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Riley Brassington [*] , Jocelyn Mara , Nick Ball , Gordon Waddington , Julie Cooke

Posted Date: 20 May 2026

doi: 10.20944/preprints202605.1323.v1

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Visual, Vestibular, and Somatosensory Function in Female Rugby League Athletes

Riley Brassington [1,2,*], Jocelyn Mara [1], Nick Ball [1], Gordon Waddington [1] and Julie Cooke [1]

[1] University of Canberra Research Institute of Sport and Exercise
[2] Research Institute of Sport and Exercise, University of Canberra, Canberra, Australia
* Correspondence: riley.brassington@canberra.edu.au.

Abstract

Female rugby league performance is influenced by multiple interacting systems; however, the extent to which sensory and autonomic function differentiates playing level remains unclear. This study investigated whether visual, vestibular, somatosensory, and autonomic performance differ by playing level and positional group in female rugby league athletes. Elite and sub-elite athletes completed lower-limb proprioception testing using an Active Movement Extent Discrimination Assessment protocol, alongside visual–vestibular and autonomic measures obtained via a virtual-reality eye-tracking system. Bayesian hierarchical models were used to examine the effects of playing level, positional group (adjustables, backs, forwards), and their interaction, with posterior inference based on probability of direction and region of practical equivalence analyses. Interaction effects between level and position were observed for selected variables across somatosensory, vestibulo-oculomotor, and autonomic domains. Elite adjustables demonstrated higher ankle proprioceptive acuity than sub-elite adjustables (PD = 0.94), with additional interaction effects identified for vestibulo-oculomotor time on target (PD = 0.95) and autonomic dilation velocity (PD = 0.98). However, findings were not consistent across positional groups or outcome measures, and substantial within-group variability was evident. Overall, sensory and autonomic performance did not consistently differentiate playing level, suggesting limited utility for cross-sectional discrimination but potential value for longitudinal, individualised athlete monitoring.

Keywords: proprioception; visual–vestibular function; pupillary light reflex; female rugby league

1. Introduction

Lower limb proprioception, the ability to sense joint position and movement, forms the foundation of balance control and is essential for skilled athletic performance. Research consistently shows that superior proprioceptive acuity at the lower limb is associated with higher levels of competition, better agility, balance, and technical execution [1–3]. Within elite sport, higher-ranked athletes demonstrate superior proprioceptive performance compared with lower-ranked national-level athletes [3] while professional adolescent athletes also exhibit greater proprioceptive acuity than non-athletic cohorts [2]. Proprioceptive acuity has further been identified as a predictor of sport performance and progression to the highest levels of competition, including international and Olympic representation [2,3]. In contrast, deficits in proprioception elevate the risk of lower limb injury, ankle sprains and chronic instability, which not only impair immediate performance but also predispose athletes to recurrent injuries that may shorten careers [4–6].

Beyond its role in injury prevention, proprioceptive acuity is fundamental to whole-limb coordination and the execution of complex athletic movements [7]. Efficient proprioceptive feedback supports precise foot placement, joint alignment, and the integration of multiple joints during high-speed, multi-planar actions such as sprinting, tackling, and rapid changes of direction [7–9]. When proprioceptive processing is well developed, movement control becomes more automatic, reducing the cognitive load required for motor regulation and allowing greater attentional resources to be allocated to higher-order tasks such as tactical awareness and decision-making [10,11]. Consistent with this, proprioceptive training interventions have been shown to enhance postural stability, agility, and explosive strength, while reducing the incidence of ankle injuries across athletic populations [5,7,9,12,13]. Collectively, this evidence highlights proprioceptive acuity as a key contributor not only to injury resilience, but also to movement efficiency and long-term athletic development in team collision sports.

Athletic performance depends on the integration of visual, vestibular, and somatosensory systems, which collectively provide continuous feedback regarding spatial orientation, movement, and environmental context [14,15]. The visual system supports anticipation and response to opponents or objects in the environment [16], while the vestibular system detects head position and acceleration, stabilising gaze and balance during dynamic movements [17]. The somatosensory system, including proprioception, supplies critical internal feedback on body position and movement [18]. Together, these systems underpin coordinated movement control, allowing athletes to perform with precision in high-speed, rapidly changing sporting environments.

Rugby league presents a particularly demanding context for multisensory integration. Players perform frequent accelerations, decelerations, directional changes, and collisions while fatigued, requiring constant recalibration of visual, vestibular, and proprioceptive input. Positional demands further influence sensory reliance: forwards engage predominantly in close-contact and wrestling actions, potentially placing greater emphasis on proprioceptive and vestibular inputs to maintain stability and technique, whereas backs perform high-speed evasive manoeuvres in open play, relying more heavily on visual processing, gaze stabilisation, and precise limb coordination to track opponents and the ball. Optimal integration of these sensory systems may enhance movement efficiency and performance consistency, while impairments may contribute to reduced postural control and increased susceptibility to injury.

Based on the importance of proprioception in performance and injury risk reduction, reliable assessment of sensory performance is vital. The Active Movement Extent Discrimination Assessment (AMEDA) protocol provides an ecologically valid, weightbearing measure of lower limb somatosensory acuity at the ankle [19]. Recent technical advances have expanded this approach through the integration of visual and vestibular assessments using a programmable headset, enabling the evaluation of smooth pursuit, saccadic eye movements, and pupillary light reflex (PLR). This combined assessment framework has demonstrated reliability and validity in both general and military populations [20,21], offering a novel opportunity to examine sensory system function in applied sporting contexts.

Despite evidence linking proprioceptive acuity and multisensory integration to athletic performance and injury risk, little is known about how these sensory systems vary across playing levels and positional groups in rugby league athletes. To date, no study has concurrently examined proprioceptive, visual, vestibular, and autonomic function across playing levels and positions within rugby league. Addressing this gap may inform targeted training and injury prevention strategies that support performance and long-term player availability leading to overall team success. Therefore, the aim of this study was to investigate differences in visual, vestibular, and somatosensory performance across playing levels and positional groups in female rugby league athletes using the AMEDA protocol combined with assessments of visual and vestibular function.

2. Materials and Methods

Participants

Participants were recruited from one elite National Rugby League Women's (NRLW) team and one sub-elite Tarsha Gale Cup team , which represents the NSW/ACT female under-19 rugby league competition. All participants were injury-free at the time of testing. Athletes with acute musculoskeletal injuries or unresolved concussion symptoms were excluded by the medical staff. Vision correction (e.g., glasses or contact lenses) was permitted, provided it was worn consistently during testing. All participants provided written informed consent prior to testing.

doi:10.20944/preprints202605.1323.v1

Anthropometric measures (age, height, and body mass) were recorded for both groups as part of routine preseason baseline testing, conducted by trained staff using standardised procedures (Table 1).

Table 1. Participant Characteristics.

Variable	Sub-elite (n = 47)	Elite (n = 33)
Age (mean ± SD)	17.8 ± 0.6	24.0 ± 4.1
Height (mean ± SD)	167.5 ± 6.5 *	167.8 ± 6.8
Weight (mean ± SD)	71.0 ±11.7 *	77.5 ± 11.8
Adjustables [n athletes (n datapoints)]	9 (17)	7 (24)
Backs [n athletes (n datapoints)]	11 (19)	9 (31)
Forwards [n athletes (n datapoints)]	27 (40)	17 (43)

* Measured from n = 34 athletes due to incomplete data.

Study Design

This study employed a cross-sectional observational design involving multiple cohorts. Ethics approval was obtained from the university's Human Research Ethics Committee prior to data collection (HREC – 12219). Data were collected during the 2023 and 2024 preseason periods from athletes representing one elite NRLW team and one sub-elite Tarsha Gale Cup team. Testing occurred in week 1 and week 8 of each team's preseason schedule, approximately eight weeks apart. Due to changes in team selection and squad composition, each testing session involved a distinct group of athletes.

Data Collection and Procedures

All assessments were conducted in a controlled indoor environment designed to minimise auditory and visual distractions and ensure consistency across sessions. To maintain standardised administration and data integrity, all testing was performed by the same experienced assessor. The AMEDA protocol and Visual-Vestibular System (VVS)(Prism Neuro®Pty Ltd) procedures used in this study have previously demonstrated strong test–retest reliability, and consistent administration was maintained across both testing sessions [20,22]. Each participant completed two consecutive five-minute assessments: a visual-vestibular system (VVS) evaluation using a virtual reality video headset, and a somatosensory assessment.

Visual-Vestibular System (VVS) Assessment

The VVS protocol utilised a Prism Neuro® Pty Ltd headset equipped with dual OLED displays (2560 × 1440 resolution), a 70 FPS refresh rate, a 100° field of view, and a 120 Hz infrared eye-tracking system with a reported median accuracy of 1.15° across the screen. Participants underwent a standardised calibration process to map gaze positions across the visual field.

Following calibration, three eye-tracking trials were administered in a fixed sequence to control for light adaptation effects:

1. Smooth pursuit: Participants tracked a small red dot moving in a circular path.
2. Pupillary response: Participants focused on a stationary red 'x' while lights flashed, allowing measurement of pupil constriction and dilation velocities.
3. Saccadic movement: Participants tracked a rapidly moving red 'x' across the screen.

Standardised instructions were provided to ensure consistency. Data were processed using proprietary blink filtering and low-pass signal smoothing algorithms.

doi:10.20944/preprints202605.1323.v1

Somatosensory Assessment

Ankle proprioceptive acuity was assessed using a Prism Neuro AMEDA system, a validated tool for evaluating somatosensory sensitivity during weight-bearing tasks [19,22]. Participants stood barefoot on the device, placing one foot on a moveable platform and the other on a fixed platform. The moveable platform rotated into five distinct inversion angles (approximately 11° to 15° in 1° increments), labelled 1 through 5. A familiarisation phase was completed on the left limb, during which participants performed three trials at each inversion depth (15 movements total). Movements were self-paced, with participants actively inverting the ankle until the platform reached a mechanical stop, then returning to neutral. Following familiarisation, participants completed 50 randomised trials per limb (10 trials per inversion depth). After each movement, they retrospectively identified the perceived position number (1–5) without feedback. Participants maintained a forward gaze and relaxed posture to minimise extraneous sensory input. Responses were manually recorded using an Android tablet and transferred to Microsoft Excel. Somatosensory acuity was quantified using the area under the curve (AUC) of a Receiver Operating Characteristic (ROC) analysis, with scores ranging from 0.5 (chance level) to 1.0 (perfect discrimination).

Statistical Analysis

Statistical analyses were conducted using RStudio (Version 2024.09.0 + 375). Descriptive statistics, including mean and standard deviation (SD), were calculated for all continuous variables. To examine the effects of playing level (elite vs. sub-elite) and positional group (adjustables, backs, forwards) on sensory performance outcomes, Bayesian hierarchical models were fitted using the '*brms*' package. Each model specified a Gaussian likelihood and included fixed effects for level, position, and their interaction, along with random intercepts for athlete ID and timepoint to account for repeated measures and nested data structure. Posterior distributions were summarised using median estimates and 95% highest density intervals (HDIs). Directional probabilities (PD) were calculated to assess the likelihood of effects being positive or negative [23]. Practical significance was evaluated using Region of Practical Equivalence (ROPE) analysis, with thresholds defined as ±0.1 standard deviations of the respective response variable. ROPE percentages were used to interpret the proportion of the posterior distribution falling within the equivalence bounds. Estimated marginal means (EMMs) were computed using the '*emmeans*' package, and pairwise contrasts were extracted using posterior draws [24]. Model convergence was assessed using R-hat statistics (< 1.01) and effective sample sizes, with all models demonstrating satisfactory convergence. Uniform priors were used for all fixed effects.

3. Results

Somatosensory Variables

There was evidence of a level x position interaction effect for AMEDA Left, indicating that the effect of level depended on position (β [Level x Backs vs Adjustables] = 5.8, 95% HDI = [-1.6, 13.3], PD = 0.94). Specifically, elite adjustables had higher AMEDA Left scores than sub-elite adjustables (β = 3.7, 95% HDI = [-2.0, 9.6], PD = 0.89), but there was limited evidence of a difference between levels for backs or forwards (Table 2).

Table 2. Contrast for different somatosensory, visual-vestibular, and autonomic variables.

Variable	Contrast	Estimate	Lower 95% HDI	Upper 95% HDI	PD	ROPE
AMEDA Left (AUC)	Elite Adjustables - Sub-Elite Adjustables	3.70	-2.21	9.36	0.89	0.08

	Elite Backs - Sub-Elite Backs	-2.02	-6.90	2.19	0.82	0.16
	Elite Forwards - Sub-Elite Forwards	0.52	-2.77	4.15	0.61	0.29
AMEDA Right (AUC)	Elite Adjustables - Sub-Elite Adjustables	1.32	-3.46	5.96	0.70	0.16
	Elite Backs - Sub-Elite Backs	-1.31	-5.04	2.73	0.76	0.19
	Elite Forwards - Sub-Elite Forwards	0.20	-2.68	3.22	0.55	0.31
Circle Tracking Error (Degrees °)	Elite Adjustables - Sub-Elite Adjustables	1.02	-4.80	6.98	0.63	0.19
	Elite Backs - Sub-Elite Backs	1.11	-3.63	6.19	0.66	0.20
	Elite Forwards - Sub-Elite Forwards	-3.15	-6.70	0.47	0.95	0.07
Time to Target (Seconds)	Elite Adjustables - Sub-Elite Adjustables	-0.01	-0.06	0.05	0.60	0.18
	Elite Backs - Sub-Elite Backs	-0.03	-0.07	0.03	0.85	0.12
	Elite Forwards - Sub-Elite Forwards	-0.02	-0.05	0.02	0.85	0.19
Time on Target (Seconds)	Elite Adjustables - Sub-Elite Adjustables	0.08	-0.01	0.17	0.96	0.05
	Elite Backs - Sub-Elite Backs	-0.02	-0.10	0.05	0.73	0.19
	Elite Forwards - Sub-Elite Forwards	0.02	-0.03	0.08	0.78	0.24
Response Delay (Milliseconds)	Elite Adjustables - Sub-Elite Adjustables	8.85	-12.51	30.05	0.80	0.13
	Elite Backs - Sub-Elite Backs	12.33	-4.83	28.37	0.92	0.08
	Elite Forwards - Sub-Elite Forwards	12.31	0.13	25.58	0.98	0.03
Dilation Velocity (Seconds)	Elite Adjustables - Sub-Elite Adjustables	0.04	-0.09	0.17	0.72	0.15
	Elite Backs - Sub-Elite Backs	-0.15	-0.24	-0.04	1.00	0.00
	Elite Forwards - Sub-Elite Forwards	0.07	-0.01	0.15	0.96	0.05

Peak Constriction Velocity (Seconds)	Elite Adjustables - Sub-Elite Adjustables	0.28	-0.32	0.98	0.82	0.12
	Elite Backs - Sub-Elite Backs	-0.30	-0.75	0.19	0.88	0.12
	Elite Forwards - Sub-Elite Forwards	0.10	-0.28	0.46	0.70	0.28

Estimate represents the median posterior effect size. Lower 95% HDI and Upper 95% HDI denote the bounds of the 95% Highest Density Interval. PD indicates the Probability of Direction ROPE reflects the proportion of the posterior distribution within the Region of Practical Equivalence.

On the other hand, there was no interaction effect (β [Level x Backs vs Adjustables] = 2.7, 95% HDI = [-3.2, 9.0], PD = 0.80; β [Level x Forwards vs Adjustables] = 1.1, 95% HDI = [-4.8, 6.6], PD = 0.65) or main effect for level for AMEDA Right(B = -1.3, 95% HDI = [-5.9, 3.5], PD = 0.70).

Vestibulo-Oculomotor Variables

There was no clear level × position interaction effect for time to target (β [Level × Backs vs Adjustables] = 0.02, 95% HDI = [−0.05, 0.09], PD = 0.69; β [Level × Forwards vs Adjustables] = 0.01, 95% HDI = [−0.05, 0.07], PD = 0.62), indicating that the effect of competition level did not differ meaningfully across positional groups (Table 2). There was also no main effect of level when averaged across positions (β = 0.01, 95% HDI = [−0.05, 0.06], PD = 0.60).

There was a level × position interaction effect for time on target, indicating that the effect of competition level depended on positional group (β [Level × Backs vs Adjustables] = 0.11, 95% HDI = [−0.02, 0.22], PD = 0.95). Elite adjustables achieved higher time on target scores than sub-elite adjustables (β = 0.08, 95% HDI = [−0.01, 0.17], PD = 0.89), whereas sub-elite backs achieved higher scores than elite backs (β = −0.11, 95% HDI = [−0.22, 0.02], PD = 0.95) (Table 2).

There was no clear level × position interaction effect for circular tracking error (β [Level × Backs vs Adjustables] = −0.05, 95% HDI = [−8.04, 7.49], PD = 0.50; β [Level × Forwards vs Adjustables] = 4.07, 95% HDI = [−3.25, 10.60], PD = 0.88), indicating similar effects of competition level across positional groups (Table 2). Likewise, there was no main effect of level for circular tracking error (β = 1.02, 95% HDI = [−6.9, 4.9], PD = 0.63).

Autonomic Variables

There was no clear level × position interaction effect for response speed (β [Level × Backs vs Adjustables] = 3.28, 95% HDI = [−33.96, 21.69], PD = 0.60; β [Level × Forwards vs Adjustables] = 3.41, 95% HDI = [−28.88, 21.13], PD = 0.61), indicating that competition level had a similar effect across positional groups (Table 2). There was also no main effect of level when averaged across positions (β = 8.85, 95% HDI = [−30.05, 12.51], PD = 0.80).

There was a level × position interaction effect for dilation velocity, indicating that the effect of competition level differed by position (β [Level × Backs vs Adjustables] = 0.18, 95% HDI = [0.03, 0.36], PD = 0.98). Elite backs demonstrated higher dilation velocity scores than sub-elite backs (β = 0.07, 95% HDI = [−0.07, 0.18], PD = 0.84), while no clear differences between levels were observed for adjustables or forwards (Table 2)

There was a level × position interaction effect for peak constriction velocity, indicating that the effect of competition level depended on positional group (β [Level × Backs vs Adjustables] = 0.60, 95% HDI = [−0.24, 1.38], PD = 0.92). Elite adjustables demonstrated higher peak constriction velocity scores than sub-elite adjustables (β = 0.28, 95% HDI = [−0.33, 0.97], PD = 0.82). In contrast, sub-elite backs achieved higher peak constriction velocity scores than elite backs (β = 0.40, 95% HDI = [−0.16, 1.03], PD = 0.89), with no clear differences observed between levels for forwards (Table 2).

4. Discussion

This study investigated the degree of association between playing levels and positional grouping on visual, vestibular, somatosensory, and autonomic performance metrics in female rugby league athletes. Overall, no one measure had statistically significant differences observed between elite and sub-elite players across the positional domains. Although some autonomic measures favoured elite athletes and others favoured sub-elite athletes, the direction and magnitude of these effects were generally weak to moderate. Collectively, these findings suggest that playing level, in isolation, may not be a strong or reliable determinant of sensory or autonomic function, and that positional demands likely contribute to the observed variability.

Importantly, the present findings indicate that sensory and autonomic measures were not consistently associated with playing level across positional groups. Instead, differences were task- and position-specific, and substantial variability existed within both elite and sub-elite cohorts. These findings suggest that neurosensory and autonomic function may not serve as reliable standalone indicators of competition level but rather reflect dynamic physiological and neurological status influenced by positional demands, training exposure, and individual factors.

Response speed, defined as the latency from light stimulus onset to pupil constriction initiation, serves as an indicator of neural conduction efficiency, with shorter latencies reflecting more rapid processing. Although elite forwards demonstrated trends toward faster response speeds and higher pupil dilation velocities compared with sub-elite forwards, the magnitude and certainty of these differences were modest. These findings suggest potential physiological differences but do not provide strong evidence of systematic superiority associated with playing level. Existing literature indicates that higher-level athletes may demonstrate enhanced autonomic and neural responsiveness during cognitively demanding tasks [25–27]; however, within relatively homogeneous athletic cohorts, such differences may be attenuated or influenced by contextual factors such as training phase and cumulative load.

In contrast, sub-elite backs demonstrated higher parasympathetic and sympathetic PLR metrics compared with elite backs. Although unexpected, both cohorts were assessed late in the pre-season, a period characterised by elevated training loads and accumulated fatigue. Elite athletes are typically exposed to higher absolute training loads during this phase, which may influence autonomic responses at the time of testing. The PLR, governed by parasympathetic (constriction) and sympathetic (dilation) pathways, is recognised as an indicator of neurological and physiological status [28]. Accordingly, these findings may reflect differences in physiological state rather than inherent competition-level characteristics.

Ankle somatosensory acuity, assessed using the AMEDA protocol, showed no consistent differences between elite and sub-elite players and no clear separation across positional groups (Figure 1). This contrasts with previous studies reporting superior proprioceptive acuity in elite compared with lower-level or non-athletic populations [2,3]. However, within trained athletic cohorts, shared exposure to sport-specific training and neuromuscular demands may result in broadly similar proprioceptive capability, limiting its utility as a discriminator of playing level. These findings suggest that proprioceptive function may reach a ceiling effect within trained rugby league athletes, reducing observable differences between competitive tiers.

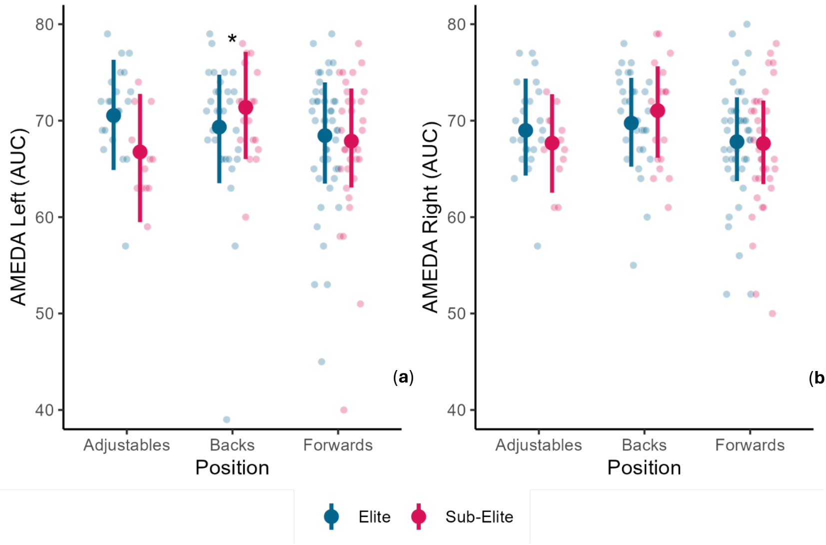

Figure 1. Ankle proprioceptive acuity of elite and sub-elite female rugby league athletes assessed using the AMEDA protocol. (a) AMEDA Left (AUC); (b) AMEDA Right (AUC), presented by positional group (adjustables, backs, forwards). Faded points represent individual observations. Solid points represent model-estimated marginal means, with error bars indicating 95% highest density intervals (HDIs). The double asterisk (**) denotes strong evidence for a between-level difference within the backs positional group (probability of direction, PD > 0.95).

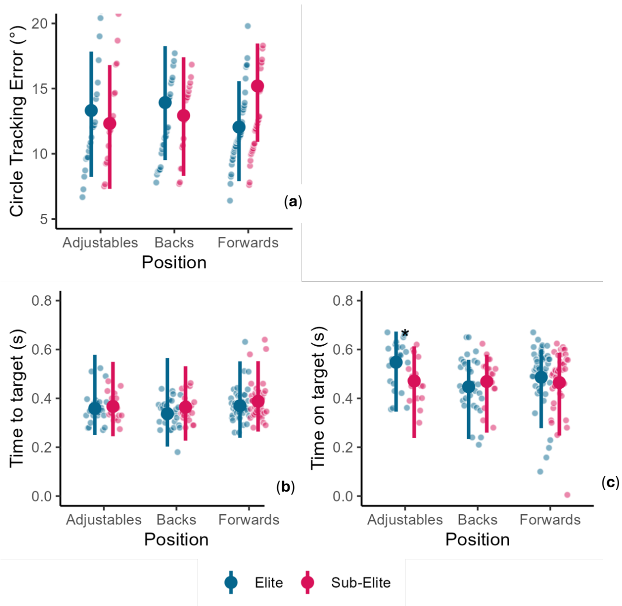

Figure 2. Vestibulo-oculomotor performance of elite and sub-elite female rugby league athletes assessed via Prism Neuro eye-tracking. (a) Circle tracking error (°); (b) time to target (s); (c) time on target (s), presented by positional group (adjustables, backs, forwards). Faded points represent individual observations. Solid points represent model-estimated marginal means, with error bars indicating 95% highest density intervals (HDIs). The asterisk (*) denotes strong evidence for a between-level difference within the adjustables group (probability of direction, PD > 0.95).

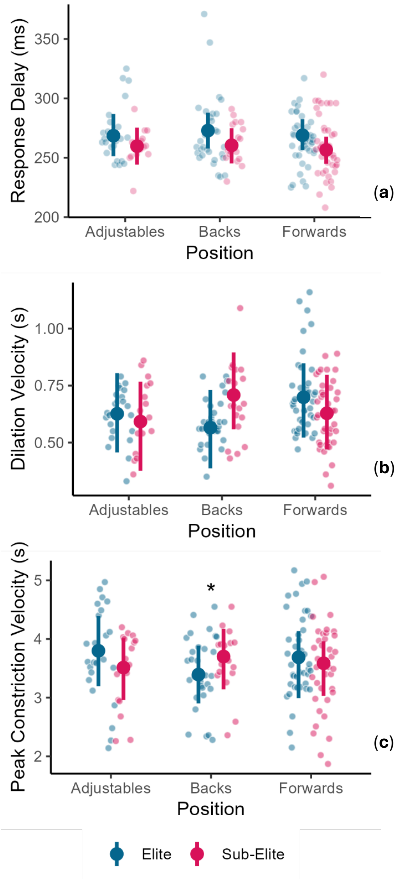

Figure 3. Autonomic performance of elite and sub-elite female rugby league athletes assessed via Prism Neuro eye-tracking. (a) Response delay (ms); (b) dilation velocity (s); (c) peak constriction velocity (s), presented by positional group (adjustables, backs, forwards). Faded points represent individual observations. Solid points represent model-estimated marginal means, with error bars indicating 95% highest density intervals (HDIs). The asterisk (*) denotes strong evidence for a between-level difference within the backs positional group (probability of direction, PD > 0.95).

Contextual factors should be considered when interpreting these findings. Testing occurred during the late pre-season, when elevated training loads and accumulated fatigue may influence sensory and autonomic function. Sample size and positional group distribution may also have affected estimate precision. Additionally, individual physiological factors, including recovery status and hormonal variation, were not controlled and may contribute to variability. These factors highlight the importance of interpreting neurosensory and autonomic measures within athlete-specific contexts.

From an applied perspective, the limited and inconsistent level-based differences observed in this study suggest that sensory and autonomic measures may have restricted utility as standalone tools for cross-sectional athlete discrimination in female rugby league. However, their sensitivity to physiological and neurological state indicates potential value within longitudinal monitoring frameworks. When interpreted relative to individual baselines and integrated with workload and recovery metrics, measures such as PLR and proprioceptive performance may provide complementary insight into athlete readiness, fatigue, and adaptation.

5. Conclusions

These findings suggest that sensory and autonomic function in female rugby league athletes reflects complex interactions between physiological state, positional demands, and individual variability rather than competition level alone. While these measures may have limited utility for distinguishing playing level in cross-sectional comparisons, their responsiveness to physiological

doi:10.20944/preprints202605.1323.v1

status highlights their potential value within athlete monitoring systems. Integrating neurosensory and autonomic assessment alongside existing monitoring tools may enhance understanding of readiness, recovery, and adaptation in female collision sport athletes.

Author Contributions: Article Design: Riley Brassington, Jocelyn Mara, Nick Ball, Gordon Waddington, Julie Cooke. Literature Search: Riley Brassington, Julie Cooke; Data Analysis: Riley Brassington, Jocelyn Mara; Writing: Riley Brassington; Drafting: Jocelyn Mara, Nick Ball, Gordon Waddington, Julie Cooke.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee of **University of Canberra** (protocol code **HREC–12219** and date of approval **05 January 2024**).

Informed Consent Statement: Written informed consent was obtained from all participants prior to participation. For participants under 18 years of age, written informed consent was obtained from a parent or legal guardian, and participant assent was obtained where applicable.:

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

Acknowledgments: This research project was part of the University of Canberra's 50:50 Women in Sport Scholarship with the Canberra Raiders. I would like to express our gratitude to the University of Canberra for providing the support and resources essential to this study. I also extend thanks to the colleagues at the University of Canberra Research Institute for Sport and Exercise for their invaluable assistance, their insightful guidance, and feedback throughout the project.

Conflicts of Interest: The author Gordon Waddington is a founder and shareholder in Prism Neuro Pty Ltd an Australian perceptual neuroscience equipment company. The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AMEDA	Active Movement Extent Discrimination Assessment
AUC	Area Under the Curve
PD	Probability of Direction
PLR	Pupillary Light Reflex
NRLW	National Rugby League Women's
VVS	Visual-Vestibular System
ROPE	Region of Practical Equivalence
EMM	Estimated Marginal Means
β	Estimate

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