratory fitness, psychological stress, and potentially overtraining syndrome have been proposed [78,89,157].

Of the studies identified in Chapter 2 that considered the relationship between HRV and aerobic fitness, none focused specifically on the law enforcement population [159,162,163]. While one study linked self-reported physical activity levels with HRV in a cohort of US police officers [160], there remains no established link between fitness and HRV in the law enforcement community. As previous investigations in this thesis (Study 2: Chapter 4) established only a limited relationship between aerobic fitness and HRV during occupational task completion, the relationship between anaerobic fitness and HRV merits further exploration as an alternative factor influencing HRV in the population of interest. This is especially relevant as many police tasks rely heavily on anaerobic capacity [199,200]. For example, foot pursuits may often conclude in less than a minute [247]. Further, tasks such as grappling, dragging an incapacitated colleague or victim, or rapidly exiting a vehicle all rely on anaerobic metabolic pathways for execution [180,248].

The use of lethal force is also an essential police task, particularly pertinent for specialist teams, as incidents involving firearms are handled by these teams when possible. Given the great recent interest in police usage of lethal force [176,249], it is critical that these personnel are provided every means of enhancing their decision making and manual proficiency to ensure the most optimal outcomes for the entire community. Physical fitness and autonomic regulation are potential domains that may be crucially linked to firearms proficiency and thereby a means of enhancing both officer and community safety as related to firearms utilisation under stress [123,250].

HRV monitoring utilisation in operational specialist police training, to date, has been limited despite the need for specialist police operators to meet high performance occupational demands to protect and serve their communities [55]. The nature of stress in tactical environments may act to impart both physiological and psychosocial demand [55]. Many physiological demands encountered may be anaerobic in their metabolic nature. As such, anaerobic fitness may be more closely linked with HRV modulation under stress in specialist police personnel than aerobic fitness. Therefore, the purpose of this study was to explore relationships existed between HRV measurements following training stress exposure and time to completion on a predominately anaerobically demanding obstacle-course. It was hypothesised that officers with greater performance on the occupational obstacle course would be more resistant to HRV depression imposed by the firearms training stress event.

9.4 Methods

9.4.1 Experimental Approach

The present study utilised a combination of retrospective and prospective data; obstacle course times were provided by the unit commander from a prior training event (approximately seven days previously), and prospective HRV measurements were obtained on one day of scheduled firearms handling training. To analyse HRV, 3-lead ECGs were collected at baseline (before training) and after a firearms qualification and training exercise. HRV was assessed as the within-operator change from baseline to post-training across time and nonlinear domains. Frequency domain assessments were not considered as recordings were limited to five-minute instances on a single training day. The changes in HRV were compared within-operator against obstacle course completion times to determine what relationships, if any, existed between the physical/occupational fitness assessment (obstacle course completion time) and changes in HRV during firearms training.

9.4.2 Participants

A total of fifteen collateral duties US specialist police operators volunteered to participate, with an average of 5.2±4.3 years of experience. No further anthropometric data were available as per a privacy agreement with the team. However, all operators disclosed that they were taking no medications for cardiovascular, renal, or respiratory conditions as a requirement of participation in this study. These limitations have been noted in previous research conducted with specialist police personnel [189]. All team members provided their informed written consent, and the unit commander provided permission for publication of this work. The research protocol was approved by the Messiah University Institutional review board (2019-022) and the Bond University Research Ethics committee (2019-022 amnd 2).

9.4.3 Procedures

9.4.3.1 Obstacle course

The obstacle course consisted of an 8.83m sprint, after which the operator cleared a series of 3 benches (1m) spaced 6.07m apart, followed by negotiation of nine tires, a 29.87m sprint to a 1.82m wall obstacle, and a 40.84m sprint into the training facility building. Once inside the building, the operator jumped over a 1.23m wall, exited through a window and proceeded down a flight of stairs. Upon reaching the bottom of the stairs, the operator obtained a battering ram (~15kg), carried it to the second story of the training building, dropped the ram and pulled a standard 20kg weight plate to the second story via a rope. The operator then ran to the far side of the roof of the training building, dragged an 81kg dummy using a Sked litter across the width of the building, returned to the second story, recovered the battering ram, returned to ground level, used the battering ram to exit a closed door and sprinted to another 1.23m wall. Once over the wall, the operator obtained two 20kg dumbbells, which were carried around two sets of cones spaced 9.75m apart, followed by a sprint to the final set of cones. To complete the course, the operator weaved around a set of three trees. The maximum time permitted was 3 minutes (180 seconds). Operator time was recorded on a stopwatch and times were rounded to the nearest whole second. A diagram is provided in Figure 16.

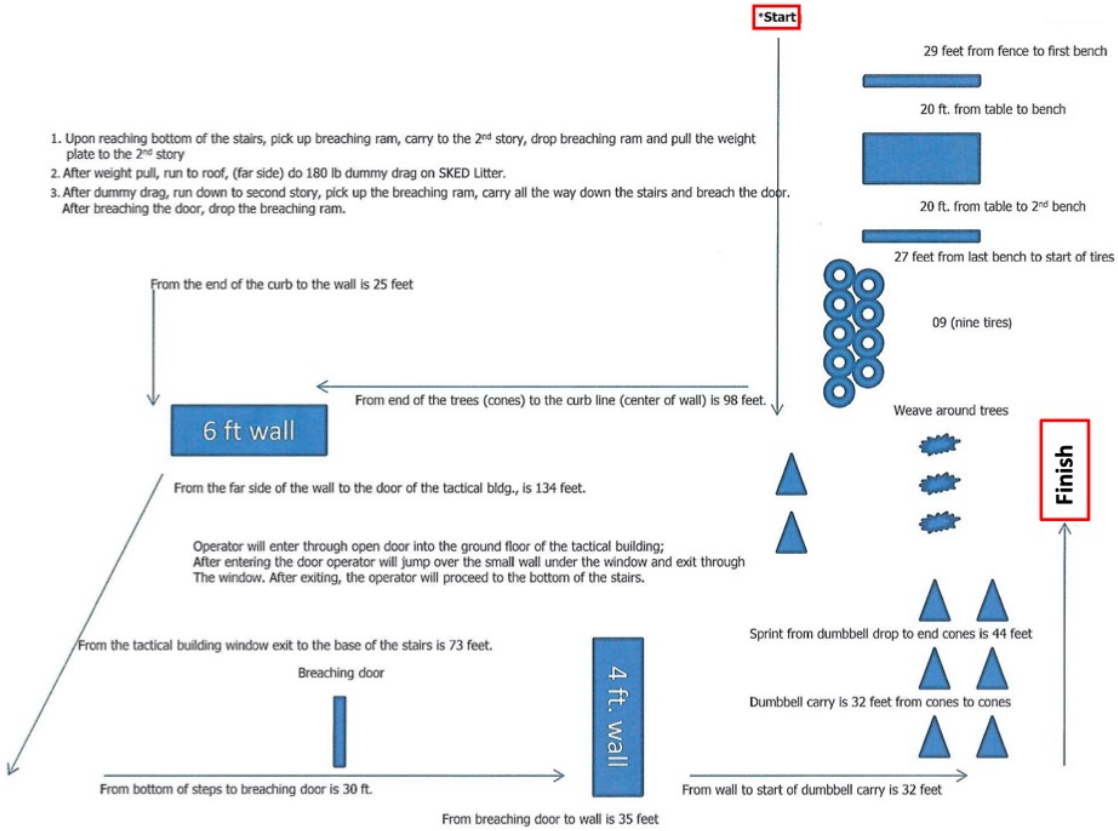


Figure 16. Occupational obstacle course assessment schematic

9.4.3.2 Firearms Qualification and Training

The firearms qualification event began with an evaluation of static and dynamic standing handgun (.40 S&W Glock 22, Glock Ges.m.b.H., Austria) and rifle (5.56mm NATO M4, Various manufacturers, USA) engagement at 3, 5, 7, 10, 15, and 25m. Only the rifle was utilised at 15 and 25m. Operators were required to wear all standard issue gear (boots, uniform, plate carrier vest, helmet) and accurately place shots on all targets at all distances. Operators were dismissed from the unit if at any time a shot was missed. Those who successfully landed all shots on all targets at all distances proceeded to a training event. The training event consisted of various handgun (.40 S&W Glock 22, Glock Ges.m.b.H., Austria) engagements against 2” diameter targets directed by the range instructor. Operators completed 10m shuttle runs between training scenarios. Again, all standard issue gear (boots, uniform, plate carrier vest, helmet) was required to be worn for all scenarios.

9.4.3.3 Heart Rate Variability measurement

Three-lead seated ECGs were recorded for five minutes using ADI Instruments an Powerlab T7 and Lab Chart v7 (ADInstruments, Sydney, Australia). All operators were measured at baseline (at initial report time for training), immediately after qualification, and immediately after conclusion of the training event described above. HRV data were processed with a LabChart v8 student license (ADInstruments, Sydney, Australia). Visual ECG examination was performed in combination with visual analysis of R-R plots to exclude outlier and ectopic beats. Changes in frequency domain HRV, the percentage of R-R intervals varying by at least 50ms (ΔpRR50), and nonlinear HRV were considered.

9.4.4 Statistical Analyses

Visual box plot analysis was conducted to assess for substantial outliers and Shapiro-Wilk testing was used to determine normality of the data. Differences between baseline and post qualification, and then baseline and post-training measurements were assessed for significance using Wilcoxon signed-ranks tests. Linear regression models were developed to examine relationships between HRV changes from baseline to post-qualification and post-training with obstacle course time as the covariate. All analyses were conducted in JASP 0.17.1 (JASP Team, Amsterdam, The Netherlands).

9.5 Results

The mean obstacle course time was 143±12 seconds. All operators successfully passed qualification and proceeded to training. However, some operators were required for duties outside of qualification and training, and so not all operators for which baseline values were obtained were able to provide post-qualification and post-training values. In total, of the 15 operators recruited (n = 15), 10 were able to provide post-qualification measures (n = 10) and eight were able to provide post-training measures (n = 8). No significant differences were identified between baseline and post-qualification values. The Wilcoxon signed-rank tests identified significant differences between baseline and post-training values for HR, pRR50, LF, HF, and SD2. Descriptions of the baseline to post-qualification change and the baseline to post-training change data can be found in Table 15.

Table 15. Heart Rate and Heart Rate Variability Description by Phase

	HR (bpm)	RMSSD (ms)	pRR50 (%)	VLF (ms^2)	LF (ms^2)	HF (ms^2)	SD1 (ms)	SD2 (ms)
Baseline	115±124	64±138.97	8.94± 14.78	1131.08± 1632.10	1057.48± 763.58	526.39± 1143.90	20.05± 15.41	69.30± 28.62
Post-Qualification	87±16	52.68± 41.85	10.95± 17.55	1256.83±2310.04	1188.89± 959.55	1143.05±1650.94	37.30± 29.63	85.49± 41.73
Post-Training	105±20**	20.72± 13.66	2.34± 5.32*	1313.63±2862.58	432.13± 597.62*	73.72± 93.30*	14.66± 9.67	52.76± 33.55*

Heart rate (HR); Root-mean square of successive differences (RMSSD); Very-low frequency (VLF); Low frequency (LF); High frequency (HF); Poincare plot X Axis standard deviation (SD1); Poincare plot Y Axis standard deviation (SD2)

***indicates p<0.01 for difference from baseline. Wilcoxon signed rank test.*

**Indicates p<0.05 for difference from baseline. Wilcoxon signed rank test.*

9.5.1 HRV and Obstacle Course Time

Linear regression models were developed and identified obstacle course time as a significant predictor of VLF HRV deviation from baseline following firearms qualification; $r^2 = 0.446$, $F(1,8) = 6.446$, $p = 0.035$. The linear equation is described below in Equation 1:

$$\Delta \boldsymbol{HRV}\ (\boldsymbol{VLF}) = \mathbf{6226.815} + (\mathbf{-44.383} \bullet \boldsymbol{obstacle\ course\ time})$$

Equation 1. Linear Regression describing VLF HRV and Occupational Obstacle Course Time

The marginal effects plot of the above linear model can be found in Figure 17. Other measures of HRV were not significantly predicted by obstacle course completion time. HR was also not predicted by obstacle course time (p = 0.671).

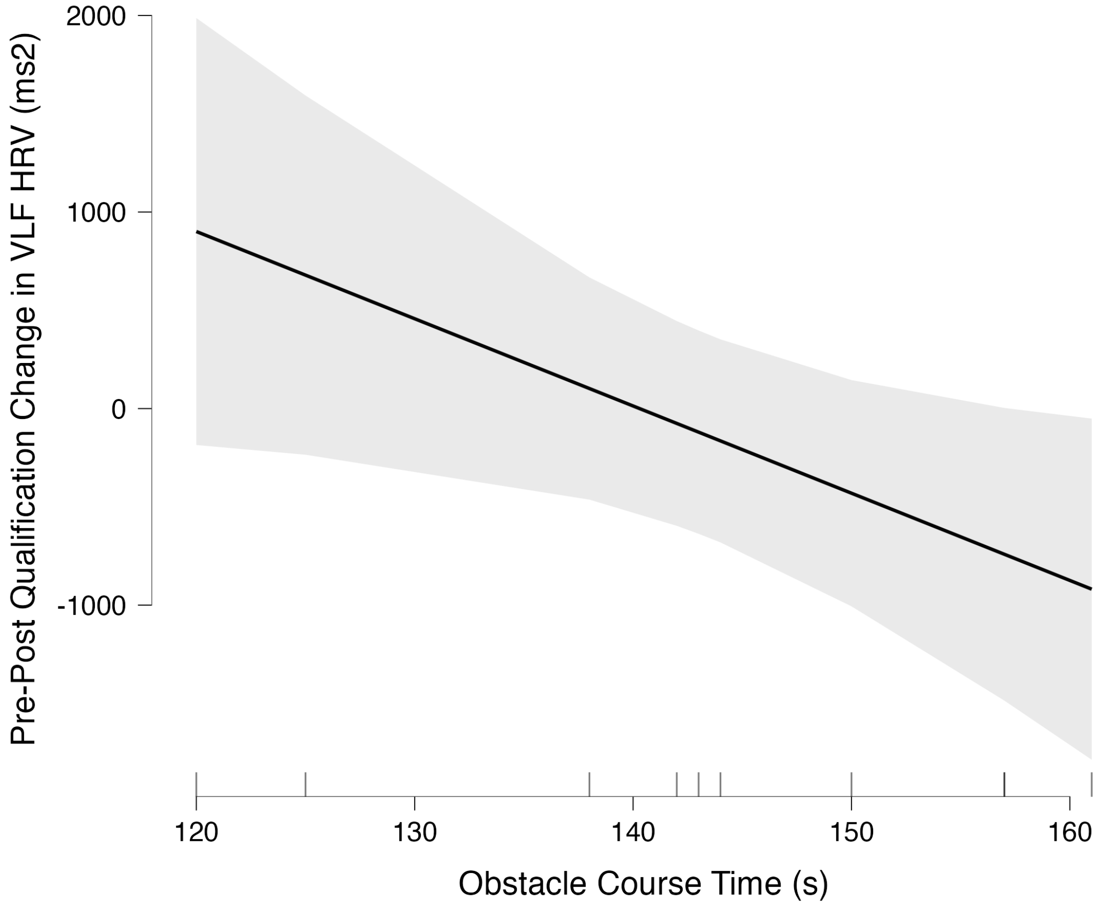


Figure 17. Marginal Effects Plot of Obstacle course time in seconds on very-low frequency HRV change from pre- to post-qualification.

Regarding the post-training change data, two models were developed that identified obstacle course time as a significant predictor of HRV deviation from baseline following firearms qualification. The specific domains of HRV that were predicted in modelling were pRR50; $r^2 = 0.507$, $F(1,6) = 6.165$, $p = 0.048$ and HF; $r^2 = 0.617$, $F(1,6) = 9.652$, $p = 0.021$. The VLF model did not remain significant ($p = 0.119$). HR was again not significantly predicted by obstacle course time ($p = 0.968$). The linear equations for the statistically significant models are described below in Equation 2 and

Equation 3. The marginal effects plots for these models are shown in

Figure 18 and Figure 19.

$$\Delta HRV\ (pRR50) = -124.059 + (0.783 \bullet obstacle\ course\ time)$$

Equation 2. Linear Regression describing pRR50 HRV and Obstacle Course Time

$$\Delta HRV\ (HF) = -13686.257 + (89.665 \bullet obstacle\ course\ time)$$

Equation 3. Linear Regression describing HF HRV and Obstacle Course Time

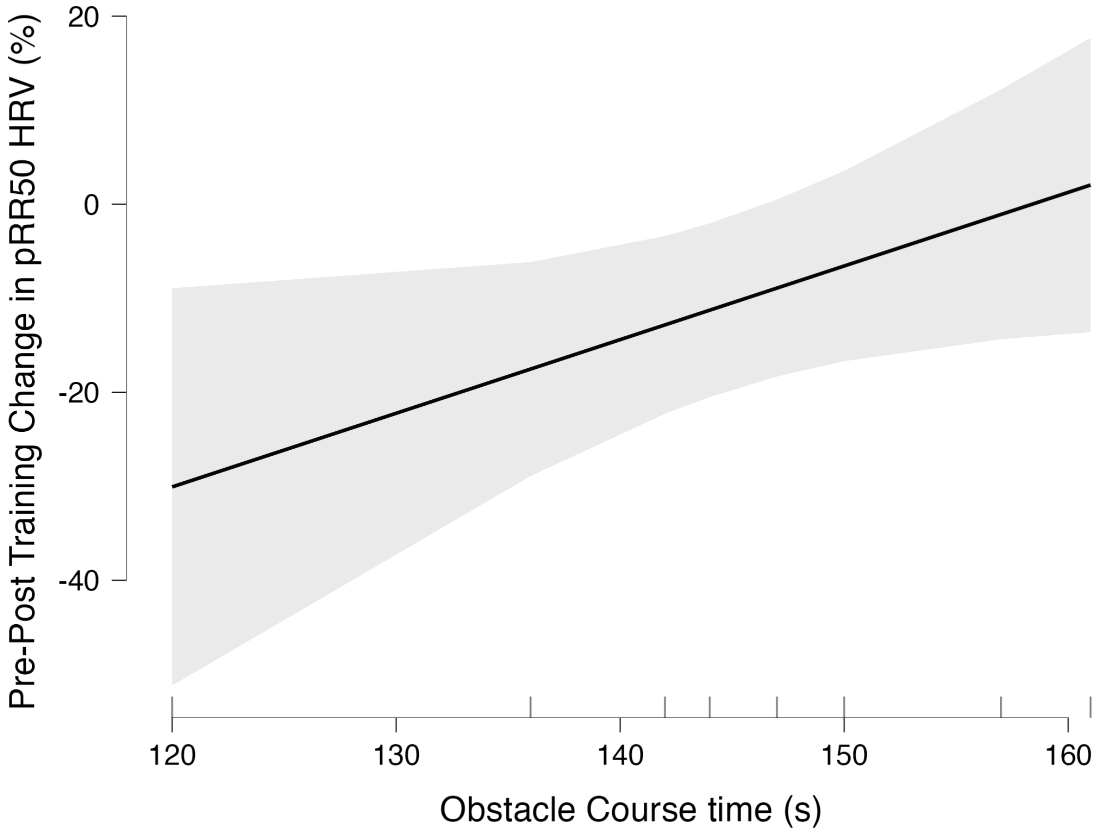


Figure 18. Marginal Effects Plot of Obstacle course time in seconds on pRR50 HRV change from pre- to post-training.

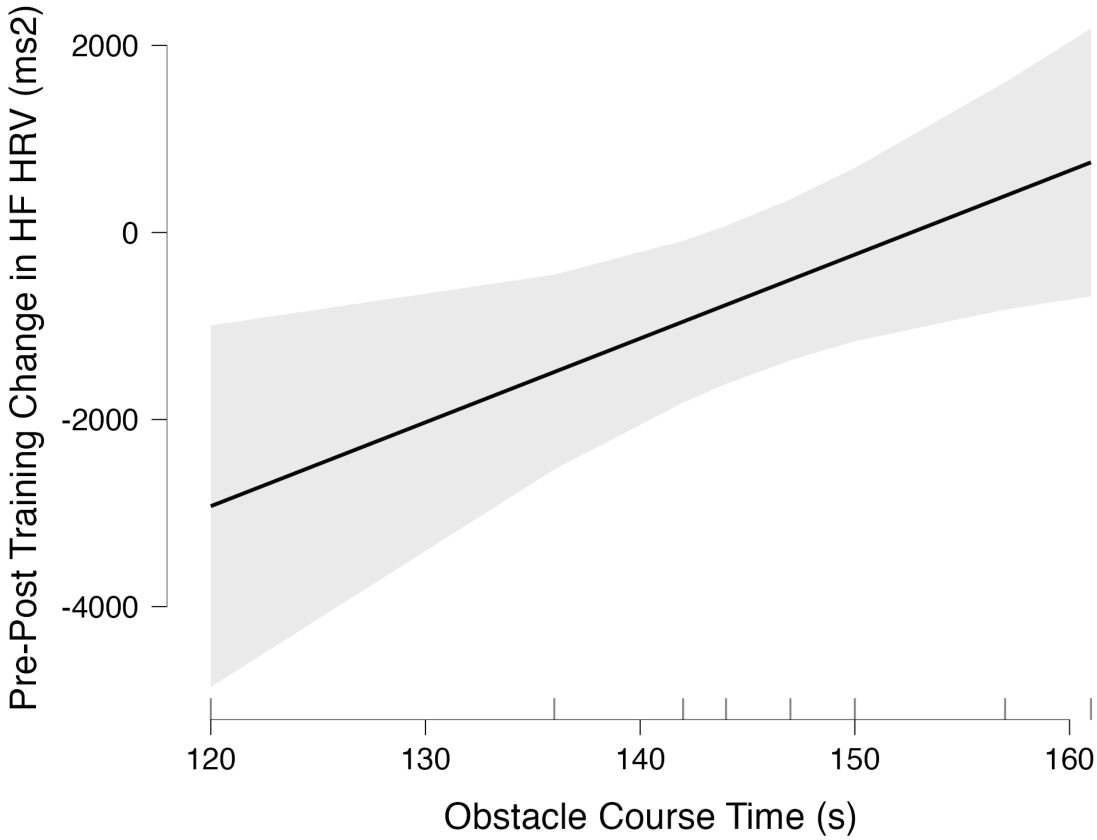


Figure 19. Marginal Effects Plot of Obstacle course time in seconds on high-frequency HRV change from pre- to post-training.

9.6 Discussion

The aim of this study was to explore relationships between HRV measurements at baseline, following firearms qualification, and following a firearms training exercise in consideration of time to completion on an occupationally relevant, anaerobically natured, obstacle-course. The obstacle course was primarily an anaerobic assessment of fitness and occupational suitability. Likewise, the training following qualification was also highly anaerobic in nature. While there were no statistically significant differences between baseline and post-qualification values, there were significant differences from baseline to post-training. Given the intensity of the physical activity undertaken during the training relative to the qualification, this finding is not surprising. More interestingly, the linear regression model did successfully identify obstacle course time as a significant predictor of VLF HRV deviation from baseline following firearms qualification. The VLF measure of HRV is defined as those oscillations of the HRV spectra that range from 0.0033-0.04 Hz [51]. It is of unique interest because it is intrinsically generated by the heart, but also modulated by sympathetic activity and has been associated with cardiac death, PTSD, and inflammation [69,251]. For these reasons, the VLF domain has been a target of interest in previous studies [55,75]. VLF is also known to be associated with cognitive workloads and aerobic fitness [52,113,234]. While it is a long-term measure, the 5-min recording window is sufficiently robust to capture fluctuations in VLF [101]. Nonetheless, further longitudinal study may consider further explorations in this population between VLF HRV, fitness, and mentally challenging tasks. The strength of this linear model even with the limited sample size may have been due to the potential for elevated fitness, specifically anaerobic fitness, to attenuate the integrated stress response intensity; more anaerobically fit operators, as measured by the occupational obstacle course time, deviated less from their own baseline HRV values during activities demanding cognitive and fine motor aptitude, or had greater VLF at the conclusion of the qualification event. For those operators that improved in VLF HRV, this may have been due to the resolution of uncertainty associated with notification of the successful outcome of qualification, although this model did not persist through to the post-training measurement time [132,219].

Nonetheless, the potential implication is that performance on the obstacle course, and thereby anaerobic fitness, influenced HRV stability during a primarily cognitive/fine motor event with high emotional stakes, but without a strong physical component (HR was only 87bpm on average following qualification). Further models were developed from the post-training data. These models utilised the pRR50 index, a simple time-domain measurement of HR stability, and HF, a frequency domain measure associated with respiratory activity and stress levels [99,252]. Specifically, pRR50 is the percentage of all measured R-R intervals that varied by at least 50ms from their preceding neighbour. HF is another frequency domain measure that includes spectra from 0.15-0.4 Hz. Both may trend closely as they typically increase with greater aerobic capacity in the general population and respond to elevated PNS activity [69]. pRR50 specifically has some applicability in the cardiac clinical setting [113]. In the present study, the pRR50 interval appears to be useful as it is robust to noise or shorter sampling timeframes, and indeed was a valuable metric in previous research in tactical police settings [90,253]. Frequency-domain measures may be more volatile and should be interpreted with more caution [72,214]. Regardless, it is plausible that the operators in this study with greater pRR50/HF values post-training experienced less PNS withdrawal from the training, and so either metric, depending on signal quality, could be used to calibrate intensity in future training events.

One further advantage of HRV analysis as opposed to HR analysis alone is the consideration for sources of stress beyond the purely physical and consideration of cardiac influences such as respiratory activity that may often be modulated under stress [36]. Previous research has described changes in HRV when undergoing marksmanship tasks that lack a physically demanding element [157]. This finding confirms some of the conclusions drawn in Study 1 (Chapter 2), as well as Study 2 (Chapter 4) in that HR alone is likely not sufficiently sensitive to provide detail regarding how aerobic fitness may be associated with performance during essential tactical tasks that combine physical stressors with cognitive load in adverse conditions. Indeed, some of research makes note of strong relationships between heart rate and marksmanship performance [250,254], and others do not [255]; HRV analysis may be key in reconciling these differences in the literature, though certainly further investigation is warranted. Regardless, the findings from this study provide support for the paradigm of general physical preparedness providing advantages in occupational scenarios; for example, accurately discharging a weapon under duress [123]. These findings also support the premise that physical fitness enhances resilience (as indicated by resistance to excessive HRV loss) in tactical personnel. Specifically, these findings suggest that short-duration, high intensity training, similar to the demands of the obstacle course, and relevant to many police tasks, may be the most effective for mitigating undesirable changes in physiology that are indicated by HRV. It may be possible that enhancing anaerobic capacity or training the ability to recovery quickly from anaerobic exertion may be a beneficial performance augmentation strategy to improve autonomic regulation under stress, and thereby firearms proficiency. Such activities may include events similar to those reported here, wherein an intermittent anaerobic activity is integrated with an occupational task. Other potential examples may include simulated casualty evacuations, utilisation of a forced entry tool, or other physical or occupational exercises that demand strength and power. Finally, regular application of a variety of anaerobic challenges may also promote adaptation and drive response and recovery that could be protective against type II allostatic load processes, a known concern in law enforcement personnel [56].

The present study design also provides an example for organisations seeking to consider HRV as a tool for modulating or calibrating training intensity. By focusing on within-operator changes in HRV across a training session, rather than on absolute HRV or traditional HR values alone, the volatility of HRV as a biosignal can be mitigated [214], providing more valuable data for individual operators and unit leadership that HR cannot demonstrate. Further, at the time of data collection, no personnel were ill, injured, or on limited duties, and so the present data could be utilised to establish a reference point against which additional training exercises could be measured. However, for this approach to be effective, additional data points would be required over time to determine if the training stimulus was optimal. Research has suggested 28-day rolling averages for the most robust analysis [75].

9.6.1 Limitations

Further research is necessary in this population; the results reported here are among the first known of their kind, and as such, are not without limitations. Namely, the model incorporating VLF HRV, and obstacle course performance was not statistically significant across all measurements (only post-qualification and not post-training). Further, many variables that may influence HRV could not be accounted for in this study, such as sleep status, dietary intake, and hydration, as it was intended to be a purely observational analysis. Indeed, highly controlled data collection would be of limited use to the organisation whose personnel must operate in uncontrolled conditions, and if HRV did not demonstrate utility outside of the lab, it would not viably serve the organisation. Certainly though, as the nonlinear metrics failed to effectively integrate into the linear model. Nonlinear metrics have been reported as particularly robust analyses for HRV, and as such, these results, while still promising, should be interpreted with caution.

9.7 Conclusions

Physical fitness, specifically anaerobic fitness, has been established as a key indicator of occupational performance in the tactical setting [177] and is known to be protective against chronic disease [149,256]. These results indicate that more anaerobically fit operators were more resilient to the psychophysiological demands imposed by the training exercise. As such, anaerobic capacity and recovery may play a key role performance within this population and merits further investigation. Practically, these data provide a template for integrating HRV analysis in specialist police training settings. The results tentatively indicate the ability to stratify operators and may be a viable basis against which further repeated measures could be compared to calibrate training intensity over time. Physical fitness and psychophysiological stress management through sports psychology and tactical strength and conditioning methodologies may further benefit these teams.

9.8 Afterword

This study reported in this chapter demonstrated a tentative relationship between performance on a generally anaerobic occupational obstacle course and HRV during annual firearms qualification and training in an operational specialist police unit. In addition, Study 6 (Chapter 8), also on qualified officers has found that overnight shift work imparts negative effects on HRV, potentially impairing the resolution of uncertainty known to be a driver of allostatic load [56,132].

While the effects of rigorous selection training have been thoroughly described within this thesis (Studies 2-5, Chapters 4 - 7) and in previous related literature [77,95,97,110,]and now in operational specialist police officers (Studies 6 and 7, Chapters 8 and 9), no known studies have investigated the nexus between these two, notably for the qualified officers who have to conduct these specialist police selection courses. While this duty serves as another key role operational specialist police personnel must be prepared to carry out, and indeed personnel may be pulled from operational duty to conduct these selection courses with minimal notice due to changes in staffing or operational tempo, the impacts of qualified officers serving in this capacity has not been reported. Thus, the final study in this program of research, is a case study of an operational specialist police officer serving as a primary Directing Staff (DS) officer for a selection course into the unit.

Chapter 10 – Operations: A Case Study Investigating Heart Rate Variability in a Specialist Police Selection Course Directing Staff Officer

10.1 Preface

Previous chapters have considered the effects of training in various capacities on heart rate variability (HRV) and how key factors, such as aerobic, anaerobic, or occupation-specific fitness, may attenuate undesirable fluctuations of HRV. This may be particularly true during high stress conditions. High stress conditions are not exclusive to incident responses for operational personnel; training and selection activities must be supervised by operational officers, serving in a directing staff (DS) role. These DS are typically redirected from operational status for selection and training support purposes. While much research attention has been provided in this thesis and the extant literature on candidates undergoing selection, those operational personnel serving as DS, and the impacts of the role, have not been the subject of research on psychophysiological stress responses, such as HRV. Therefore, the effect of serving as DS member on a specialist police selection and training course, as measured through HRV, is focus of this chapter.

This study has been accepted for presentation at the 6th International Congress on Soldiers' Physical Performance 2023 and has been solicited for publication in the *Annals of Non-invasive Cardiology*.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

The accepted abstract is provided below.

10.2 Abstract

Purpose: Specialist police units within Police Tactical Groups (PTG) are tasked with a wide scope of duties, many of which are potentially hazardous or highly fatiguing. One such duty is service as a selection course assessor. Given the intensity of selection courses, which includes high amounts of physical activity with little or no sleep, holistic health and performance monitoring of selection course staff may benefit the member and their unit. Heart Rate Variability (HRV) is one holistic measure obtainable through wearable technology monitoring. However, while research has investigated candidates undergoing challenging selection courses, no known measurements of course staff have been reported to date. The purpose of this case study was to profile HRV of a PTG selection course staff member, specifically nonlinear SD1, SD2, and SD2/SD1 ratio during a PTG selection course.

Methods: The selection course was a 32-hour continuous battery of physical, occupational, and teamwork/leadership assessment tasks. The PTG staff member that volunteered for this study wore a supplied Equivital™ EQ02+ LifeMonitor (ADInstruments, Sydney, Australia) device, collecting a 2-lead ECG over 25 hours. HRV data were reported as summarised consecutive short-term measurements to illustrate changes with maximal resolution while maintaining measurement fidelity. HRV fluctuations were aligned with key events in the selection process and with an off-duty period during which sleep was permitted.

Results: The assessor's HRV values demonstrated depressed dynamic adaptive response during on-duty hours. Specifically, the assessor was responsible for coordinating safety and measuring candidate performance during a land navigation exercise and as such displayed minimal HRV (SD1 = 16.68ms, SD2 = 124.7ms). Some recovery was noted leading up to and during the rest period, in which the environment was less demanding (SD1 = 30.36ms, SD2 = 130.2ms). However, it should be noted that recovery was likely incomplete as values returned to previously measured levels once the assessor resumed working (SD1 = 28.5ms SD2 = 157.7ms).

Conclusions: This research agrees with previous investigations into extended on-duty hours worked by specialist police in which insufficient recovery may be marked by limited increases in HRV despite rest. While tentative as a case study, this research demonstrates that PTG staff are also subject to psychophysiological demands during PTG selection.

Military impact: Staff involved in the conduct of, and assessment during, specialist selection courses are also subjected to psychophysiological demands. Unit leadership may consider the impact on running selection courses on staff when developing a training and reinforcement cycle.

10.2.1 Keywords: SWAT; biomarkers; data visualisation; shift work; stress

10.2.2 Practitioner Points

1. Tactical professionals, such as specialist police, are subject to extreme physical and mental demands.
2. Physiological monitoring, specifically heart rate variability, may provide important information regarding the health and performance of specialist police personnel.
3. This data can be efficiently visualised to inform both individuals and unit leadership.

10.3 Introduction

Elite tactical units, such as military and police special operations and special forces are faced with executing a wide variety of demanding occupational tasks, including search and rescue, barricaded person/hostage scenario mediation, explosive ordnance disposal, illicit substance seizure, high risk warrant service, and other high-risk or particularly dangerous operations [173,176,189]. These tasks must often be successfully completed in challenging environments and in the face of potentially life-threatening human and environmental dangers [35,181]. As such, the selection and training of personnel for these occupations has been a perpetual challenge for unit supervisors since at least the Second World War, and has drawn the attention of substantial research efforts [43,48,49], particularly following the advent of the Global War on Terror in 2001, and its downstream effects on military, paramilitary, policing, and national security operations [3,16,152,198]. One reason for the interest in specialist training and selection is that candidates must be evaluated holistically – in consideration of physical, mental, and social attributes, such as teamwork and leadership, under conditions that are as realistic as possible, meaning that maximal stress must be applied to candidates within the bounds of safety [13,14,35]. However, while much research attention has been directed towards candidates undergoing selection courses, literature considering the effects of these courses on the specialist police officers serving in a directing staff (DS) role is scarce. DS will often report directly from operational duties to selection and training. While they may not necessarily be participating in the same levels of physical exertion as the candidates under their supervision, they may at times endure similar levels of sleep and food deprivation, must maintain administrative and safety oversight of each training element, and prepare training events, then return to their operational capacity. Potentially, this may be without opportunity for recovery. Effective monitoring and evaluation, not only for determining success or failure, but also health and safety, is therefore an important objective. As such, the application of wearable technology may be of interest not only for candidate selection, but also for the support of DS managing selection and training activities.

Heart rate variability (HRV), the natural oscillation and fluctuations of heart beats over time in response to external and internal stimuli can capture individual responses to a wide variety of stressors, including those of a physical, cognitive, or emotional nature [55,69,75]. With developments in wearable technology, high-fidelity ECG recordings that can provide a signal of sufficient quality for HRV analysis over long windows of time, up to 24 hours and beyond [193], can be effectively implemented in tactical environments [183]. Therefore, the purpose of this study was to monitor and analyse the HRV of one Australian Police Tactical Group (PTG) officer serving as DS during a PTG selection course. The intent of the research will be to profile the collected data in order to provide an initial exploration upon which further research in this area may be based.

10.4 Methods

This investigation was conducted at an Australian State PTG facility in Autumn of 2022. During the selection process, temperature ranged from 24.2 – 34.4°C and relative humidity ranged from 60 – 75%. Six selected individuals participated in the two-day selection course. This course consisted of physical training activities, but also essential specialist police task training and assessment, such as cross-country navigation, firearms manipulation, threat de-escalation, load carriage, and casualty evacuation managed by a team of 16 DS and was conducted continuously through the day and night, approximating 32 hours in total. The focus of this report is on the lead

DS officer for the first 24-hours of selection. The ECG presented began at 0556, approximately the time of selection initiation, and ended at 0618 the next day, at which point DS shift changes occurred.

Electrocardiogram (ECG) data were obtained from a wearable 2-lead unit, the Equivital™ EQ02+LifeMonitor (ADInstruments, Sydney, Australia) harness sampling at 256Hz. The DS was appropriately sized and instructed on how don and doff the harness by a professional experienced with the technology (CT). Further information regarding the DS participant is unavailable due to a privacy agreement with the host organisation and so as maintain research participant anonymity. Data were downloaded from the device via accompanying software (EQ View Pro, Hidalgo, UK) and analysed in LabChart 8 Pro (ADInstruments, Sydney, Australia). The participating DS provided written informed consent, and the PTG unit approved publication of this work. The research protocol was approved by the Bond University Human Research Ethics Committee (2019-022 amnd 2) and all procedures were conducted in accordance with the Declaration of Helsinki of 1964 and its later amendments [215].

HRV measurements were considered 'short-term' in this investigation, utilising 5-minute traces analysed every 5-minutes for the duration of the course [101]. While many HRV metrics are reported in literature, this investigation primarily considered the pRR15 (percentage of adjacent R-R intervals varying by at 15ms) as this metric is easily approachable by the end-user, such as an on-site exercise physiologist or strength and conditioning professional [75]. It has also been identified as a clinically important feature when assessing for risk of cardiovascular disease [111,216], known to affect the law enforcement population to a greater extent than the general population [133], and is also less volatile and more amendable to use in short-term recordings than frequency-domain measures [69].

Nonlinear HRV was also considered. SD1 (short-term) and SD2 (long-term) geometric indices are widely utilised in the literature, specifically within tactical settings, where their robust properties may be useful for the attenuation of noise or signal disruption caused by the intensity of work endemic to these professions [55,75]. Each HRV measurement was plotted as a time-series, yielding 298 consecutive short-term analyses. A total of two time-series plots were generated; one plot contains the pRR15% value, with mean heart rate added for context and comparison. The other visualisation contains both nonlinear HRV measures. Contextual analysis was then applied to each time series, undertaken by identifying deviations from typical oscillating HRV patterns. These anomalous regions were compared against the observed training activities and duty roster to generate a final description of HRV and plausible occupationally relevant influences.

10.5 Results

Throughout the ~24 hours recorded; mean heart rate was 85±15 bpm. Mean pRR15 was 9.69±9.39%. Figure 20 displays the finalised time-series visualisations. Table 16 and Table 17 provide descriptive statistical information regarding the entire data collection window and differences in HRV by duty status.

Table 16. Descriptive values of directing staff heart rate and heart rate variability.

	Mean	**Median**	**SD**	**Max**	**Min**
Heart Rate (bpm)	85.64	87.45	15.11	122	54
pRR15 (%)	9.69	5.96	9.39	39.85	0
SD1 (ms)	29.02	19.85	25.70	141.10	4.33
SD2 (ms)	102.50	94.41	39.44	242.63	40.23

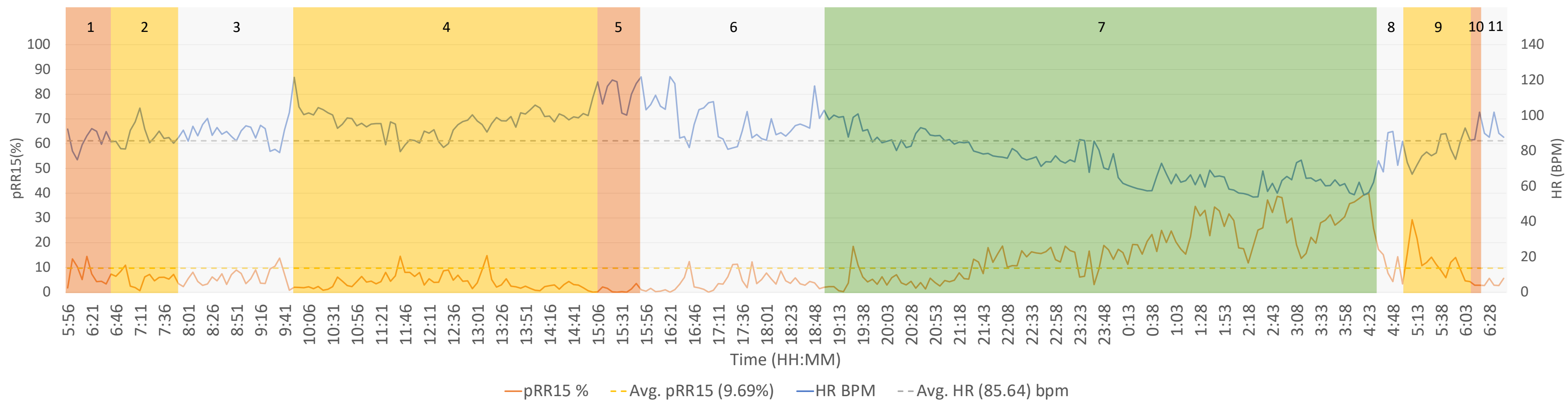
Standard deviation (SD); Percentage of R-R intervals varying by at least 15ms (pRR15); Poincare plot X Axis standard deviation (SD1); Poincare plot Y Axis standard deviation (SD2)

Table 17. Descriptive values of directing staff heart rate and heart rate variability by shift period

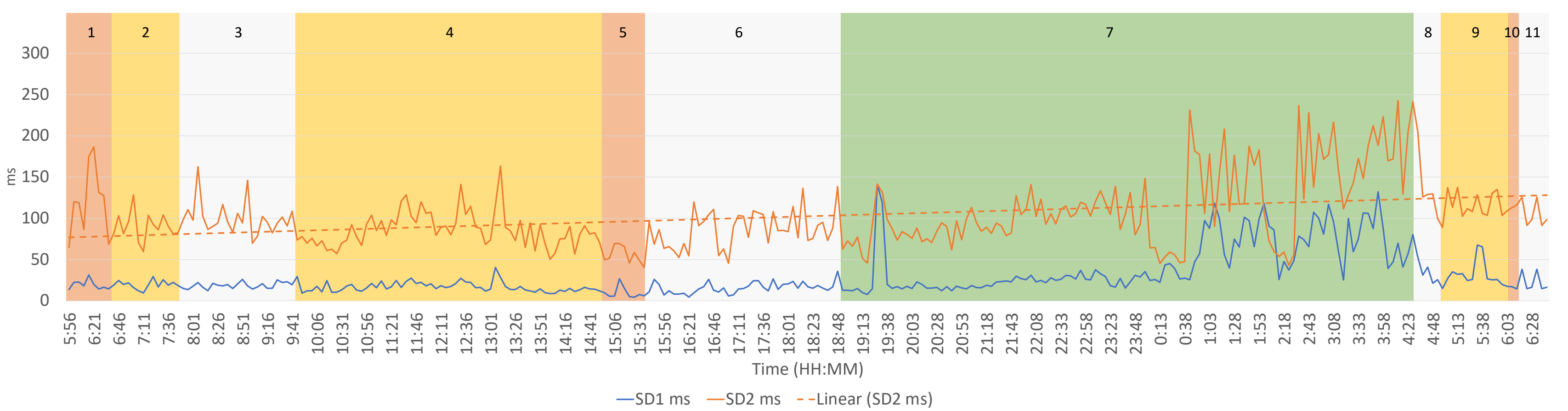
	Shift 1 (13:00)	**Off-Duty (9:35)**	**Shift 2 (1:20)**
Heart Rate (bpm)	95.12±9.78	73.53±13.04	82.55±9.96
pRR15 (%)	4.49±3.37	16.61±10.84	10.22±7.19
SD1 (ms)	16.82±6.23	45.12±33.74	30.84±17.15

SD2 (ms)	89.07±24.96	116.05±49.45	121.66±32.63

Time in parentheses indicates duration of the period in hours. Values are presented as mean ± standard deviation. Percentage of R-R intervals varying by at least 15ms (pRR15); Poincare plot X Axis standard deviation (SD1); Poincare plot Y Axis standard deviation (SD2)



A.



B.

Figure 20. Time Series Plot of DS HRV Values

Figure 20A. DS HR and HRV time series plot. Figure 20B. Nonlinear HRV time-series plot

Legend: 1. Physical fitness assessment briefing and supervision. 2. Briefing presentation and oral instruction. 3. Written examination delivery and supervision. 4. Land navigation supervision. 5. Transit and administrative organisation. 6. Pack march supervision (stationary). 7. Off duty. 8. Written examination delivery and supervision. 9. Candidate rest period supervision. 10. Less-lethal device deployment. 11. Physical training supervision

After a slight peak in pRR15 above the mean, the DS demonstrated depressed values until the first instances of written examinations were distributed to the candidates. The time would have allowed for minimal supervision required in a controlled environment, during which a potential modest recovery may have occurred. Through the load carriage event, lasting approximately seven hours from ~10:00 - ~17:00, HRV values were predominately low. Another trough is noted during the orchestration of the next event, a pack march. Unlike the land navigation event, which took place at a range facility, outside the PTG compound, the load carriage event occurred within the confines of the host organisation's station. Participants followed a predetermined route for multiple laps, allowing the DS to supervise from a stationary location. Once released from duties, an upward trend in HRV is noted; the rapid increase in pRR15 and increased amplitude of oscillation in SD1 from approximately 00:53 to 04:00 suggests recovery and likely includes a sleep cycle. However, all values of HRV again decrease upon returning to duty, potentially indicating insufficient recovery, as HRV values were generally similar to those from before the off-duty period and continued to trend downwards until the ECG trace ends. This is particularly exemplified in the nonlinear values; the amplitude of oscillations dramatically decreased upon returning to duty.

10.6 Discussion

The primary aim of this study was to monitor and analyse the HRV of one Australian Police Tactical Group (PTG) DS member for 24 hours, and document and describe the resultant data. In most instances, decreased values of pRR15% and SD1 indicated less variation in HR. It is therefore thought that during periods of depressed HRV, there is commensurate decreased adaptive external and internal environmental responses, which may signal excessive psychophysiological stress [68]. Regarding the relationship between HR and HRV, states of overstress are often characterised by an abnormally high resting heart rate [139,257], but in this study the average heart rate, even in consideration of periods of activity, was 85.64 – a value within normal range for a resting HR [223]. Conversely, the average pRR15% value was 9.69%. While a clear clinical value for the indication of overstress by pRR15 measurement is not yet established, the similar, but less sensitive index of pRR50% has been noted as closely associated with cardiovascular disease [111,216]. This value is generally accepted as approximately 3% [114]. While the pRR15 value of 9.69

suggests that an even less sensitive measure would yield an even higher percentage value, the lack of oscillatory patterns, that is the stability of the value near the mean may be itself suggestive of a preclinical overstress state. Indeed, such links have been suggested in previous literature [56]; it is the dynamic response of the internal environment to internal and external stimuli that characterises the theoretical basis of HRV analysis and interpretation [68,76], and the evaluation of healthy or unhealthy HRV patterns. The continuous exchange between sympathetic and parasympathetic, amongst other influences, may be especially critical in professions defined by unpredictability, such as law enforcement [36,56]. Sustained sympathetic activity, detectable by HRV in the form of limited fluctuation, likely contributes to chronic disease acquisition and acceleration [56,76]. This paradigm may manifest as allostatic load, and while tentative, reduced fluctuation in HRV over time may be a candidate non-invasive marker for allostatic load [56,126,258]. Increasing dominance of SD2 values relative to SD1 values are likewise reported to signal diminished adaptive capacity [75]. Research in the general population and athletics have specifically linked this metric to overtraining syndrome and suggest its use in particular [259]. However, when interpreting HRV, a dichotomous view of values, that is either a 'high' or 'low' result and therefore either a 'good' or 'bad' determination is not always tenable [224]. The off-duty SD1 and SD2 values demonstrate this concept; SD2 appears to increase during the off-duty period, and therefore may be interpreted as further deterioration, however, research on the SD1/SD2 pair during sleep reveals that light sleep actually elevates SD2 values, whereas it is deep sleep only that attenuates SD2 [260]. Therefore, while the actual periods and quality of sleep were not evaluated in this study, it may be possible that the increase in SD2 during the off-duty period indicated, light, but not deep sleep. This may further support the hypothesis that the immediate decline in all other HRV values noted when the DS member returned to the next shift was due to incomplete recovery, perhaps due in part to the lack of deep sleep while off-duty, as indicated by elevated SD2 HRV. The premise posited here of limited recovery agrees with previous research in the tactical police setting suggesting that overnight shift work impairs the capacity to attenuate adverse changes in physiology potentially indicated by HRV analysis [90,132,195]. Specifically, personnel working overnight did not exhibit the expected change in HRV related to resolution of uncertainty relative to peers that did exhibit these changes but were off duty the night before. Indeed, while difficult to compare directly in terms of HRV alone, the DS member described in this case shares some similarities with the candidate described previously (Study 3, Chapter V). Namely, the strong drop in HRV values after waking or reporting in.

These data illustrate the value of HRV monitoring beyond traditional HR measurement alone in detecting signs of overstress. Practically, regular HRV analysis of individuals in high-stress occupations, such as military and healthcare personnel that must contend with similar rotating shift schedules, sleep and food deprivation, and physical labour may provide more precise information to health and performance support personnel. These multidisciplinary teams may include psychologists, physiotherapists, and strength and conditioning staff, as well as unit leadership assigning duties.

10.6.1 Limitations

While this case study is the first report known of its kind, benefits from unhindered 24-hour ECG recording, and was generally free of noise, the chief limitation of its nature as a case study remains. Additionally, the most robust indication for true decreased adaptive ability is established in the literature as a 28-day rolling average of HRV [75], rather than single instances of measurement. As such, this report does not benefit from multiday HRV analyses from either before or after the present reported data and cannot determine if these values are truly anomalous for this individual. Additional research is certainly indicated and may aim to delineate the impact of other PTG roles, including other DS capacities. Also, as mentioned above, there is not a clear indication of when sleep occurred during the recording, if at all. Finally, controlling for substances that are known confounders of HRV measurement, such as alcohol, caffeine, and tobacco were not accounted for, though as the aim of this study was to provide information regarding the value of HRV in the occupational setting where such controls are not feasible.

10.7 Conclusions

While tentative as a case study, this is the first known report to assess the HRV profile of a DS staff member directing tactical police candidate selection. While it is difficult to compare between individuals using HRV data alone, it is not unreasonable to consider that the DS are undergoing similar stress to the candidates under their supervision.

Certainly, at the least, directing a selection course should not be considered a 'light' or otherwise less severe duty. The study also confirms previous research presented in this volume of work that HRV monitoring in PTG personnel, including DS members, may be viable as a multidisciplinary or transdisciplinary screening tool. The principles described may also be transferrable to other high stress occupations, though additional research is needed determine if and how stress accumulates across individuals and the extent to which HRV measurements correspond with real-world changes in health or performance.

10.8 Afterword

This chapter investigated the effects of training supervision and selection activities on the directional staff, as measured by HRV. This chapter concludes the investigations undertaken for this thesis on applying HRV at both selection and operational levels to support the health and performance of specialist police personnel. The following chapter provides an operational guide for applying HRV in a tactical context, incorporating key lessons learned from the preceding studies and the most recent relevant literature. It also concludes this thesis, considering its strengths, limitations, and describes future directions for further research in the discipline.

10.9 Future Directions

As mentioned above, there is not a clear indication of when sleep occurred during the recording and was in integral component of the visual HRV analysis. The chief limitation of its nature as a case study must also be considered. Beyond the limitations of this particular study is the lack of consensus regarding pRRx values and their clinical interpretations – further research establishing HRV thresholds would likely enhance attempts at screening for overstress conditions and potentially aid multidisciplinary teams seeking to ameliorate the negative health effects of allostatic load in specialist police personnel, other tactical professionals, and other occupational areas where cumulative stress is a concern.

Chapter 11 – Thesis summation, conclusions, and future direction

11.1 Preface

This chapter summates the research conducted as part of the program of works informing this thesis. The main volume of evidence is condensed and discussed regarding what this evidence suggests, and where this evidence integrates with and expands the knowledge in this field. Noted limitations, conclusions and suggested future directions for the field are also provided.

11.2 Introduction

In the preceding chapters of this PhD thesis, the intricate landscape of heart rate variability (HRV) within the context of selection and operations within specialist police organisations has been explored. The literature review in Study 1 (Chapter 2) investigated the value of HRV monitoring applications in various tactical scenarios; however, it was noted that scant attention had been paid to the specialist police cohort. This specialised group of law enforcement professionals, typically chosen from a pool of seasoned officers, operates in dynamic environments and require multifaceted skill sets. Chapter 3 lays out the premise for each future study, illustrating the literature gap it aims to fill, defining the research question, and articulating its relationship with previous and following studies. Chapter 3 also described the research structure of the overall thesis. Explanation was given regarding the need for a selection and an operational research arm, and how each arm was supported by the other to achieve the ultimate aim of thesis: determine the utility of HRV assessment as a human performance optimisation (HPO) tool and decision-making support within specialist police organisations and alert stakeholders to conditions of potential overstress and allostatic load. The further investigations in Studies 2 – 8 (Chapters 4 – 10) sought to address the key literature gaps identified in Chapter 3 by the way of empirical field-based research. This final chapter (Chapter 11) culminates the research endeavours into this population, which have been bifurcated into two distinct yet interconnected arms, each tailored to address the distinct challenges presented by selection and operational contexts. The ensuing content encapsulates and synthesises the findings from these two research trajectories, culminating in an enhanced understanding of the implications of HRV within specialist police units.

11.3 Summary of findings

Beginning with Chapter 2, The review yielded 20 papers considered to be of generally high quality, but with limited examples of true experimental design, limiting the explanation of causal relationships. The research extracted suggests HRV monitoring appears to provide valuable insight into the psychophysiological responses of tactical personnel during occupationally relevant activities and recovery from those activities. While strong evidence is still emerging, based on the quality and general agreement of studies included in this review, the measurement and application of HRV indices to monitor psychological, physiological, and more specifically, autonomic stress, encountered by the tactical operator continues to be developed and significant strides over the past decade have been made in terms of utilisation by a wide range of organisations.

Chapter 4 (study 2) was able to confirm the primary established hypothesis that HRV exhibits a higher sensitivity to allostatic load responses compared to HR. However, the secondary hypothesis positing a stronger relationship between HRV and aerobic fitness than between HR and aerobic fitness during selection activities was not entirely verified. The diversity of stress sources candidates encountered, including submaximal physical demands, environmental conditions, the pursuit of success, cognitive challenges, and the imposition of uncertainty underscores the limitations of HR as a standalone measure. In contrast, the nuanced fluctuations in HRV, reflecting sensitivity not only to physical load but also cognitive load, emerge as more effective indicators of potential overstress in these scenarios. Given the low HRV observed in this study without commensurate elevation in HR suggests that either additional factors like cognitive load and uncertainty intolerance were present to drive a greater stress response than HR would indicate, and (or) a level of exhaustion was present [53,67,195].

With the relationship between aerobic fitness and HRV explored in the target population, Chapter 5 (Study 3) followed six male candidates (n = 6) throughout one day of a tactical police selection course involving land navigation and load carriage activities. For this study, HRV was defined as the percentage of R-R intervals that varied by at least 50ms (pRR50). Data were summarised in a heat map. A logistic regression model was generated that effectively predicted attrition. HRV successfully predicted attrition but did not identify the most successful candidate.

Chapter 6 (Study 4) profiled HRV characteristics of the successful candidate identified in the previous study. This case study highlights the practical benefits of harnessing HRV data to gain a more holistic understanding of candidate suitability for specialist tactical police service. By supplementing traditional assessments with HRV data, selection personnel can make more informed choices regarding individuals' capacity to succeed in roles demanding exceptional physical and psychological resilience. The approach demonstrated in this study, coupled with visualisation tools for HRV data interpretation, has the potential to enhance the efficacy of selection processes for high-pressure professions.

Chapter 7 (Study 5) served as a nexus between the selection and operational arms of research. In this chapter, candidates were involved in selection activities that were directly related to operational tasks and routine, ongoing training events expected of operational personnel. The findings indicated that HRV, specifically LnVLF, may be a valuable metric for quantifying load holistically in tactical police training, specifically those instances where the objectives are highly technical in nature. For LnVLF, the successful participant trended positively, whereas the others trended negatively in that domain. More generally, the individual with the highest rated performance by the directional staff also demonstrated the most optimal HRV values across multiple instances. HRV can be collected and measured in instances where leadership can immediately utilise the data as a component of their decision-making matrix, rather than exclusively in laboratory environments.

To further move into the operational research arm, Chapter 8 (Study 6) conducted an investigation on operational male specialist police officers (n = 11) reporting to annual requalification after either A) working an overnight shift work or B) having no assigned duties for at least 8 hours prior to presenting for qualification. This study found HRV values deteriorated after the resolution of a stress training event in officers who worked overnight, whereas HRV improved after training in those who were off duty overnight.

With further study, organisations employing collateral duty specialist police may be able to more effectively calibrate shift lengths and scheduling as related to training or other operational considerations to optimise operator health.

Chapter 9 (Study 7) further explored those fluctuations observed in Chapter 8. The results of this study noted that more anaerobically fit operators were more resilient to the psychophysiological demands imposed by the training exercise. As such, anaerobic capacity and recovery may play a key role performance within this population and merits further investigation. Practically, the presented data provide a template for integrating HRV analysis in specialist police training settings. It was tentatively identified that the ability to stratify operators and may be a viable basis against which further repeated measures could be compared to calibrate training intensity over time. Physical fitness and psychophysiological stress management through sports psychology and tactical strength and conditioning methodologies may further benefit these teams.

Chapter 10 (Study 8) considered one critical operational role, that of directional staff (DS) cadre. While it is difficult to compare between individuals using HRV data alone, it is not unreasonable to consider that the DS are undergoing similar stress to the candidates under their supervision. Certainly, at the least, directing a selection course should not be considered a 'light' or otherwise less severe duty. The study also confirms previous research presented in this volume of work that HRV monitoring in PTG personnel, including DS members, may be viable as a multidisciplinary or transdisciplinary screening tool. The principles described may also be transferrable to other high stress occupations.

11.4 Interface with key bodies of knowledge

Overall, the findings reached across this program of study generally concur with research in other populations [52]. The primary literature bodies are those regarding indications of overstress or overtraining, cognitive and physical load estimation, and uncertainty or its resolution. Each of these is explored in further depth independently before a summarised reintegration is presented along with a general guide to inform the practical and technical elements of HRV monitoring for tactical personnel.

The studies from this thesis with a primary focus on overstress and overtraining were Studies 3, 4, 6, and 8 discussed in Chapters 5, 6, 8, 10 respectively. In Study 3 (Chapter 5) it was found that HRV could effectively differentiate between candidates that withdrew and those that did not in a cohort of specialist police candidates. While current research suggests the rolling data for 28 days is best practice [75], shorter epochs, such as the few hours utilised in Study 3 (Chapter 5), might be viable as well. Overall, HRV is more sensitive and provides more rich information than traditional HR measures for exertion. In Study 4 (Chapter 6) HRV was found to potentially signal overstress situations, such as extreme fear. While this is expected given the surrounding knowledge on this topic [83,94,202,211], the value for tactical police stakeholders is in measuring that response while also taking note of individuals that perform in spite of great physiological response. In Study 6, overnight shift work was identified as a source of reduced HRV. Therefore, it may also be a source of allostatic load in specialist police [31,56,163,170,183,239]. This is of note given that shift work is a common requitement of specialist police [31]. Finally in Study 8 (Chapter 10), Nonlinear HRV was studied in an officer serving as a directing staff member on a specialist police selection course. Nonlinear HRV has been linked to overtraining syndrome [259], which may therefore be present in specialist police staff.

Regarding cognitive and physical load estimation specifically, the primary studies from this thesis conducted in consideration of that body of literature were Studies 2,3,5, and 7 (Chapters 4,5,7, and 9). In Study 2 (Chapter 4) the hypothesis that aerobic fitness trends with HRV was utilised as a basis for exploration, grounded in the premise that HRV is more sensitive to physiological adaptation than HR [69]. Specifically, it was postulated that increased aerobic fitness supports increased HRV, which is generally supportive of health and performance, and generally accepted in the athletic literature [52-54]. Thereby, improvements in both aerobic capacity and HRV may attenuate adverse changes during challenging conditions, such as a specialist police selection course. However, the body of research conducted within this thesis overall has identified a possible ceiling to the established relationship between HRV and aerobic fitness [55], in which the relationship between HRV and aerobic fitness deteriorates as aerobic fitness reaches elite levels. Study 3 (Chapter 5) found HRV to be an effective indicator of overload, as evidenced by its ability to identify attrition with limited data. This again supports the value of HRV in signalling the presence of overtraining conditions that are otherwise difficult to detect [261].

Limitations in traditional HR monitoring are again demonstrated by Study 5 (Chapter 7), building on Study 2 (Chapter 4) in which one domain of HRV (VLF frequency) linked closely with cognitive load differentiated successful from unsuccessful candidates, but HR data alone were unremarkable [4,226]. Finally, in Study 7 (Chapter 9) it was found that anaerobic fitness may attenuate adverse fluctuations in HRV, especially if those tasks are anaerobic in nature as well. There is little extant investigation regarding HRV and anaerobic fitness, and so this study is generally on a frontier in the literature [55].

Regarding uncertainty and resolution of uncertainty specifically, the primary studies from this thesis conducted in consideration of that body of literature were Studies 5 and 6, reported in Chapters 7 and 8 respectively. In Study 5 (Chapter 7) The most successful candidate trended positively in terms of HRV throughout the training and selection period, whereas the other candidates generally did not. In terms of resolution of uncertainty, this finding indicates that perhaps the successful candidate achieved a degree of familiarity and confidence with the process as the day progressed, whereas the others deteriorated in terms of HRV as the challenging and dynamic conditions increased in complexity and rigor. This assertion agrees with the theoretical literature on the topic [132,218,219], but has not been verified in context, and so remains unverified [195]. Study 6 (Chapter 8) determined that overnight shift work may inhibit resolution of uncertainty, in that expected increases in HRV were not exhibited by those personnel that successfully completed a difficult marksmanship event. The body of evidence considering uncertainty and its resolution has made links with allostatic load that may be relevant to police populations in which incomplete information is a constant occupational reality [36,132,142,195,219].

However, as there is still very little research published that may be compare directly to the findings developed in this thesis, both general population, clinical, and athletic literature have been key in understanding the data collected and applying it. To further understanding in this field, large data sets of personnel involved in public safety should be assessed with HRV to provide more robust baseline information to truly develop stratification from disease to high performance [262].

11.5 Limitations

The greatest limitations encountered in this thesis were related to the population of interest, namely sample size. While generally all available individuals were recruited, those numbers still remained small. Longitudinal access was also a notable concern. Studies were generally brief, as the research team was given access to the units only when there would not otherwise be any interference with necessary operational function. Studies were also primarily observational in nature for this same reason, in that experimental studies would not be accepted by the host units that required uniform conditions for all personnel.

When considering investigations into unique populations, while novel, and potentially crucial for community safety in this context particularly, it is not at all unusual to contend with limited populations and samples. Indeed, while the aim of large scale studies is to generalise results, research in these specialised niches, such as with elite athletes [263], specialist police personnel [264], or even astronauts [265], may aim instead to serve the end-user, and may not aim to generalise to broader populations that may not share similar experiences. Regarding the short and observational nature of the studies, research was conducted such that the presence of the research team introduced as little change in standard operations as possible. While this was a condition of access to personnel and data, it also was important for the applicability of the findings to local population; if the practices advocated for by this body of research presented an undue burden to the potential end-user, the value is limited, and the ultimate adoption of the recommendations provided would be unlikely.

11.6 Future Direction

As a result of these limitations, some of which were further exacerbated by the COVID-19 pandemic, the conclusions drawn from the studies in this thesis must be interpreted with caution and many have not been verified through independent duplication. This is particularly true of those works that are the first of their kind (Studies 3 and 8 particularly, but also 4 and 6 to lesser extent).

To progress this line of inquiry, an on-site specialist may be needed to mitigate the sampling and access difficulties. An embedded and dedicated officer or civilian undertaking health and performance optimisation measures would have sufficient access and rapport to assess for some of the confounding factors encountered in this research and develop multifactor models that incorporate not only HRV, but other valuable health and performance data over sufficiently lengthy timespans. To facilitate this ongoing objective, a general guide to inform the practical and technical elements of HRV monitoring for tactical personnel has been developed. The construction and distribution of this work will hopefully further allow for translation to practice and to guide future research. As personnel within organisations, and those collaborating with specialist police organisations consider human health and performance objectives, this following document may aid in the facilitation of HRV application.

11.7 Conclusions

The main volume of evidence developed in this thesis suggests that HRV can be applied in field settings to support the training and operations of tactical police personnel. Even limited data, for example small sample sizes, or limited data capture windows, can provide value to unit stakeholders. The visualisation and presentation of this data may be just as important as more technical aspects of its collection, though obtaining quality ECG signals with limited noise and artifacts is essential. While allostatic load and related conditions such as overtraining syndrome or relative energy deficiency are difficult to diagnose [56,135,136], especially without additional supporting information, and generally require an expert clinician [257,261], HRV shows promise in the specialist police population for alerting individuals to potential overstress and could serve as an early warning indicator for further follow-up from a comprehensive human performance optimisation team.

Chapter 12 – Heart Rate Variability Application Guide for Tactical Professionals: Defining, Measuring and Monitoring Resilience for the Tactical Professional

12.1 Preface

This chapter contains content adapted for publication in the 'TSAC Report'. The citation is as follows:

Tomes C, Schram B, Orr RM. Defining, measuring, and monitoring resilience for the tactical professional: Part 3- Heart Rate Variability Application Guide for Tactical Professionals. TSAC Report. 2022 (65):18-23. Reproduced with permission from NSCA.

Note: Formatting and introductory content changes have been made in this chapter to improve readability and continuity across the entirety of the thesis.

12.2 Review of HRV Monitoring purpose

Heart rate variability (HRV), first pioneered in hospital settings [51], is now being utilised widely by athletes and tactical personnel to inform health and performance optimisation teams [52]. Advances in measuring, analysing, interpreting, and applying HRV continue to be made in many settings [53,54], including tactical environments, where comprehensive and objective measures of holistic load are especially valuable [55]. Military, fire and rescue, and law enforcement agencies are now able to actively participate not only in improving the health and performance of their members, but also in pushing these scientific boundaries [116].

However, tactical environments are not laboratories, and organisations and personnel are often unable or not amenable to deploy other physiological monitoring tools [5]. Therefore, HRV may serve as one of the most viable means for detecting insufficient coping before clinical manifestations are present, and as an objective measure of excessive stress [75]. At first, an individual may experience subclinical disruption of optimal fluctuation between sympathetic nervous system (SNS), parasympathetic nervous system (PNS), and other influences on the cardiovascular system. Left unchecked and unmitigated, this decompensation may eventually lead to a devastating health or performance consequence such as injury, illness, or psychosocial catastrophe [76,124]. These initial chronic clinical or subclinical disruptions have been previously described as allostatic load [125].

12.2.1 Practical Overview

At the most essential level, HRV is the computational model for the complex, integrated, and holistic psychophysiological responses that occur when the time between consecutive heart beats, also known as beat-to-beat or inter-beat-intervals (IBI) is modulated by one or more influencing factors [69]. As described in 1.5 Part 2: Holistic Assessment, these factors range from basic survival purposes and resting regulation (respiratory sinus arrythmia, circadian rhythm, among others), to the dynamic effects of mental and physical stress, exercise, and the cumulative biopsychosocial demands that contribute to allostatic load [56].

With recent technological developments, HRV data are now available and interpretable by coaches and individuals, and while careful interpretation is necessary, specialist appointments to read or understand results are no longer necessarily required to obtain actionable information [50]. Correlations between HRV measurements and process or outcome measures are allowing for readily accessible insights to valuable health and fitness data [52,98] and have been associated with the prediction of morbidity from a wide variety of chronic and acute disorders [55].

12.2.2 Technical Overview

The variety of mathematical strategies and data approaches to HRV may initially seem overwhelming but can generally be categorised into the following: frequency domain, time domain and nonlinear domain analyses. The roles and applications of each assessment technique are summarised in Table 18.

Table 18. HRV Measures, Definitions, Applications, and Interpretations

Measurement	Units	Definition	Application	Interpretation
RMSSD	ms	Root-mean square of successive differences	Primary measurement for short term PNS assessment	Values generally increase with cardiovascular fitness[69]. Decreasing trends in time-domain components over repeated measurements may indicate failure to adapt[75]
pNN20	%	Percentage of adjacent intervals that differ by *more than* 20ms	Assessment of PNS Possible disease marker	
pNN50	%	Percentage of adjacent intervals that differ by *more than* 50ms		
SDNN (SDRR)	ms	Standard deviation of all interbeat intervals during the sample timeframe	Accepted cardiovascular disease risk assessment if recorded over 24 hours or longer	
VLF	ms^2	Very low-frequency power band (0.0033–0.04 Hz)	Long-term measurement	Increased LF values may indicate failure to adapt[75]
LF	ms^2	Low-frequency power band (0.04–0.15 Hz)	Baroreceptor activity Combined SNS and PNS activity	Decreased HF values are associated with high stress[99]

HF	ms^2	High-frequency power band (0.15–0.4 Hz)	PNS and respiratory activity Cognitive and emotional response depending on measurement conditions	Decreased TP may indicate failure to adapt[75]
TP	ms^2	Total power; summation of all frequency bands	General autonomic activity	Surrogate for RMSSD, pNN50 or SDNN when recordings contain noise or other flaws[100]
SD1	ms	Standard deviation with the respect to the y-axis on Poincare plot	Nonlinear short term detrended assessment	Surrogate for LF power when recordings contain noise or other flaws[69]
SD2	ms	Standard deviation with respect to the x-axis on Poincare plot	Nonlinear long term detrended assessment	Values generally increase with cardiovascular fitness[69]. Decreasing trends in time-domain components over repeated measurements

				may indicate failure to adapt[75]

In general, the computational goal of HRV analysis is to assess the stability or instability of various increasing or decreasing trends in heart rate. Much like daily temperature generally increases throughout the day and then decreases at night, but also more broadly increases in the summer and decreases in the winter, fluctuations in heart rate can also be observed and appreciated over both brief and lengthy windows. The patterns can be decomposed into time, frequency, and nonlinear descriptions. Based on the qualities of the pattern of interest, the physiological governing mechanism can be estimated – typically a signal is attributed to either the parasympathetic nervous system, sympathetic nervous system, or a combination of the two, or another source. Ultimately, a balance and exchange between sympathetic and parasympathetic influences is likely ideal. Indeed, in the psychiatric literature, a U-shape distribution of HRV has been proposed for risk of disease; suggesting that HRV values that are either excessively high or excessively low predispose and individual to ill health [211]. This concept is illustrated in Figure 21.

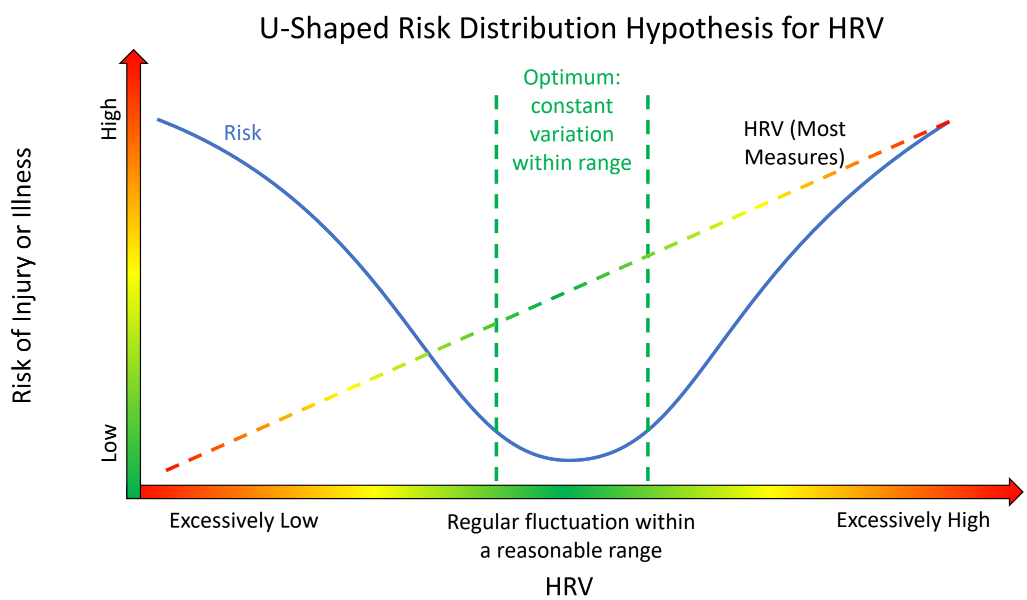


Figure 21. Visualisation of U-Shaped Risk & HRV

Therefore, when personnel are healthy, adapting to challenges effectively, and managing the multifactorial stress influences in their lives and careers, the systems that create HRV patterns are stable and produce consistent oscillations. A failure to adapt, insufficient stress management capacity, injury, disease, or another source of allostatic load results in deviations from these patterns.

However, the precise manifestation of these systems and patterns is highly variable from individual to individual, and so the most effective strategy for detecting a problem is by comparing an individual today against their historical measurements; a 28-day rolling average is advised in the literature as the most precise and practical period for measurement comparison [75]. When a team member displays a significant change in the specific HRV measurement detailed below, begins to demonstrate a trend that is not correcting, exhibits a large change in HRV between their initial and final values surrounding a rigorous event, or otherwise fails to return to their baseline the HPO team may be alerted for possible intervention [55,90].

With respect to specifics of the analytical methods, the frequency domain aims to illustrate how much each cycle of increasing or decreasing heart rate lies within each established frequency band over a range of frequencies. The frequencies most typically encountered in heart rate variability analysis are the very low, low, and high frequency bands [51]. LF power accounts for both SNS and PNS activity [72,107]. Baroreceptors, nerve endings found in the linings of arteries responsible in part for regulating blood pressure, and intrinsic cardiac ganglia also contribute to the LF component [108,109]. As a result of the multitude of influences on LF HRV, it may not be a suitable metric for determining if personnel are experiencing excessive stress [55,75].

The HF power band however, a faster oscillatory period, much more directly reflects parasympathetic activity because the PNS generally functions over shorter timeframes than the SNS [68]. Respiratory and cognitive demands, as well as emotion can also contribute to HF HRV [68,95,110]. Decreased contribution of HF to the total spectrum of power observed in a recording may effectively indicate to the HPO team that an individual is at risk of overexertion, insufficient recovery or impaired occupational performance; either psychosocial or physical [52].

Other bands exist but are generally not of interest in tactical human performance. Each component is associated with particular functional elements of autonomic nervous system activity based on how fast or slow the influence occurs. However, the two main branches, the sympathetic and parasympathetic nervous systems, can overlap in terms of signal production, and the complexities of cardiac autonomic function are not limited to only SNS and PNS activity. Therefore, inferring autonomic function from the frequency domain alone requires careful consideration, and decisions regarding health, performance, or occupation should be in consideration of not only additional HRV measurements, but also additional subjective and objective data.

12.2.3 Summary of time domain HRV

Time domain is generally less complex than frequency domain but can still reveal critical information unavailable with the simple assessment of heart rate. The variability within a given time frame can provide insight as to which branch of the autonomic nervous system is more predominant; as explained in 1.5 Part 2: Holistic Assessment, the heart is dually innervated – both the SNS and PNS are active simultaneously, but because different neurobiological pathways are utilised by each system, the resulting effect on the heart of each branch will unfold over different timespans [74]. This can be reflected and measured in time domain HRV analysis. Two common approaches are the standard deviation of the N-N intervals (SDNN), a simple approach familiar to anyone with a background in statistics, and the root mean square of the differences in adjacent N-N intervals (RMSSD). The RMSSD utilises the absolute value of differences in time between adjacent heartbeats [69].

Other metrics, such as cut-off thresholds over a full sample, such as the percentage of total intervals that vary by more than 12, 20 or 50ms can also serve as approachable metrics [111]; personnel with values below certain reference ranges established in epidemiological research can be rapidly identified flagged for quick evaluation prior to operations or training [90]. While nonspecific, these strategies may allow for an opportunity for support teams to start conversations with particularly stoic individuals.

12.2.4 Summary of nonlinear HRV

The nonlinear domain of assessment may be the least thoroughly explored but shows particular promise for the tactical community because it is an especially robust approach that can yield valuable information, even from shorter or noisy samples [69,100]. For example, data which may be collected in a rush or with the confounding influence of protective equipment and load carriage that may interfere with equipment remain suitable for these analyses. The Poincare SD1 and SD2 are highlighted examples of nonlinear analytical methods. Poincare plots simply map the first RR interval on the x-axis against the difference relative to the next interval on the y-axis to yield a geometric analysis of HRV [115]. The standard deviations are the width and height of the general elliptical shape that is produced and correspond to short term (SD1) and long term (SD2) variability. The time windows generally considered are 1 to 5 minutes for short-term and 24 hours for long-term. SD1 correlates closely with HF and total power and can therefore serve many of the same applications mentioned above when traditional frequency domain analyses are confounded.

12.2.5 Monitoring strategies – time windows

The time windows typical in HRV research are usually designated long term (>10mins to 24 hours), short term (1-2 mins to 5 mins) and ultra-short term (10-30 seconds) recording windows [69]. 24-hour recordings using 3 or more lead ECG are generally considered the gold standard measurement as they allow for the most precise, accurate, and noiseless measurement of heart rate variability [51]; both the longest, circadian oscillations, and shortest, respiratory sinus arrythmia oscillations, are observed. However, depending on the desired objective, shorter recordings of at least 5 minutes may still be sufficiently robust, and are generally more practically achieved in a tactical setting [75].

There are several windows of opportunity that may arise for HRV measurement and analysis, especially in training or selection courses, or surrounding regularly established rotating shift periods. While the continuous, 24-hour ECG monitoring solution is generally accepted as the gold standard, this may not be practical or even possible in many tactical units; resources may simply be unavailable, or equipment may become damaged or destroyed throughout the day due to the demands of tactical work. Five-minute recordings both preceding and following bouts of highly strenuous activity has demonstrated value in a variety of settings and can be effective as a tool to not only provide relatively real-time and meaningful feedback, but also resource sparing screening [55,75,116]. Intervals as short as 10-30 seconds have been described in the literature and demonstrated utility but come at the cost of some sacrificed precision [101,117]. Indeed, research conducted in this thesis effectively generated actionable information for the tactical professional [253].

HRV monitoring is also used to assess sleep health, though the relationships are complex and not fully understood. Nonetheless, wearable technologies have become increasingly popular [116], and given the well-established relationship between sleep and injury [119,120], in addition to other performance outcomes [121], the importance of sleep health in the tactical community cannot be overlooked [21]. While again not a replacement for a true 24-hour recording, utilising HRV analysis overnight when feasible in addition to five-minute recordings before and after rigorous activity may provide the most comprehensive analysis possible while remaining practical for use in tactical training or operations [75,116].

With this in mind, a combination of measurement tools may be required to maximise data availability. While 3-lead ECG has been defined in the literature as the gold standard and is preferable for short or ultra-short-term recordings to maximise precision, smaller, less obtrusive devices may be desired for overnight recordings. Devices worn on the finger utilise pulse plethysmography (PPG), and rely on optical measurement of the arterial pulse, rather than direct electrical measurement of heart activity itself. While PPG, familiar to anyone with an emergency medical services background, has demonstrated validity and reliability as an HRV monitoring strategy [122], such devices may best be utilised for overnight use, or when ECG is unavailable or impractical.

When considering the practical applications of HRV analysis, a great deal of actionable information can be obtained and synthesised in a relatively short period of time, with minimal expense of resources, hence its advantages and subsequent popularity. A sample program is described below to illustrate how different measurement tools and HRV analyses can be combined to contribute to tactical HPO (Table 19).

Table 19. HRV Program Implementation Guidance by Profession

	Measurement Timeframes	Measurement Tools	HRV Indices	Interpretation
Military: Training or Selection Scenario	Baseline 5-min recording at onboarding. Daily 5 min recordings before and after physical training Overnight recordings Record overnight/throughout field training events as safe and practical	Utilise ECG chest strap or traditional leads whenever possible. Utilise PPG overnight or if more practical for field training events	RMSSD pRR50 HF SD1 SD2 (overnight only)	Consider measurements relative to baseline onboarding measurement. Observe for decreasing trends in time domain measures. Observe for unusual fluctuations. Combine with subjective and other objective data
Police	5 min recordings before and after shift Obtain recordings throughout training activities as safe and practical	Utilise ECG chest strap or traditional leads whenever possible	RMSSD pRR50 HF SD1	Compare pre-shift to post-shift. Compare pre-shift measurements to 28-day rolling average once established. Observe for unusual

				fluctuations across shifts. Consider return to baseline capacity following particularly intense training or operations
Fire/EMS	5 min recordings before and after shift Obtain recordings throughout training activities as safe and practical. Consider continuous monitoring when personnel are sleeping at the station. Consider obtaining 5 min recordings when personnel return from calls. Consider obtaining measurements during motor vehicle accident response	Utilise ECG chest strap or traditional leads whenever possible. Avoid wearable devices when high temperatures are likely. Utilise PPG when personnel are sleeping	RMSSD pRR50 HF SD1 SD2 (overnight only)	Compare pre-shift to post-shift. Compare pre-shift measurements to 28-day rolling average once established. Observe for unusual fluctuations across shifts. Consider return to baseline capacity following particularly intense training or operations

12.2.6 Important confounding variables

However, interpretation must be managed carefully, as HRV analyses suffer from known confounders and shortcomings. For example, the frequency domain is known to be particularly volatile, meaning that information derived from the frequency domain are likely to change significantly and quickly over time. Due to the complexity of factors influence HRV, and particularly frequency-domain measures, comparisons between individuals are not advised, and consideration only of a single operator over time is indicated. Substances common and perhaps endemic to the tactical professions, particularly caffeine and alcohol both influence HRV, and while the known usage of either should not preclude HRV analysis from being considered, there are several key factors to note.

12.2.6.1 Alcohol

The effects of alcohol consumption are of critical interest because while all cell membranes are highly permeable to ethanol, and so every cell in the body can be affected, acute and chronic alcohol intake appears to exert the majority of its effects through the central and autonomic nervous systems [266]. When consumed in moderate (2 standard drinks or 14-25g) quantities [267], alcohol binds strongly to gamma-aminobutyric acid (GABA) receptors in the brain [268]. GABA is the primary inhibitory neurotransmitter in the central nervous system and is responsible for decreasing the activity of cells within the brain [269]. While this role is important for reducing unwanted activity, it is the interaction of alcohol with GABA receptors that causes the depressive effects seen with drinking [268,269]. Simultaneously, ethanol appears to increase central stress response activity; the sympathetic nervous system, renin-angiotensin-aldosterone system, vasopressin, and natriuretic peptide, all become more prevalent and active with alcohol consumption [267,270]. There is also evidence that chronic alcohol consumption can damage the vagus nerve, impairing parasympathetic nervous system activity [104,271]. When these effects are measured with HRV analysis, the result, while variable across individuals and studies, generally appears to consist of the following: time-domain and the high frequency band tend to decrease overall, due to vagal withdrawal and the aforementioned increased sympathetic activity and its resultant cascades [272]. With acute consumption, these effects may dissipate within the timeframe the alcohol is metabolised [267]. However, because alcohol negatively influences sleep quality [268], if alcohol is consumed at night, and HRV is measured the next morning, the effects from drinking the previous night may influence

HRV in morning as a result of poor sleep [104]. However, because few studies have investigated the short term effects of heavy alcohol consumption, and no studies have considered the compounding effects of life and work in tactical environments, it is likely that the effects of alcohol consumption on HRV are generally underestimated, and so careful consideration should be given to the alcohol intake habits of personnel when utilising HRV in contexts outside of training and those specific operational environments where alcohol intake is limited or completely unavailable. In settings where alcohol is more freely available, more careful interpretation is likely needed.

12.2.6.2 Caffeine

Likewise, caffeine is a widely popular substance that is utilised frequently in personnel working overnight, for extended periods, or with high levels of exertion; military personnel report consuming 212-285mg/day on average [273]. While coffee consumption in moderate doses (5, 8oz cups per day or less) appears to have greater health benefits than potential risks [274], excessive caffeine consumption can lead to health problems, including tachycardia, restlessness, and irritability [275]. These negative effects may occur particularly with the use of high-sugar beverages containing caffeine and other agents at levels not found in natural sources [276]. The effects of caffeine in the body are widespread, and include respiratory, renal, and smooth muscle effects, as well as effects on mood, in addition to generally enhancing memory, alertness, physical, and cognitive performance [277]. With regards to the cardiovascular system, the extensive effects of adenosine competitive antagonism by caffeine may result in increased vagal activity beyond any increases seen in sympathetic activity, with the net effect of increasing HRV, particularly the HF component of the frequency domain [262]. These effects may be reversed with exercise, as one study demonstrated exaggerated vagal withdrawal after a bout of stationary cycling [278]. Therefore, practitioners utilising HRV analysis as a means of monitoring recovery in personnel may need to consider the caffeine intake of personnel to avoid erroneous results.

12.2.6.3 Nicotine

Lastly, nicotine, usually in the form of tobacco, is another widely utilised substance in tactical professionals, with approximately 1 in 5 personnel in military, fire, or police service admitting regular use [279,280]. Like caffeine, neuroimaging studies have shown that nicotine increases activity in the prefrontal cortex, thalamus, and visual system [281], likely contributing to its popularity in professions where alertness and acuity are key for success and survival. These effects are realised when nicotine enters the bloodstream, typically via the lungs, and binds to cholinergic receptors, upregulating the release of neurotransmitter and initiating the complex cascade of effects, involving the above mentioned responses, in addition to increased circulating levels of dopamine and GABA [281]. As a sympathomimetic drug, nicotine releases catecholamines, which in turn increase heart rate and force of heart contraction, constrict cutaneous and coronary blood vessels, and transiently increase blood pressure [282]. As a result of these actions, smoking likely contributes to a similarly acute and transient decrease in PNS control of the heart [283]. Literature indicates that heavy tobacco consumption causes long-term inhibition of vagal cardiac control and reduces sensitivity of cardioregulatory processes in response to changes of position [283]. With respect to sensitivity over the short term, even a modest (4mg) dose of nicotine can produce a significant reduction in HRV, namely a decrease in the HF domain [105]. As such, while the immediate effects of nicotine may not be realised unless personnel are consuming tobacco within 15-20 minutes of HRV recording and analysis [284], tactical human performance optimisation (HPO) personnel relying on HRV should be aware of long-term tobacco use habits of personnel, and account for diminished PNS influences in HRV that will likely be observed in those personnel accordingly.

12.3 Wrap-up and Bottom line

In summary, HRV can be a useful tool within tactical organisations to holistically assess for stress. Because of the dynamic, potentially dangerous, physically, cognitively, and psychologically demanding nature of work in tactical professions, a means of monitoring personnel that considers every aspect of encountered stressors that can be deployed in austere environments is called for. If personnel are unable to accommodate and respond to the summation of these stressors encountered in training and over a career, the resulting physiological decompensation can lead to severe health and performance consequences, known as allostatic load. Allostatic load may be detected by HRV analysis as reduced fluctuations in expected patterns of variation that occur over cycles as short as drawing a breath and as long as the 24-hour circadian rhythm. HRV is a sensitive and effective means of measuring normal physiological variations in heart rate patterns over time.

Personnel supporting tactical professionals can utilise HRV in both training and operational environments to maximise their capacity to detect and intervene, promoting maximal health and performance of the unit. HRV can be applied by recording heart rate with electrocardiogram (ECG) or photoplethysmogram (PPG) devices, over timespans as short as 5 minutes or as long as 24-hours. The results must be interpreted with respect to the situational context, length of recording, noise or disruption encountered in the recording. The presentation and visualisation of HRV data may be as critical to the application of HRV analysis as the measurements themselves. Key influencing substances, such as alcohol, caffeine, and nicotine should be accounted for as able, but may not always be practically controlled for in tactical settings. When carefully and optimally applied, HRV analysis can be a cost and time effective augmentation to any high-performance team environment within tactical training and operations.

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14. Appendix 1 — Ethical Approval Statements

14.1 Messiah University Protocol 2019-022

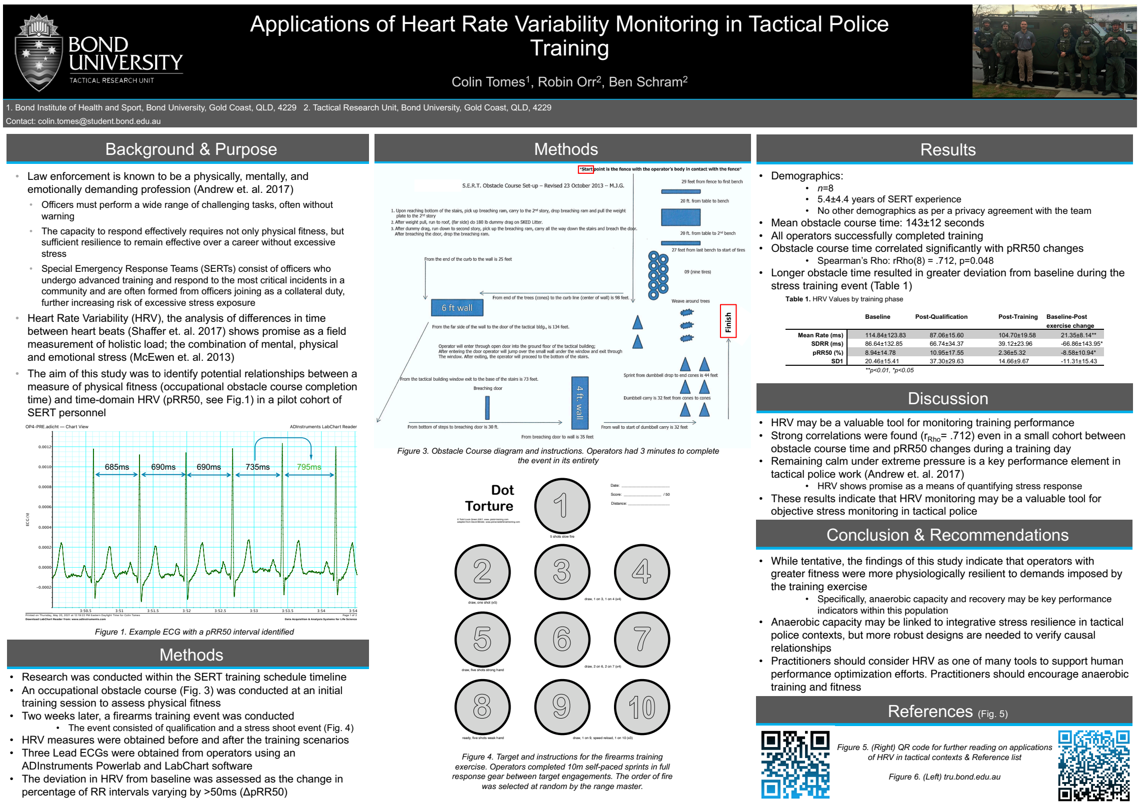
14.2 Bond University Protocol 2019-022 Amnd 1

14.3 Bond University Protocol BS02165

14.4 Bond University Protocol 2019-022 Amnd 2

15. Appendix 2 — Poster Presentations

15.1 NSCA National Conference 2021 (Chapter 9)



BOND UNIVERSITY
TACTICAL RESEARCH UNIT

Incorporation of heart rate variability into police tactical group small unit tactics selection

MORAVIAN UNIVERSITY

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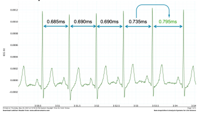
Background & Purpose

- Law enforcement is known to be a physically, mentally, and emotionally demanding profession (Andrew et. al., 2017)
  - Police Tactical Group (PTG) personnel are subject to additional demands that may include search and rescue, counterterrorism, explosive ordnance disposal, and active shooter response (Robinson, et. al., 2022)
- For these reasons, selection for PTG service is physically and technically challenging (Maupin et. al., 2017)
  - Individuals must be assessed holistically
- Heart Rate Variability (HRV) may provide quantitative measures of holistic stress and load, providing unit leadership additional information on candidate suitability (Shaffer et. al., 2017)
  - Therefore, The purpose of this study was to measure HRV relative to performance in a cohort of PTG candidates



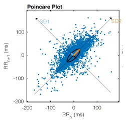


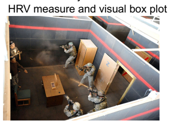
Figure 1 (Above Left). Example ECG with a pRR50 interval identified.
Figure 2 (Above Right). Example Poincaré Plot identifying nonlinear HRV (SD1 & SD2)

Methods

- This study was a prospective cross-sectional study of three male PTG candidates (n = 3)
- 3-lead ambulatory ECGs were recorded for five hours during the training session, between 13:00 and 18:00.
  - Participants were supplied with body worn Equivital™ EQ02+LifeMonitor (ADInstruments, Sydney, Australia)
- Participants were introduced to a room clearance training structure comprised of residential and commercial specification rooms and hallways.
- Scaled room clearance training scenarios were performed (Figure 3)
  - Role players engaged candidates as active shooters.
  - Duration of the selection events ranged from seconds to clear a single room to several minutes for multiple room clearances.
  - Participants were assessed on movement technique, tactical proficiency and transition from primary to second weapons (Figure 4).
  - Verbal and non-verbal communication was also assessed, as was safety and overall outcome of each scenario.
- HRV (Table 1) was analysed via the following metrics:
  - Heart rate descriptives were also explored: min heart rate, max heart rate, and mean heart rate during the recording window.
  - Frequency-domain HRV: natural log (Ln) High, Low, and Very Low
  - Root-mean square of successive RR differences (RMSSD)
  - Percentage of adjacent R to R wave (RR) ECG intervals varying by at least 50ms (pRR50)
  - Nonlinear short-term (SD1) and long-term (SD2) variability

Methods

- Statistical analysis consisted of maximum, minimum, and mean for each HRV measure and visual box plot analysis (Figs. 5-9)



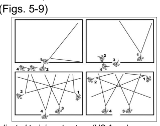
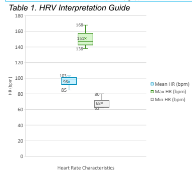


Figure 3 (Above Left). Room clearance training in a dedicated training structure (US Army).
Figure 4 (Above Right). Four-person room clearance procedure schematic (US Army).

Metric	Units	Definition	Application	Interpretation
RMSSD	ms	Root-mean square of successive differences	Primary measurement for short term PNS assessment	Values generally increase with cardiovascular fitness
pRR50	%	Percentage of adjacent intervals that differ by more than 50ms	Accepted cardiovascular disease risk assessment in epidemiological literature	Decreasing trends in time-domain components over repeated measurements may indicate failure to adapt or overstress
SD1	ms	Standard deviation with the respect to the y-axis on Poincare plot	Nonlinear short term detrended assessment	Surrogate for time-domain measures when recordings contain noise or other flaws
SD2	ms	Standard deviation with respect to the x-axis on Poincare plot	Nonlinear long term detrended assessment	Surrogate for LF power when recordings contain noise or other flaws

Table 1. HRV Interpretation Guide



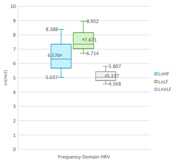
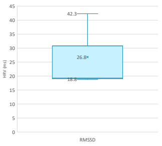


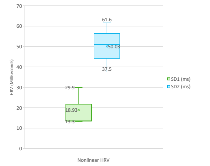
Figure 5 (Above Left). Heart Rate Characteristics, with max, min, and mean values
Figure 6 (Above Right). Ln Frequency Domain HRV, with max, min, and mean values

Results

- All three candidates successfully completed the selection procedures
  - Only one participant was approved to progress beyond this stage of selection
- Data from that participant appeared to consistently skew results
  - Maximum values for mean RRI, RMSSD, pRR50, SD1, and SD2 were all derived from a single participant.
  - That same participant also held the lowest maximum heart rate and lowest mean heart rate.

Results





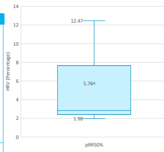


Figure 7 (Above left). RMSSD HRV, with max, min, and mean values
Figure 8 (Above Right). Nonlinear HRV, with max, min, and mean values of SD1 and SD2
Figure 9 (Below Left). pRR50% HRV, with max, min, and mean values

Discussion

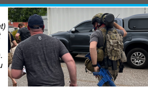
- The maximum pRR50 value was above the 6.25% threshold posited as a cardiovascular disease risk indictor (Mietus et. al., 2002).
  - both the mean and minimum were below.
- The levels of agreement between the HRV values observed in this study and previous specialist police candidate studies are also of note.
- Even this tentative finding is of potential interest for determining the presence of excessive stress in the present personnel

Conclusion & Recommendations

- HRV may be a valuable metric for quantifying load holistically in tactical police training
  - The individual with the highest rated performance by the directional staff also demonstrated the most optimal HRV values.
- HRV can be collected and measured in instances where leadership can immediately utilise the data

References

Figure 10. (Right) Reference List QR code
Figure 11 (Left). tru.bond.edu.au



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Heart Rate Variability Assessment of Land Navigation and Load Carriage in Specialist Police Selection Training

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BOND UNIVERSITY
TACTICAL RESEARCH UNIT

MORAVIAN UNIVERSITY

Introduction

- In Australia, specialist police personnel assigned to police tactical groups (PTGs) are often tasked with atypical or paramilitary duties
- Consequently, PTG selection courses must also be highly rigorous
  - Attrition is often high and candidate failure/withdrawal is typical[1]
- Health and performance monitoring may therefore be beneficial
- Heart Rate Variability (HRV) is one holistic measure obtainable through wearable technology monitoring
  - HRV is a valid measure of holistic stress response[2]
  - Pragmatic in austere field environments[3]

Methods

- Initial cohort of 18 male police officers attempted a 1-day assessment
- Of those, six progressed to an additional two-day selection course, on which this study is focused
  - Two-day selection course consisted of additional occupational tasks
- HRV response during 13 hr of load carriage was of primary interest
- 2-lead ECGs acquired from EQ02+ LifeMonitors (Equivital™, Cambridge, UK)
- HRV: percentage of R-R intervals varying by ≥50 ms (pRR50%)
  - Epidemiological studies and previous research in specialist police report pRR50%[4]
- Data were summarized in a heat map
- Logistic regression analysis was selected to predict attrition

Conclusions

- Assessment and heat mapping of HRV can provide additional insight to selection staff and unit leadership during selection courses
- HRV data using allowed for a statistically significant regression model predicting attrition
  - Not possible with raw HRV values alone
  - Only high HRV was predictive
- This approach can identify poorly performing candidates as well as exceptional performers
- Those who continue to demonstrate competence despite potential psychophysiological overstress as measured by HRV can also be identified
- Additional insight for selection purposes and further training or recovery referral
- Real-time HRV monitoring, or more frequent data processing may be beneficial to acquire this valuable data before attrition occurs

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Purpose

- This study aimed to:
  1) Generate HRV profiles of PTG candidates
  2) Summarize data in a format accessible by end-users
  3) Determine the relationship between HRV and attrition

Results

- Three candidates withdrew during the pack march event
- Only one candidate completed the entire two-day course
- Temperatures ranged from 24.2 – 34.4° C and relative humidity ranged from 60 – 75%
- The heat map can be found in **Figure 1**
- 153 consecutive 5-minute HRV measurements were yielded
- Heat map shading was informed by Hopkins and Buchheit[5]
- Tables 2 and 3 describe count data derived from the heat map
- Quantitative values of interest from the heat map include:
  - Total amount of time each candidate had shaded for red and green respectively
  - Longest epoch without change in shaded colour
    - Represents prolonged high (green) or low (red) HRV
- Logistic regression model: χ2 (6) = 8.318, **p = 0.004**
  - Count data of 5-min blocks with pRR50 intervals >½SD from the mean value during the beginning of the selection through to the end of the land navigation exercise (0700 – 1430)
  - Correctly identified 100% of pack march passes and 100% of failures
  - The resultant sensitivity and specificity of high HRV predicting that a candidate would pass the pack march event that followed was 1.0

Figure 1 (right). Heat map of candidate pRR50 values in 5-min blocks. Male PTG Candidates, n = 6. Red regions indicate values <½SD of the participant's mean, yellow regions indicate values within ±½SD of the participant's mean and green regions indicate values >½SD from each participant's mean. The furthest right column indicates activities throughout the recording period.

Military Impact

Previous HRV research has combined specialist police and military cohorts[6]. This novel approach to HRV assessment may translate across tactical organisations **seeking additional selection process supports**

Table 1. Anthropometric, Load Carriage and Fitness data of Australian PTG Candidates *Legend: body mass index (BMI), multistage fitness test (MSFT)*

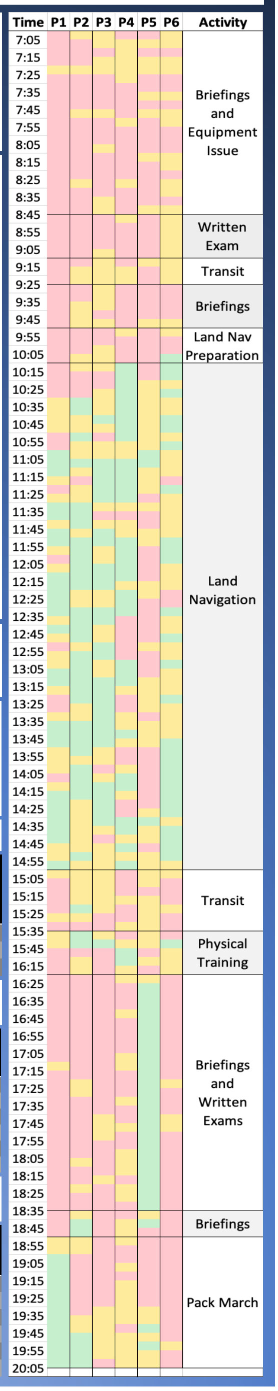
Value	Body Mass (Kg)	Height (cm)	Age (Years)	Land Nav Equipment Mass (Kg)	Pack March Equipment Mass (Kg)	BMI	MSFT (level. shuttles)
Mean	93.63	180.17	30.67	12.24	11.95	28.88	10.1
SD	8.83	5.98	2.94	0.14	1.32	2.92	0.5
Median	94.78	181.00	31.00	12.24	11.96	29.22	10.1

Table 2. Count Data: Total and longest consecutive time of HRV (pRR50) registered below ½SD of the participant's mean
[1] Only candidate to complete entire selection course

Candidate	Total time (min)	Consecutive minutes	Time	Finish/Did not finish (DNF) pack march
P1	430	185	7:25 – 10:30	DNF
P2	320	60	16:20 – 17:20	Finished [1]
P3	330	80	16:20 – 17:40	Finished
P4	330	30	07:55 – 08:25	Finished
P5	335	45	18:45 – 19:30	DNF
P6	325	120	17:50 – 19:50	DNF

Table 3. Count Data: Total and longest consecutive time of HRV (pRR50) registered above ½SD of the participant's mean
[1] Only candidate to complete entire selection course

Candidate	Total time (min)	Consecutive Minutes	Time	Finish/Did not Finish (DNF) Pack March
P1	190	65	19:00-20:05	DNF
P2	205	30	11:50-12:10	Finished [1]
P3	145	40	1310-1350	Finished
P4	170	45	1010-1055	Finished
P5	160	130	1625-1835	DNF
P6	145	45	1345-1430	DNF



Heart Rate Variability Profile Of A Specialist Police Selection Assessor

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Introduction

- Specialist police units such as Australian Police Tactical Groups (PTGs) are tasked with numerous duties, many potentially hazardous or fatiguing
- One such duty is as a selection course (SC) assessor
- Given the high physical intensity of SCs and imposition of sleep deprivation, health and performance monitoring may benefit SC staff and units
- Heart Rate Variability (HRV) is one holistic measure obtainable from wearable technology
- HRV effectively measures holistic stress response
- Practically integrated in tactical settings where other stress biosignals may not be feasibly acquired[1]

Methods

- The SC was a 32-hour continuous battery of physical, occupational, and teamwork/leadership assessment tasks
- The study volunteer wore a supplied EQ02+ LifeMonitor (Equivital™, Cambridge, UK) device, collecting a 2-lead ECG over 25 hours
- HRV data were reported as the summary of 298 consecutive short-term (five minute) measurements, illustrating changes with maximal resolution while maintaining measurement fidelity[2]
- HRV fluctuations were aligned with key SC events to profile HRV response in a novel population and setting

Purpose

- This case study aimed to profile HRV of a PTG SC assessor
- Heart Rate, pRR15 (percentage of R-R intervals varying by ≥15 ms), nonlinear SD1 (Poincare plot x-axis), SD2 (Poincare plot y-axis), and SD2:SD1 (geometric HRV ratio) were obtained

Results

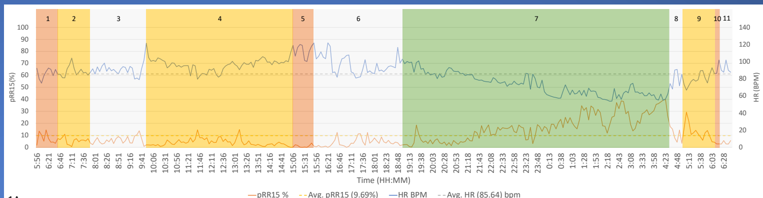
- Figure 1 (A and B) displays the finalized time-series visualisation, and Table 1 describes the overall descriptive statistics of the data collection period
  - Table 2 provides comparisons of key values before, during, and after the off-duty period
- These data are the first known reported of their kind
- HRV values were consistent with depressed dynamic adaptive response during on-duty hours
  - While the assessor was responsible for coordinating safety and evaluating candidates during a land navigation exercise, HRV was limited (SD1 = 16.68 ms, SD2 = 124.7 ms) (Regions 2 – 5)
- Some recovery was noted during a rest period (SD1 = 30.36 ms, SD2 = 130.2 ms) (Region 7)
  - Recovery was possibly incomplete; values rapidly returned to depressed levels once the assessor resumed working (SD1 = 28.5ms SD2 = 157.7ms) (Region 8)
  - Nonetheless, HRV values were generally improved during the second shift period (Regions 8 – 11) (Table 2)
  - SD2 continued to rise throughout the entire duration or recording (orange trendline in Figure 1B)

Table 1. Descriptive Values of HR and HRV

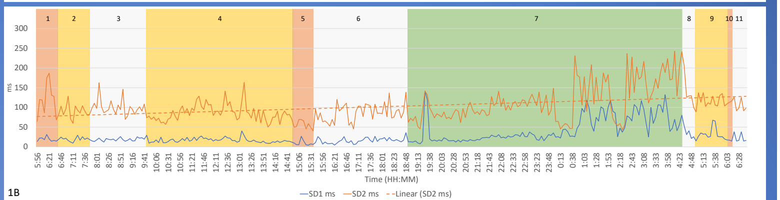
	Mean	Median	SD	Max	Min
Heart Rate (bpm)	85.64	87.45	15.11	122	54
pRR15 (%)	9.69	5.96	9.39	39.85	0
SD1 (ms)	29.02	19.85	25.70	141.10	4.33
SD2 (ms)	102.50	94.41	39.44	242.63	40.23

Table 2. Comparison of HR and HRV Values by Duty Status

	Shift 1 (13:00)	Off-Duty (9:35)	Shift 2 (1:20)
Heart Rate (bpm)	95.12± 9.78	73.53± 13.04	82.55± 9.96
pRR15 (%)	4.49± 3.37	16.61± 10.84	10.22± 7.19
SD1 (ms)	16.82± 6.23	45.12± 33.74	30.84± 17.15
SD2 (ms)	89.07± 24.96	116.05± 49.45	121.66± 32.63



1A



1B

Figure 1A. Time Series Plot of DS HRV Values
Figure 1B. Nonlinear HRV Time Series Plot of DS HRV Values
Legend: 1. Physical fitness assessment briefing and supervision 2. Briefing presentation and oral instruction 3. Written examination delivery and supervision 4. Land navigation supervision 5. Transit and administrative organization 6. Pack march supervision (stationary) 7. Off duty 8. Written examination delivery and supervision 9. Candidate rest period supervision 10. Less-lethal device deployment 11. Physical training supervision

Conclusions

- HRV monitoring in PTG personnel, including instructors, may be viable as a screening tool for overstress[3]
  - Nonlinear HRV may be particularly valuable[5]
- HRV more sensitive to change in activity and accumulated load than HR
  - Values at rest consistent with light, but not deep sleep[4]
- These principles may transfer to other high stress occupations

Military Impact

- HRV monitoring may more effectively assess for overstress than HR in high-intensity occupations, such as military and specialist police personnel who must contend with:
  - Rotating shift schedules, sleep and food deprivation, and high physical exertion
- HRV may provide more precise information to human performance support teams

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16. Appendix 4 — Supplementary Material: Chapter 5

Presented below are histograms visualizing the distribution of each participant's HRV values for each 5min HRV analysis (153 in total).

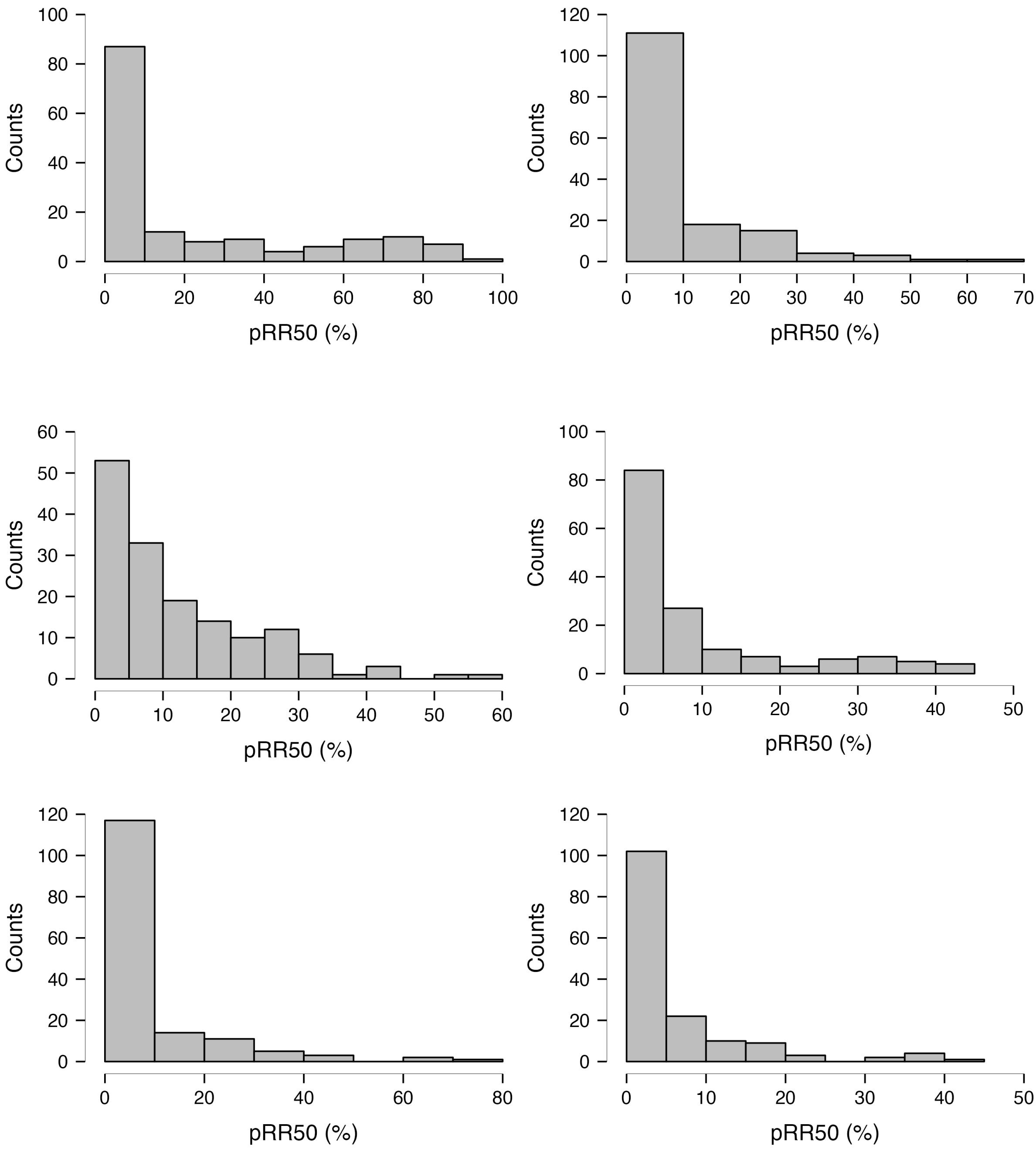

Figure 22. Histogram plots of each participant's pRR50 values for each 5 min HRV analysis.

The one who seeks finds; and to the one who knocks, the door will be opened.

Matthew 7:8