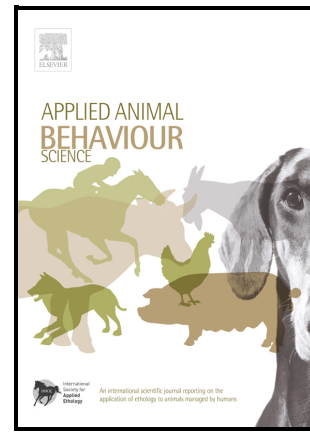


A pilot study on real-time monitoring of canine responses to exercise

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PII: S0168-1591(26)00196-6

DOI: <https://doi.org/10.1016/j.applanim.2026.107105>

Reference: APPLAN107105

To appear in: *Applied Animal Behaviour Science*

Received date: 13 February 2026

Revised date: 10 June 2026

Accepted date: 13 June 2026

Please cite this article as: Paul Damien McGreevy, Melissa J. Starling, Paul P. Breen, Carolyn Broderick, Cameron A. Clark, Barry Flower, Clara Grazian, Titus Jayarathna, Ollie Jay, Philip Leong, Sabrina Lomax and Scott A. Sisson, A pilot study on real-time monitoring of canine responses to exercise, *Applied Animal Behaviour Science*, (2026)
doi:<https://doi.org/10.1016/j.applanim.2026.107105>

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A pilot study on real-time monitoring of canine responses to exercise

Corresponding author : Paul Damien McGreevy

University of Sydney, Sydney, NSW AUSTRALIA

Corresponding author email : paul.mcgreevy@sydney.edu.au

Melissa J. Starling : The University of Sydney

mjstarling@hotmail.com

Paul P. Breen : University of Western Sydney

P.Breen@westernsydney.edu.au

Carolyn Broderick : University of New South Wales

c.broderick@unsw.edu.au

Cameron A. Clark : Charles Sturt University

camclark@csu.edu.au

Barry Flower : The University of Sydney

barry.flower@sydney.edu.au

Clara Grazian :

The University of Sydney

clara.grazian@sydney.edu.au

Titus Jayarathna : University of Western Sydney
t.jayarathna@westernsydney.edu.au

Ollie Jay : The University of Sydney
ollie.jay@sydney.edu.au

Philip Leong : The University of Sydney
philip.leong@sydney.edu.au

Sabrina Lomax : The University of Sydney
sabrina.lomax@sydney.edu.au

Scott A. Sisson : University of New South Wales
scott.sisson@unsw.edu.au

Abstract

A pilot study was conducted to explore the viability of using biosensors in the field to monitor the physiology and behaviour of dogs during exercise. Seven dogs, consisting of 3 working Australian Kelpies and four companion dogs of similar size and shape, (aged 1-10 years, weight 15-22 kg) were enrolled in exercise trials. Four dogs took part in both steady-state cantering and intense incremental exercise, two dogs took part in only steady-state cantering, and one dog did not complete steady-state cantering and did not participate in intense incremental exercise. We trialed a biosensor array embedded into a commercial dog harness to measure heart rate, respiration rate, and surface temperature

along with implanted data loggers (EmbediVet) to measure heart rate, temperature and motion, and ingested thermistor pills (BodyCap) to measure core body temperature. Hidden Markov models were used to organise the data into statistically distinct states of exertion. The data from all sources reliably produced a five-state solution (Akaike Information Criterion and Bayesian Information Criterion comparison of 2-7 state models), providing strong evidence that there are a stable number of states of exertion in dogs that can be identified from physiological data but not from observable behaviour such as gait, lagging, or seeking shade alone. Core body temperature peaked at 40.5°C during exercise, with heart rate strongly correlated with exercise intensity ($r = 0.87$, $P < 0.001$). Harness-embedded temperature sensors showed strong correlations with implantable sensors ($r > 0.90$) and thermistor pills ($r > 0.85$). Critically, physiological state transitions frequently occurred before observable behavioural changes, suggesting that handlers relying solely on behavioural cues, such as excessive panting, may miss early indicators of physiological stress. The harness biosensors, particularly the respiratory band, represent a viable, long-term monitoring system that can be fitted into harnesses that military working dogs currently wear, although ECG sensors required periodic gel application and EmbediVet implants showed limited feasibility due to battery life and migration risk.

Keywords: biosensors, canine, exercise, heart rate, thermoregulation, working dogs

1. Introduction

Working dogs are used across the globe in a variety of tasks. Many of those tasks, such as search and rescue, police and military operations, and scent detection, often involve dogs

working at high intensity for extended periods, sometimes over several days (Early et al., 2016). Dogs may be required to carry out this work in environmental conditions that challenge canine abilities to maintain an optimal core body temperature. Military working dogs (MWDs) face particular challenges, with heat-related injuries and trauma being leading causes of morbidity and mortality during deployment (Miller et al., 2018). In the case of MWDs, handlers bear the responsibility of regulating their dogs' work and rest periods to avoid overheating.

MWDs are highly motivated and tend to be inattentive to conditions that may impair performance or threaten wellbeing (e.g., pain, exhaustion). As such, they may be entirely reliant on handlers to enforce rest periods. However, monitoring MWDs' thermoregulatory state is currently achieved through behavioural observations alone, such as seeking shade, refusing to return to handler after a retrieve, excessive panting, flattened tongue, squinting eyes, ears back, and retracted lip commissures (see Otto et al. 2021).

Heat stress is a poorly defined term in the literature, so here we use the definition recently proposed by Hall et al. (2020) of mild heat stress, which is characterised by heavy, continuous panting that does not resolve when exercise ceases or the dog is moved to a cooler environment, and may also include lethargy, stiffness, or an unwillingness to move. Some of these signs of heat gain overlap with those of general high arousal (e.g. heavy panting). The challenge for MWD handlers is to distinguish between such causes and, if possible, to plan their dogs' work and rest periods such that their performance is optimal and they are protected from heat or fatigue-related injuries. The pathophysiology of canine heatstroke, including the systemic inflammatory cascade, haemostatic

derangements, and multi-organ dysfunction that can follow undetected heat stress, has been comprehensively reviewed by Bruchim et al. (2017), underscoring the clinical urgency of early detection.

The welfare of working dogs has received increasing attention, with recognition that handler decision-making plays a crucial role in maintaining both performance and wellbeing (Rooney et al., 2009). Studies examining causes for discharge from service have shown that musculoskeletal injuries, behavioural issues, and health problems account for substantial losses of trained dogs (Evans et al., 2007), representing significant financial and operational costs. Handlers typically rely on observable behaviours such as panting rate, gait abnormalities, reluctance to work, and changes in attentiveness to make decisions about when dogs need rest (Haverbeke et al., 2008). However, these behavioural indicators may not become apparent until physiological stress is already significant, potentially compromising both welfare and performance. Optimising handler decision-making through improved monitoring technology could help reduce these losses while protecting animal welfare.

Recent studies on MWDs have developed algorithms for calculating work and rest periods based on the type of work and current environmental conditions (O'Brien et al., 2020). The current pilot study goes one step further by building predictive models on data collected from individual dogs in real-time. Such data could provide handlers with early warning of fatigue and heavy exertion as well as more information to assist in decision-making around dog deployment.

2. Materials and Methods

2.1. Animals

Seven privately owned working kelpies (3 males and 4 females, aged 1-10 years, weight 15-22 kg) were recruited from one of the University of Sydney's farms and from friends of the researchers via word of mouth. Three of the dogs (2 females and 1 male all under 4 years) were working stock dogs housed in kennels. The remaining four dogs (2 males and 2 females, 3 under 5 years and 1 aged 10 years) were companion animals housed with access to a yard and the house. All dogs were cared for by their owners and in good health (no known medical conditions or physical barriers to completing the exercise trials). From this pool of 7 candidate dogs, 6 dogs (3 working dogs, 3 companion dogs) ultimately completed exercise trials and were included in the final analysis.

<Insert table 1>

2.2. Biosensors

The three working kelpies were surgically implanted with EmbediVet sensory devices (Livestock Labs, Eveleigh, Australia), which were inserted subcutaneously under general anaesthetic between the dorsal aspects of the scapulae. The EmbediVet implants were designed to collect accelerometer data, heart rate, and body temperature. They measured 50×25×6 mm and weighed 6.5g. The dogs who received implants were given a 10-day rest period to allow for the surgical wound to heal. The EmbediVet devices communicated with via a smartphone app, which could put them in low power usage mode or high sampling rate mode. The high sampling rate mode was used for exercise

trials. However, heart rate data from the EmbediVet implants ultimately proved unusable and these data were excluded from the final physiological state analysis (see Section 3.4).

All dogs participating in exercise trials were given a BodyCap eCelsius Performance ingestible thermistor capsule (P022, BodyCap Medical, Hérouville Saint-Clair, France) 15-30 minutes before the exercise trials began to monitor core body temperature, as previously described in dogs (Angle and Gillette, 2011; Osinchuk et al., 2014). Dosing was achieved by a researcher either placing the pill in the back of the dog's mouth or burying the pill in a small amount of peanut butter and allowing the dog to ingest pill and peanut butter together. These pills are 17.7 mm long, approved by the US Federal Communications Commission (FCC), carry the European Conformite Europeenne (CE) mark, and have a 20-day battery life. Their sampling period was set to 30 s. A data logger was placed beside the dogs periodically to download stored data.

2.3. Harness and sensor array

The externally worn dog harness was required to synchronously capture respiratory pattern, heart rate, temperature and activity level of the dog. Data recorded from the harness consisted of four variables: temperature at the top of the harness, temperature at the bottom of the harness, ECG and accelerometer readings. ECG and respiratory band data were sampled at a rate of 100 Hz, while body temperature was sampled at a rate of 1.07 Hz.

Respiration was measured using a custom conductive fabric-based stretch sensor that changes resistance as a function of stretch length. The stretch sensor was wrapped around the thoracic area of the dog, and as breathing and panting change the volume within the

band, the output reflects breathing pattern directly. The fabric sensor (Stretch conductive fabric 4900, Holland Shielding) was configured in a U-shaped pattern allowing two layers of conductive fabric to be placed in parallel, increasing the initial resistance of the sensor.

Heart rate was measured using electrocardiogram (ECG) with spring-loaded dry electrodes positioned on the dog's body. ECG electrodes were designed to penetrate dog haircoat and could be wetted with conductive gel to increase conductivity. The ECG measurement system consisted of a MAX30003 (Maxim Integrated) single lead ECG sensor. Three electrodes were positioned to capture the ECG waveform, with the signal-to-noise ratio being highly dependent on the use of ECG gel requiring periodic application.

The harness electronics, including the ECG and respiratory band systems, have been validated in prior laboratory and clinical settings (Jayarathna et al., 2019; Breen et al., 2022). The ECG component produces reliable readings when a clean signal is obtained, consistent with its broad application across biomedical research contexts. Respiratory band data were analysed only from periods when dogs were stationary or moving at low speed, thereby minimising locomotion artefact. As an additional internal consistency check, the tri-axial accelerometer captured whole-body movement, enabling separation of respiratory signal from movement-related noise when compared with the local thoracic movement recorded by the respiratory band.

Surface temperature measurements were taken by digital temperature Integrated Circuits (MAX30205, Maxim Integrated) with an accuracy of $\pm 0.1^{\circ}\text{C}$. The harness included two

temperature sensors, one placed against the dog's ventrum and one over the dorsum. A metal cylinder was placed under the IC to boost thermal conductivity from the skin to the sensor. A tri-axial accelerometer (LIS2DH, ST) was also integrated to record movement data.

Table 2 shows the sensors and ICs used in the harness (see Table 2). A custom printed circuit board (PCB) was developed to support data acquisition, storing and wireless transmission. All sensors, devices and wiring loom were embedded into a single tactical dog harness (Auroth Tactical Dog Training Harness, small) for maximal comfort, flexibility and portability. The data recording unit was manufactured with a 1mm thick PCB, powered by a 600 mAh battery, allowing 28 hours of continuous data recording. The firmware uses a Texas Instruments Bluetooth Low Energy 4.2 software stack. A custom Android mobile application was developed to display live, raw data including respiratory waveform, ECG waveform, heart rate, heart rate variability, tri-axial accelerometer readings, and temperature readings from both temperature sensors (see Figure 1).

<Insert Table 2 here>

<Insert Figure 1 here >

2.4. Exercise trials

Steady exercise trials. Start time for exercise trials was used to synchronise biosensor logs. Steady exercise trials comprised four active periods separated by rest periods of 1-

hour duration. 15-30 minutes before beginning exercise trials, dogs were fitted with harnesses, swallowed BodyCap pills, and had their EmbediVet implants changed to high sampling rate mode. Exercise trials began with a warm-up period of up to 5 minutes where dogs were encouraged to walk and trot at a slow pace alongside a bicycle or utility terrain vehicle (UTV). As the exercise trials commenced, the bicycle or UTV increased speed until the dogs were maintaining a slow canter, usually at approximately 12 km/h. The four active periods used in the exercise trial were as follows: (A) 5-minute canter; (B) 5-minute canter + 10-minute rest + 5-minute canter; (C) 10-minute canter; (D) 10-minute canter + 10-minute rest + 10-minute canter. Dogs participated in all four active periods throughout the trial, but the order varied and was decided upon by the dog's handler or the researchers, chiefly to maximise the dogs' compliance with cues. Dogs were allowed access to water during the 10-minute rest breaks, and were tethered in the shade for the 1-hour rest periods between active periods, during which they had access to cool drinking water at all times.

Dogs following bicycles (companion dogs) were off-leash with their owner riding alongside. Dogs following the UTV (working dogs) had a long (approximately 15m) lead attached to their collar with an experimenter on the UTV dedicated to applying gentle intermittent traction from the lead as required and minimising any risk of the lead becoming a trip hazard. Dogs were never pulled by the leash. The trial was ended when the dog showed reluctance to continue, either in the form of lagging well behind the UTV or bicycle, being difficult to coax into following, or seeking shade. All working stock dogs that started steady-state exercise trials were able to complete all four activity

periods. Three of the four companion dogs completed all activities; one companion dog (Toby) became reluctant to continue on the third activity.

Intense incremental exercise trials. The data from the first two dogs to participate in steady exercise trials showed minor elevations in body temperature that did not reflect the higher core body temperatures reported in the literature for exercising dogs. An intense, incremental exercise trial was therefore introduced and approved by the University of Sydney Animal Ethics committee to be completed at the end of the steady exercise trial after the final rest period. Dogs were encouraged to participate in a high intensity activity they were familiar with (chasing a ball for companion dogs, running with the UTV for working stock dogs). The intensity of the exercise was gradually increased by increasing the length of sequential exercise bouts with 1-minute increments, starting at 6-minutes. Dogs were given 1-minute rest periods between increments to allow them to drink and to allow the biosensors to record clean data. Incremental exercise trials were ended when the dog lagged well behind the UTV or no longer brought the ball directly back to the owner. At the completion of the incremental exercise trial, dogs were given access to shade and water and the biosensors continued to collect data for another 30-minutes while the dogs rested. Two working kelpies and two companion kelpies participated in this trial. One companion dogs did not participate because the trials were ended prematurely due to their reluctance to continue.

Behaviour observations were recorded during exercise trials and rest periods using an ethogram (see Table 2). These included behaviours that may indicate a dog is tiring or needs to cool, as well as behaviours that may indicate the dog is in heat stress, such as: lags behind vehicle, drinks water, trots instead of canters, seeks shade, digs in soil, and

persistent panting. This study was approved by the University of Sydney Animal Ethics committee and included criteria for ending the study if a dog started limping, was unable to close its mouth, showed signs of lethargy, vomiting, or unsteadiness, or refused to continue. A dog showing signs of heat stress would be aggressively cooled and then veterinary attention sought, but this was unlikely to occur because experiment end-points aimed to cease exercise trials before heat stress. In the event, exercise trials were ceased due to two dogs' reluctance to continue, a monitoring procedure of temperature and behaviour was implemented to ensure body temperature was in a safe range and falling with rest.

Environmental conditions were recorded before beginning each active period and 30-minutes into the rest periods using either a TSI QUESTemp 34 Heat Stress Meter or a Kestrel 5400 series. Readings included wet bulb temperature, dry bulb temperature, black globe temperature, humidity, and heat index, as appropriate to the device used.

2.5. Data analysis

Hidden Markov models (HMM) were implemented to identify latent states of the dog from the time series data. The main assumption of the HMMs is that, at any point, the observations are distributed as a mixture of k components (or states), and that the time-dependence of the observations is due to the time-dependence between the mixture components. These models permit estimation of the transition probabilities between components from one time point to the next. These transition probabilities were assumed to follow a first-order Markov process. Gaussian components were assumed for the response variables and a multinomial distribution for the states.

Models were fitted and estimated separately for data recorded with the BodyCap thermistor pill and the harness. The Hidden Markov model for data recorded with the BodyCap thermistor pill was implemented for the time series of temperature, while the hidden Markov model for data recorded with the harness was implemented on the four-dimensional time series of temperature recorded at the ventrum of the dog, at the dorsum of the dog, the ECG, and the respiratory band. The ECG and respiratory time series were filtered to remove high frequency noise and respiration bias from the signal. Parameter estimation was performed using the expectation-maximisation (EM) algorithm. Models with 2 to 7 components were fitted and compared through Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Statistical analyses were performed using appropriate parametric and non-parametric tests as warranted by the data distribution. Significance was set at $P < 0.05$.

2.6. Ethics committee approval

All procedures were approved by the University of Sydney Animal Ethics Committee (approval number 2020/1807) and complied with the International Guiding Principles for Biomedical Research Involving Animals and the ethical guidelines published by the International Society for Applied Ethology.

3. Results

3.1. Physiological responses to exercise

Body temperature increased significantly during exercise trials ($P < 0.001$), with peak temperatures reaching 40.5°C. Core body temperature as measured by thermistor pills showed a steady rise during exercise periods followed by either a plateau or a decline

during rest periods. Dogs with body temperatures over 40°C showed heavy panting but recovered quickly with rest and access to drinking water. Temperature readings from thermistor pills dropped by up to 2°C immediately after dogs drank cool water in the first few hours of the experiment, with this effect lasting approximately 3 minutes and weakening as time progressed. Heart rate showed a strong positive correlation with exercise intensity (steady state vs intense) ($r = 0.87$, $P < 0.001$). Respiratory rate increased during both steady-state and interval exercise, with changes occurring dynamically in response to exercise intensity and body temperature. Respiratory rate readings were disrupted by heavy locomotion, such as cantering, but provided clean data during rest periods and light locomotion, such as walking.

3.2. Hidden Markov model analysis

The Hidden Markov model analysis consistently identified five distinct physiological states across all dogs and data sources. Models with 2 to 7 components were fitted and compared using AIC and BIC, with the five-state solution providing the best fit across all data sources (see Figure 2). These five states represented different levels of physical exertion and thermoregulatory demand, though the specific physiological characteristics of each state varied somewhat between individual dogs and trials. Data from respiration, ECG, surface temperatures, and core body temperature all produced models with comparable states. Based on temporal correspondence with exercise protocols and associated physiological parameters, we interpreted these states as representing: rest; steady and sustainable exercise at low and moderate intensities; transitions between states; and a state associated with strenuous exercise that is not sustainable for long periods. The five-state solution provided the best fit to the data based on AIC

comparison. The estimated Gaussian emission parameters for each state and sensor channel are presented in Table 2. The estimated transition probability matrix is presented in Table 3 (see Section 3.3).

<Insert Figure 2 here >

<Insert Tables 3 and 4 here>

3.3. State transitions

Dogs transitioned between states in predictable patterns related to exercise intensity and duration. Transitions from low to high exertion states occurred more rapidly than transitions in the reverse direction, consistent with differences in physiological response and recovery kinetics. The models permit estimation of transition probabilities between states from one time point to the next. These transition probabilities showed consistency across individual dogs, suggesting that the identified states represent robust physiological phenomena rather than individual variation. Transition patterns were influenced by exercise intensity, ambient temperature, and individual dog characteristics such as fitness level (see Figure 3). There is no guarantee that the 5-state solution proposed by the model identifies the same 5 states in each dog, so characterising states requires further data collection from a larger number of dogs.

<Insert Figure 3 here >

3.4. Biosensor performance

The harness-embedded temperature sensors (see Table 5) showed strong correlation with EmbediVet implant temperature readings ($r > 0.90$) and BodyCap thermistor pills ($r > 0.85$). The harness system successfully recorded data throughout extended exercise sessions without technical failures. However, the respiratory data and, to a lesser degree, the ECG data, became too noisy to interpret when dogs moved at a canter or gallop. The signal-to-noise ratio of the ECG sensors was highly dependent on the use of ECG gel, requiring periodic re-application of conductive gel to provide ongoing quality data. The stretch sensor for respiratory monitoring functioned with maximum signal-to-noise ratio when the harness was fitted snugly. Surface temperature sensors did not always correlate with core body temperature. Notably, the ventral surface temperature varied considerably and tended to drop during exercise, suggesting a cooling effect from air flow under the harness at higher speeds.

<Insert Table 5 here>

The EmbediVet implants had significant technical limitations. Heart rate data from the implants were unusable, and temperature data may have been influenced by sunlight exposure. Additionally, there was a significant risk of migrating units, and the batteries lasted less than 12 months. The implants required a mobile phone handset in close proximity (<2m) to the dog to stream real-time data. BodyCap thermistor pills were reliable but were eliminated by the dog within a few days and uploaded data only to a proprietary data reader.

Importantly, physiological state transitions detected by the biosensor system frequently occurred before observable changes in behaviour, suggesting that handlers relying solely on behavioural cues may miss early indicators of physiological stress.

3.5. Behavioral observations during exercise trials

A total of 77 discrete behavioural events were systematically recorded across all exercise trials with the six Australian kelpies (Bobby, Frankie, Mallee, Ruby, Tess, and Toby (whose data represents the periods completed prior to trial cessation)). Behavioural observations were conducted opportunistically during trials, with researchers noting behaviors from the 14-item ethogram (Table 5) as they occurred.

<Insert Table 5 here>

The most frequently observed behaviors were drinking water (n=27, 35% of all observations), lagging more than 10 metres behind the vehicle/bicycle (n=18, 23%), and transitioning from canter to trot gait (n=14, 18%). Table 6 presents the comprehensive frequency distribution of all observed behaviors organized by behavioral category.

<Insert Table 6 here>

All working stock dogs (n=3) successfully completed all four steady-state exercise periods. Three of the four companion dogs completed all activities; one companion dog (Toby) became reluctant to continue during the third activity period despite body temperatures remaining below 40°C. This behavioural reluctance in the absence of elevated body temperature readings demonstrated a notable disconnect between objective physiological measurements and subjective apparent behavioural willingness to continue

exercise. These dogs could not be coaxed by their owners to continue cantering alongside the bicycle, necessitating early termination of steady-state trials for these individuals.

During intense incremental exercise trials conducted at the conclusion of steady-state protocols, behavioral indicators of fatigue emerged rapidly. Two farm dogs undergoing incremental exercise alongside the UTV (mean speed approximately 25 km/h) both exhibited lagging behaviour by the end of the first 6-minute increment. One dog additionally transitioned from canter to trot gait, indicating reduced capacity to maintain the requested pace. Both incremental tests were terminated after 6 minutes based on these behavioural criteria. Two companion dogs completed incremental exercise through ball-chasing activity, successfully completing 8 minutes of active exercise across three increments (6, 7, and 8 minutes respectively, with 20 minutes total duration including rest periods).

Marked individual variation was observed in behavioural responses to exercise stress. Bobby exhibited the highest frequency of lagging behavior (n=7 instances), all occurring during active exercise periods. Ruby displayed the highest overall number of behavioural observations (n=24), including frequent stopping behaviors of varying durations (15-60 seconds, n=7 total) that were not observed in any other dog. Toby showed the highest frequency of trot transitions (n=5), suggesting a preference or necessity for pace reduction during sustained exercise. Table 7 presents individual behavioural profiles for each dog, demonstrating considerable inter-individual variability in behavioural responses.

<Insert Table 7 here>

Behavioral observations demonstrated clear temporal and contextual patterns. Drinking behavior occurred almost exclusively during designated rest periods (24 of 27 observations, 89%), with only 3 instances of drinking recorded during active exercise. All observed lagging behaviours (n=18) occurred during active exercise periods, with zero instances recorded during rest. Thermoregulatory behaviours including water immersion (n=3) and shade-seeking (n=2) were observed exclusively during or immediately following the most intense exercise periods (incremental tests and later steady-state trials), suggesting these behaviours emerge only under significant thermal challenge.

All exercise trials (n=6 dogs across multiple trial sessions) were terminated based on behavioural criteria rather than reaching predetermined physiological thresholds. The primary behavioural indicators leading to trial termination were lagging well behind the vehicle/bicycle, difficulty coaxing dogs to continue despite encouragement, shade-seeking behavior, or sustained gait transitions to slower paces. Critically, in cases where dogs exhibited behavioural signs of fatigue or reluctance (n=4 dogs across steady-state and incremental trials), these behavioural changes occurred when dogs had already transitioned to higher physiological states as identified by Hidden Markov Model analysis. While systematic temporal analysis was not conducted, researchers consistently noted instances where physiological state transitions detected by biosensor arrays preceded observable behavioral changes by several minutes. This temporal lag supports the hypothesis that exclusive reliance on behavioral indicators may result in delayed recognition of physiological stress, potentially allowing dogs to enter higher-risk thermal states before intervention.

4. Discussion

This study has delivered an important proof-of-concept. To the authors' knowledge, it is the first report of ECG, respiratory rate, and core body temperature having been measured in dogs during naturalistic exercise in the open as distinct from on treadmills in a controlled environment. It also reports the first use of Hidden Markov models to identify states of physiological activity in dogs exercising at various intensities and at rest.

This pilot study demonstrates that real-time biosensor monitoring of working dogs during exercise is feasible and can provide valuable physiological information beyond what is available through behavioural observation alone. The identification of five distinct physiological states suggests that dogs' responses to exercise are more nuanced than previously recognised, and cannot be accurately assessed through visual observation of behavior alone. This finding has significant implications for canine performance science, because it demonstrates the limitations of relying exclusively on behavioural indicators for assessing welfare and performance in working dogs. While handlers are skilled at recognising late signs of heat stress or early heat injury such as excessive panting, reduced responsiveness, or reluctance to work, our data suggest that physiological state changes precede these observable behavioural changes. This temporal disconnect between physiological and behavioural indicators means that by the time a handler observes behavioural signs of fatigue or heat stress, the dog may already be undergoing significant allostatic load. This finding has important implications for working dog welfare, as handlers currently rely solely on behavioral cues to make decisions about work and rest periods (Haverbeke et al., 2008).

The harness-embedded sensors performed comparably to more invasive monitoring methods, suggesting they could be suitable for long-term field deployment with working dogs. This is particularly important for military and police working dogs, where handlers need to make real-time decisions about deployment and rest periods to optimise performance while protecting animal welfare. Given that musculoskeletal injuries and health problems are leading causes of early retirement from service (Worth et al., 2013; Discepolo et al., 2025), technologies that enable early detection of physiological stress could help extend working dogs' service lives and improve welfare outcomes beyond detecting early signs of heat stress.

From a behavioural perspective, the ability to objectively quantify physiological states addresses a longstanding challenge in working dog management: the subjective nature of behavioural assessment. Different handlers may interpret the same behavioural cues differently, leading to inconsistent decisions about when dogs require rest or veterinary attention. The biosensor approach provides standardised, objective data that can complement handlers' behavioural observations, potentially improving inter-handler reliability in welfare assessments. Furthermore, the technology could be used as a training tool to help handlers calibrate their behavioural observations against objective physiological data, improving their ability to recognise subtle early warning signs. This integration of objective physiological monitoring with traditional behavioural assessment represents a significant advance in canine performance science, combining the strengths of both approaches while mitigating their individual limitations.

An important methodological consideration is that while the HMM consistently identified five distinct physiological states, the interpretation of what each state represents (e.g., rest

vs. low-intensity exercise) is based on temporal correspondence with exercise protocols and associated physiological parameter values rather than being an inherent output of the model. As more data are collected across diverse dogs, exercise contexts, and environmental conditions, pattern recognition across datasets will enable more confident and standardized interpretation of these states. Future research should focus on establishing consensus definitions for each state based on accumulated evidence, potentially leading to a standardized classification system for canine exertional states.

The ability to identify distinct physiological states in real-time could also have applications beyond heat stress monitoring. Military working dogs face elevated risks of trauma during deployment (Edwards et al., 2021), and early detection of physiological changes associated with injury or illness could improve treatment outcomes. The Hidden Markov model approach proved effective at identifying distinct physiological states from the continuous sensor data, and this analytical framework could be integrated into a real-time monitoring system to provide handlers with actionable information about their dogs' physiological status.

Feasibility considerations

The feasibility of the current prototype system should be considered in light of its validity, practicality, and cost-benefit analysis. The respiratory band can be incorporated easily into any harness and doesn't require special treatment. Our data suggest the respiratory data and ECG data are comparable in identifying physiological states. As such, it would be feasible to use the respiration band alone and forego the ECG, eliminating the need for periodic ECG gel application. Surface temperature offers a

potential alternative to core body temperature monitoring, but it is currently unclear how this should be interpreted. Our evidence suggests that a dog's neck and shoulders increase more in temperature during exercise than other parts of the body, and further investigation into optimal sensor placement may provide another indicative measurement that can be easily obtained. Accelerometers could potentially detect early signs of lameness such as changes in stride length or force on one or more limbs, offering an additional safety net for over-working MWDs beyond the risk of heat stress.

Important limitations should be noted regarding behavioural data collection. Panting behaviour, while observed throughout exercise in all dogs with apparent increases in intensity corresponding to exercise duration, was not systematically quantified.

Behavioural observations were recorded opportunistically rather than at predetermined time intervals, resulting in potential under-reporting of behaviours that occurred between observation points. No inter-observer reliability testing was conducted, and video recording was not employed to enable post-hoc behavioural coding. Despite these limitations, the recorded behavioural observations provide valuable preliminary evidence of the types, frequencies, and temporal patterns of behaviours exhibited by working-type dogs during controlled exercise trials under thermal challenge.

Further limitations of this pilot study include the small sample size ($n = 6$ dogs) and the use of controlled exercise trials rather than operational scenarios. The study used farm working dogs (Australian working kelpies) and pet kelpies rather than military or police working dogs, which may limit generalisability to those populations. Additionally, we did not systematically record detailed behavioural observations synchronised with physiological data collection, which would have allowed direct comparison of the timing

of behavioural versus physiological indicators of stress. Future research should validate these findings with larger sample sizes, multiple breeds commonly used in working roles, and test the system under actual working conditions. Importantly, future studies should include systematic ethogram-based behavioural observations recorded in parallel with biosensor data to directly quantify the temporal relationship between physiological and behavioural indicators of stress and fatigue. Such studies would provide valuable insights into which specific behaviours are most reliably associated with particular physiological states, potentially refining handler training protocols. Additionally, longitudinal studies would be valuable to determine whether the technology can predict onset of heat-related illness or other health problems before clinical signs become apparent, which would represent a significant advancement in working dog welfare (Rooney et al., 2009).

Future directions

Next steps include testing the current harness in MWDs across a range of normal training contexts to confirm that the models continue to produce consistent results. Design refinements should focus on optimising long-term viability, including streamlining sensors and waterproofing electronics. A smartphone application could feed data in real-time into the models and produce an easily interpretable output showing handlers at a glance what state the dog is currently in and the imminence of its departure to another state. Additional sensors could be incorporated, such as microphones to detect respiratory patterns and panting cycles, which may provide supplementary data when the respiratory band signal becomes noisy during high-speed movement. There is also potential for integrating respiratory detection with accelerometer data, as some quadrupeds breathe in

time with their gait, which could supplement respiratory band data during cantering or galloping.

Future studies should align with the recently published COMPASS guidelines (McGreevy et al 2026) for welfare-focused behaviour modification research, particularly regarding systematic ethogram-based behavioural observations with inter-observer reliability testing (correlation coefficients ≥ 0.80), establishment of individual baseline measurements for at least 15 minutes, and adoption of multi-modal assessment approaches that integrate physiological, behavioral, and functional indicators.

5. Conclusions

This study provides proof of concept that biosensor arrays embedded in working dog harnesses can effectively monitor physiological responses to exercise in real-time. The technology shows promise for helping handlers make informed decisions about work and rest periods for their dogs, potentially improving both performance and welfare outcomes for working dogs. By providing objective physiological data to complement behavioural observations, this technology addresses a critical gap in current working dog management practices and offers a valuable tool for canine performance science. The identification of five distinct physiological states using Hidden Markov models demonstrates that real-time monitoring can reveal nuances in dogs' exertional states that are not apparent from behavioural observation alone, opening new possibilities for optimizing working dog deployment and welfare.

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Figure and Table Captions

Table 1. Summary of dog participants

| Dog | Origin | Biosensors | Exercise trials |
|---------|---------------|--|--|
| Bobby | Working dog | Harness, thermistor pill, EmbediVet implant | Steady state |
| Tess | Working dog | Harness, thermistor pill, EmbediVet implant | Steady state |
| Abby | Working dog | Harness, thermistor pill, EmbediVet implant removed shortly after implantation due to migration. | Steady state + intense |
| Mallee | Companion dog | Harness, thermistor pill | Steady state + intense |
| Ruby | Companion dog | Harness, thermistor pill | Steady state + intense |
| Toby | Companion dog | Harness, thermistor pill | Did not complete (became reluctant during third steady-state period) |
| Frankie | Companion dog | Harness, thermistor pill | Steady state |

Table 2. Sensors and integrated circuits used in the harness-mounted biosensor array. The table shows sensor type, manufacturer specifications, and functional description for each component of the wearable monitoring system.

| Sensor/Part | Sensor name (vendor) | Description |
|--------------------|--|---|
| ECG sensor | MAX30003 (Maxim Integrated) | Captures single lead ECG waveform and R-R interval. HR and HRV can be calculated using either R-R interval or processing the ECG waveform |
| Respiratory sensor | Conductive fabric (Holland Shielding) and Analogue to digital converter IC ADS1247 (Texas instruments) | The sensor resistance is measured by supplying a constant current (250uA) and measuring the voltage across the sensor. |
| Temperature sensor | MAX30205 (Maxim integrated) | Medical grade digital temperature sensor with accuracy of +/- 0.1 °C. |
| Accelerometer | LIS2DH (ST) | 3-axis accelerometer data |
| Microcontroller | CC2640R2F (Texas instruments) | Performs data acquisition, Bluetooth data transmission and data storage to a microSD card |

| | | |
|--------------|-----------------------------|--|
| MicroSD card | 16 GB Class 10 (Sandisk) | Uses FAT32 filesystem compatible with PCs |
|--------------|-----------------------------|--|

Table 3. Estimated Gaussian emission parameters for the five-state Hidden Markov model fitted to the harness biosensor data. For each latent physiological state, the table reports the estimated mean and standard deviation of the Gaussian emission distributions for the four harness sensor channels: respiratory band, ECG, dorsal temperature sensor (TempTop), and ventral temperature sensor (TempBottom). Parameters are reported on the processed/scaled data scale used for model fitting.

| State | Channel | Mean | SD |
|-------|------------|------------|------------|
| 1 | Band | -0.0287814 | 0.21742652 |
| 1 | ECG | -0.0492741 | 1.42603093 |
| 1 | TempTop | -1.5263343 | 0.46230861 |
| 1 | TempBottom | 0.02446103 | 1.03541469 |
| 2 | Band | 0.00597603 | 0.20678481 |
| 2 | ECG | 0.01958716 | 1.08882092 |

| | | | |
|---|------------|------------|------------|
| 2 | TempTop | 1.0617276 | 0.5285697 |
| 2 | TempBottom | 0.92823985 | 0.69338474 |
| 3 | Band | -0.0047621 | 0.19538704 |
| 3 | ECG | 0.01761912 | 0.89357132 |
| 3 | TempTop | -0.2305704 | 0.40084903 |
| 3 | TempBottom | -1.1158723 | 0.58443677 |
| 4 | Band | 0.03681214 | 0.025657 |
| 4 | ECG | -0.0093603 | 0.10803505 |
| 4 | TempTop | 0.83143759 | 0.59810542 |
| 4 | TempBottom | 0.52955829 | 0.39245941 |
| 5 | Band | -0.0024772 | 0.24142862 |
| 5 | ECG | 0.02990289 | 1.14423539 |
| 5 | TempTop | 0.08773166 | 0.36734651 |
| 5 | TempBottom | 0.21110417 | 0.29115718 |

Table 4. Estimated transition probability matrix for the five-state Hidden Markov model fitted to the harness biosensor data. Rows correspond to the current latent

physiological state and columns correspond to the subsequent state. Each entry gives the estimated probability of transitioning from one state to another at the next time point under the fitted first-order Markov process.

| | To_State_1 | To_State_2 | To_State_3 | To_State_4 | To_State_5 |
|--------------|------------|------------|------------|------------|------------|
| From_State_1 | 0.9968 | 0 | 0.0024 | 0 | 8.00E-04 |
| From_State_2 | 2.00E-04 | 0.9808 | 2.00E-04 | 0.0178 | 0.001 |
| From_State_3 | 0.0012 | 0 | 0.9977 | 0 | 0.0011 |
| From_State_4 | 0 | 0.0263 | 3.00E-04 | 0.9674 | 0.0061 |
| From_State_5 | 0.0014 | 8.00E-04 | 4.00E-04 | 0.0054 | 0.992 |

Table 5. Ethogram of behaviours recorded during exercise trials and rest periods. Behaviours include indicators of fatigue, thermoregulatory stress, and recovery, with rationale for inclusion in the observation protocol.

| Behaviour | Description | Rationale |
|---------------------|--------------------------------------|----------------------------|
| Lags behind vehicle | More than 10m behind vehicle/bicycle | Suggests dog may be tiring |
| Drink water | Drinks water | Dog is hot or thirsty. |

| | | |
|-----------------------------|--|--|
| Trot | 2-beat gait with limbs moving in diagonal pairs | Dog is travelling slower than the canter aimed for. May be tiring. |
| Seeks shade | Moves from full or partial sun into shade, or from shade into deeper shade | Dog is seeking a cooler environment. |
| Digs in soil | Uses paws to scrape top layer of soil aside | Exposes cooler soil a dog may use to assist in lowering their body temperature through convection. |
| Immerses head in water | Puts head into water until the water reaches the skull above the eyes | Suggests dog is acting to reduce body temperature |
| Immerses paws/body in water | Puts paws in water so toes are entirely submerged, or lies down or sits in water (complete immersion was gently discouraged) | Suggests dog is acting to reduce body temperature |
| Runs ahead of vehicle | Travelling in front of the vehicle/bicycle | Speed may be too slow or dog is expelling more effort than desired. |

| | | |
|----------------------|--|--|
| Vomiting | Dog forcefully ejects contents of digestive tract via the mouth | Sign of heat stress |
| Will not leave shade | Several attempts to coax dog out of shade with voice and body language fail. | Suggests dog is too hot or tired to comfortably continue exercising. |
| Constant panting | Dog pants constantly with wide open mouth | Indicates dog's need to reduce body temperature is extreme |
| Limping | Gait is not even, as dog is not fully weight bearing on one or more limb. | Dog may be very tired, injured, or experiencing pain. |
| Unsteady on feet | Dog sways or stumbles while standing or walking | Sign of heat stress |
| Lethargy | Dog becomes reluctant to move, responding slowly to stimuli | Sign of heat stress |

Table 6. Frequency distribution of behavioural observations by category across all exercise trials (N=77 total observations from 6 dogs).

| Behaviour Category | Frequency (n) | Percentage (%) | Dogs Exhibiting (n=6) |
|---|--------------------------|---------------------------|----------------------------------|
| Drinking water | 27 | 35.1 | 6 |
| Lagging behind vehicle (>10m) | 18 | 23.4 | 4 |
| Transitioning to trot gait | 14 | 18.2 | 3 |
| Stopping (15-60 seconds) | 7 | 9.1 | 1 |
| Water immersion (paws/body) | 3 | 3.9 | 2 |
| Shade-seeking | 2 | 2.6 | 2 |
| Other behaviors | 6 | 7.8 | 4 |

Table 7. Individual behavioural profiles showing inter-dog variation in exercise responses (N=6).

| Dog | Total Observations | Primary Behaviours (frequency) | Notes |
|----------------|-------------------------------|---|-----------------------------|
| Bobby | 11 | Lag (7), Drink (4) | Highest lagging frequency |
| Frankie | 11 | Drink (3), Trot (2), Lag (2) | Moderate fatigue indicators |
| Mallee | 10 | Drink (5), Water immersion (2) | Active thermoregulation |

| | | | |
|-------------|----|---|-----------------------------------|
| Ruby | 24 | Drink (6), Stops (7), Trot (3), Lag (1) | Most observations; frequent stops |
| Tess | 5 | Lag (2), Drink (2) | Fewest observations |
| Toby | 16 | Drink (7), Trot (5) | Highest trot frequency |

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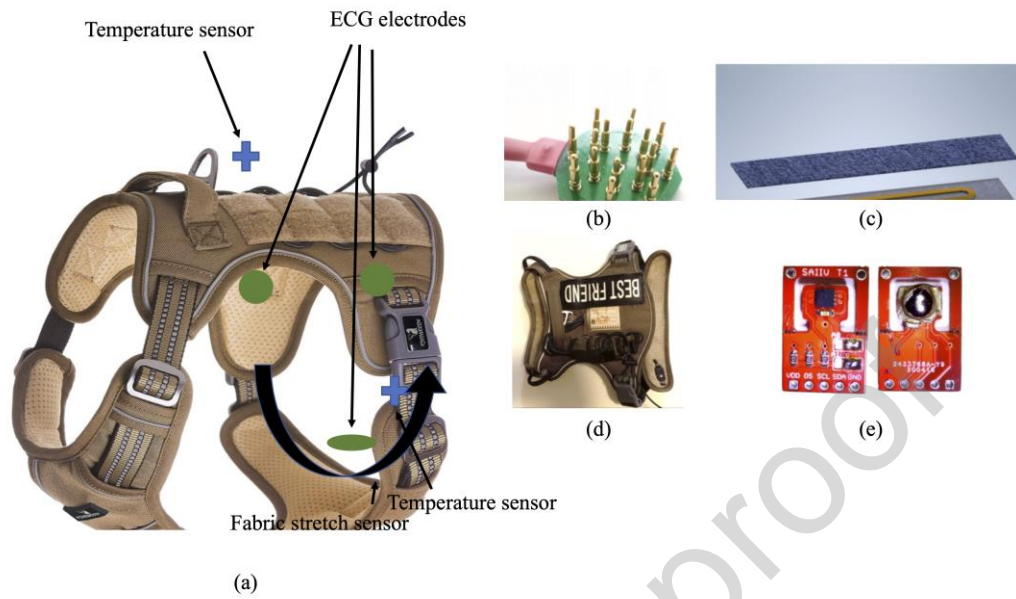


Figure 1. Harness-mounted biosensor system. (a) Dog harness showing placement of temperature sensors, ECG electrodes, and respiratory band. (b) Custom printed circuit board (PCB) showing top and bottom views with integrated battery. (c) Screenshot of mobile application displaying live physiological data including ECG waveform, respiratory pattern, heart rate, and temperature readings. (d) Working kelpie wearing the harness system during field trials. (e) Screenshot of mobile application displaying live physiological data including ECG waveform, respiratory pattern, heart rate, and temperature readings.

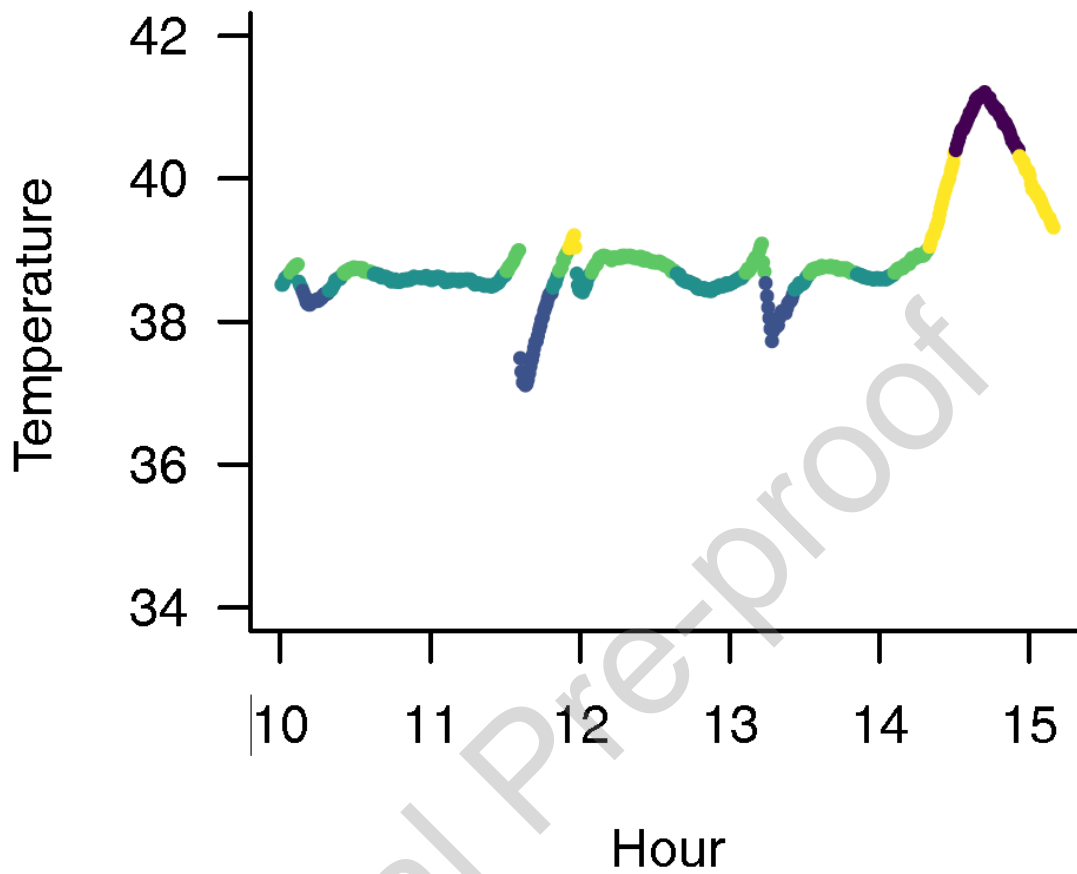


Figure 2. An example of the five statistically distinct states identified by the HMM for one dog using the data from the BodyCap thermistor pill to represent core body temperature. States are numbered 1-5; physiological interpretation of each state requires examination of temporal correspondence with exercise protocols and associated parameter values.

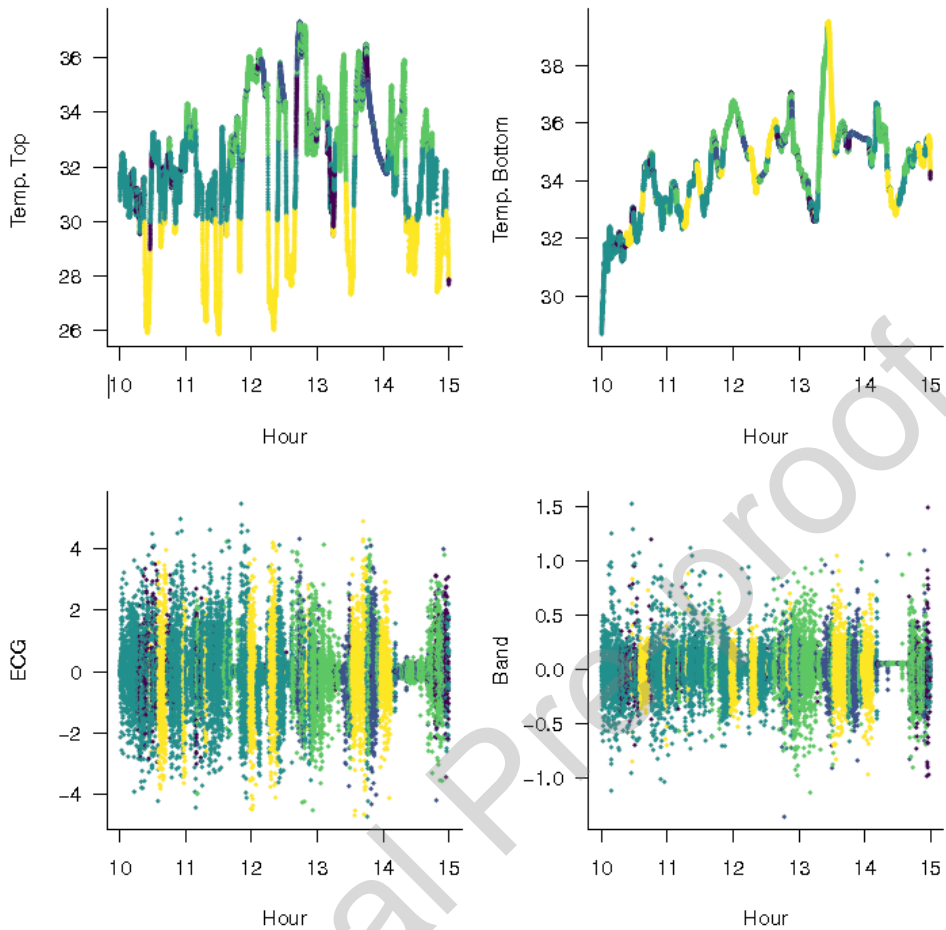


Figure 3. Representative Hidden Markov Model state transitions during exercise trial.

Time course showing transitions between five statistically distinct physiological states for one dog during steady exercise trial with rest periods. State labels (State 1: rest; State 2: low intensity exercise; State 3: moderate intensity exercise; State 4: transition/recovery; State 5: high intensity exercise) represent our interpretation based on temporal correspondence with exercise protocols and associated physiological values; these interpretations may vary between individual dogs and trials as more data are collected. Core body temperature (red line) and heart rate (blue line) are overlaid to show correspondence with state assignments.

Acknowledgments

This research was supported by the Australian Defence Innovation Network (DIN) under Project Number PP20-21_02.01 (Optimising ADF military working dog performance through next generation monitoring systems). The authors wish to thank Steve Burgun and the companion dog owners for allowing their animals to participate in this study. We are grateful to the technical staff at the participating universities for assistance with sensor development, data collection, and data analysis. We thank Livestock Labs for providing EmbediVet implants and technical support. We also thank Saiiv Monitoring Solutions for access to technology incorporated into the dog harness.

Declaration of Interest

The authors declare no conflicts of interest.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights

- Harness-embedded biosensors successfully monitored heart rate, respiration, and core temperature in working dogs during exercise, showing strong correlation ($r > 0.90$) with implantable sensors and thermistor pills
- Hidden Markov models identified five distinct physiological states, with state transitions occurring before visible behavioural signs of fatigue or thermal overload
- Real-time biosensor monitoring provides objective data to inform handler decisions about work-rest cycles, addressing the challenge that highly motivated working dogs often seem to ignore physiological limits