Pupillary light reflex metrics as an objective biomarker for sport-related concussion in elite field hockey

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ORIGINAL ARTICLE

Pupillary Light Reflex Metrics as an Objective Biomarker for Sport-Related Concussion in Elite Field Hockey

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Abstract

Background Concussion diagnosis is based on subjective assessment of several nonspecific clinical signs and symptoms with no objective test to aid in diagnosis. The pupillary system, in particular the pupil light reflexes (PLR) has attracted plausible consideration in this area, given its complex neural circuitry and autonomic function.

Aim To assess the reliability and validity of using the NeurOptics PLR-3000 pupilometer to measure PLR, and to determine normative data for female athletes.

Methods A cross sectional cohort study of 33 senior elite female field hockey athletes (aged 19–34 years) were recruited. Three valid pupillometry readings were acquired, per eye. Measurements of nine PLR metrics were obtained. Reliability was determined using intraclass coefficients, standard error of measurement (SEM), and minimum detectable change (MDC). Between group differences (concussion history vs. controls) were analysed using non-parametric tests.

Results NeurOptics PLR-3000 showed good to excellent reliability for eight PLR metrics derived from the pupilometer [latency, average constriction velocity (ACV), peak constriction velocity (PCV), average dilation velocity (ADV), $T75\%_{max}$. pupil diameter, min. pupil diameter and percent constriction]. There was no statistical difference between any of the PLR metrics in athletes who had a history of concussion and those that had no history of concussion. The two athletes with a recent history of concussion (< 3 months) showed trends towards slowed latency, ACV, PCV and ADV when compared to controls.

Conclusion This research does not support previous research that the PLR-3000 is an accurate instrument for distinguishing between those with and without a history of concussion. However, the *ICC* values for intratester reliability were good to excellent for most PLR metrics, with data comparing favourably to normative values previously reported from other populations. Some PLR metrics may distinguish between distinct group of female athletes (recent history of concussion), but this is a small sample size and exploratory in nature. Larger studies are required to confirm its validity and responsiveness.

Keywords Pupil light reflexes · Concussion · Mild traumatic brain injury · Sports · Athletes · Female

Abbreviations

SRC	Sports related concussion
PLR	Pupil light reflexes
LC	Locus coeruleus
OPN	Olivary pretectal nucleus
EWN	Edinger Westphal nucleus
IML	Intermediolateral cell nucleus
DMH	Dorsomedial hypothalamus
AVC	Average constriction velocity
PCV	Peak constriction velocity
ADV	Average dilation velocity
PDV	Peak dilation velocity
SD	Standard deviation
SEM	Standard error of measurement
MDC	Minimal detectable change

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Background

Sports related concussion (SRC) is a complex pathophysiological process affecting the brain, characterised by a rapid impairment of neurological function after an acute trauma [10]. SRC can have long-term sequelae including persistent

headaches, dizziness, poor concentration, and memory loss [20]. There is also an increased risk of future concussions and musculoskeletal injury in those who have sustained a SRC [21, 26]. It remains a significant health problem [17] and has been increasingly recognised as a substantial issue in athletes across many sporting disciplines [11]. Early recognition and appropriate management post SRC can limit complications, increasing the chance of full recovery [9]. Despite a consensus definition of SRC, an accurate diagnosis in a clinical setting remains challenging, with clinicians relying heavily on athletes to disclose their signs and symptoms [20]. Functional deficits following SRC can span multiple domains, including cognitive, vestibular, ocular, migraine and anxiety/mood and therefore clinical presentation is highly heterogeneous [9].

The autonomic nervous system is critical in maintaining physiological homeostasis. There is evidence of autonomic dysfunction after SRC that may occur through various pathophysiological process of neuroinflammation, oxidative stress, neurodegeneration and impairments in cerebral blood flow regulation [18, 28]. The autonomic nervous system can be measured through the visual system by analysis of pupillary dynamics. The pupillary response to light is a complex reflex and involves the brain, brainstem, and spinal cord levels [5]. Pupillary light reflexes (PLR) are commonly examined by healthcare professionals to inform autonomic function, with pupillary constriction and dilation dominated by the parasympathetic and sympathetic systems respectively. The equilibrium between these systems allows for normal PLRs, an insult to the brain that effects either pathway will therefore modulate PLRs.

Traditionally, assessment of PLRs involved a penlight test, where the practitioner shines a light into a patient's eye to subjectively score PLR, but this has limited reliability [24] and subtle changes in neural integrity after SRC may be undetectable. Pupillometry is a diagnostic technology offering a standardised, objective and responsive evaluation of PLRz [36]. This technology has been used routinely in neuro-critical patients [35] and following traumatic brain injuries [7]. Early research demonstrated good to excellent reliability [1, 29] with high inter-device reliability [36]. Digital pupillometry also quantifies several outcome parameters that align with key phases of PLR response including, constriction latency, average constriction and dilation velocities (ACV, ADV) and peak constriction and dilation velocities (PCV, PDV). Most pupillometry studies involve healthy male adults (military or general population), with limited normative data from female athletes.

The aim of this study is to assess the accuracy of the NeurOptics PLR-3000 pupilometer. The primary objectives are to establish intra-rater reliability of pupillometry and normative data for female athletes. As a secondary objective we will examine the pupilometer's discriminant validity, by comparing PLR metrics in athletes with/without a history of concussion. It is anticipated that key PLR metrics (constriction latency, ACV, PCV, ADV, PDV) will be slowed in cases with a history of concussion when compared to controls (no history of concussion).

Methods

Study Design, Setting and Participants

This cross-sectional study involved 33 senior elite female field hockey athletes aged between 19 and 34 years, voluntarily recruited from one national squad. Ethical approval was obtained from the University of Bath's Research Ethics Approval committee, and athletes provided written, informed consent prior to participating in the study. Cases were defined as athletes with a history of concussion ($n = 12$), with those with no history of concussion acting as controls ($n = 21$). Concussion was defined using the most recent international consensus statement [20] as rapid-onset and transient symptoms associated with traumatic brain injury induced by biomechanical forces and must have been diagnosed by appropriately trained personnel at the time of injury. Medical records were also examined to determine the number of concussions sustained by each athlete, the time taken before a full return to participation, and the time since concussion diagnosis. Exclusion criteria for both groups included any neurological or ocular disease, eye trauma, exercise within one hour of testing, and current medication that would affect PLR e.g., antidepressants, benzodiazepines.

Instrumentation

PLR was assessed using a NeurOptics PLR-3000 handheld infrared automated monocular pupilometer (Fig. 1), which has been FDA approved for research. The instrument produces a bright white light stimulus (180 μW, 0.17 s) for a duration of 6.02 s, automatically storing PLR data every 0.033/s for eight PLR metrics (Fig. 2; Table 1). The ninth metric, peak dilation velocity, was calculated from automated slope-based measures obtained from the pupilometers raw data. The rate of change of pupil diameter (mm/s) was calculated for each trail and after the data was smoothed the maximum rate of dilation speed was determined and used in the final analysis.

Procedures

PLR testing was performed by the primary researcher (RM), in a quiet room with an illumination of < 10 lx verified by a luminance App (Lux Light Meter Pro 2.1.1). Monocular
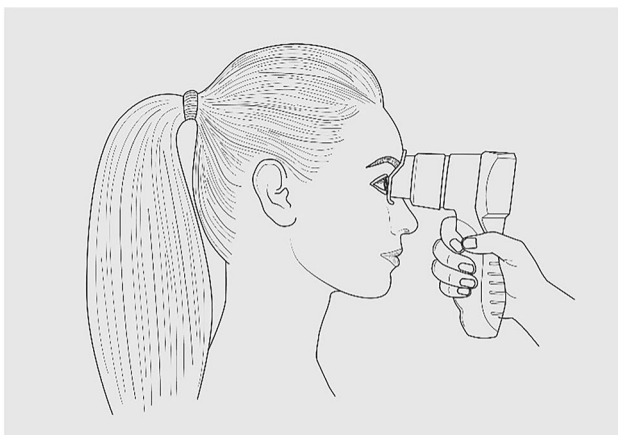
Fig. 1 NeurOptics PLR-3000 alignment during testing

measurements were taken in alternate eyes with a minimum of 30 s between tests and three valid tests per eye. A single test takes 6 s; to ensure ocular fixation and accommodation during testing, participants were asked to focus their non test eye on a target that was 3 m away. If the participant blinked, or there were other noted artefacts, the test was repeated. The mean of three valid readings per eye was used for analysis.

Statistical Analysis

Descriptive statistics were used to summarize participant demographics, concussion history, and PLR metrics. Histograms were used to examine data shape and were visually inspected for the presence of clustering at the extremes of range (floor or ceiling effects). Intra-tester reliability was calculated for each PLR metric using intraclass coefficients (*ICC*), through a two-way mixed effect model (absolute agreement), and quantified as either moderate (0.5–0.75), good (0.75–0.9) or excellent (> 0.9) [16]. We also calculated standard error of measurement (SEM) using the formula: $SEM = SD \sqrt{1-r}$ (SD – standard deviation of sample scores; r – reliability of scores) and minimum detectable change (MDC, 95%) using the formula: $MDC = 1.96 \times \sqrt{2} \times SEM$ [27].

As there were no differences in between eyes comparison for any PLR outcomes, as determined by paired *t*-test $P < 0.05$, we analysed the average eye scores per participant [4, 13, 31, 32]. To compare PLR metrics between cases (history of concussion) and controls, we calculated effect sizes (Hedge g, SMD with 95% CIs) and used a series of non-parametric Mann–Whitney tests (*P*-value threshold of < 0.05). All analyses were conducted through SPSS v28 (IBM Corp, Amarok, USA) and independent software was used to verify the results [22].

Results

Data were collected from $N = 33$ female field hockey players (mean age 24.8y; SD 4.2). None of the PLR variables were normally distributed, but there was no evidence of floor or ceiling effects as determined by visual inspection of the plots. Table 2 summarises participant demographics and concussion history. The 36% (12/33) had at least

Fig. 2 Dynamic pupillary response profile
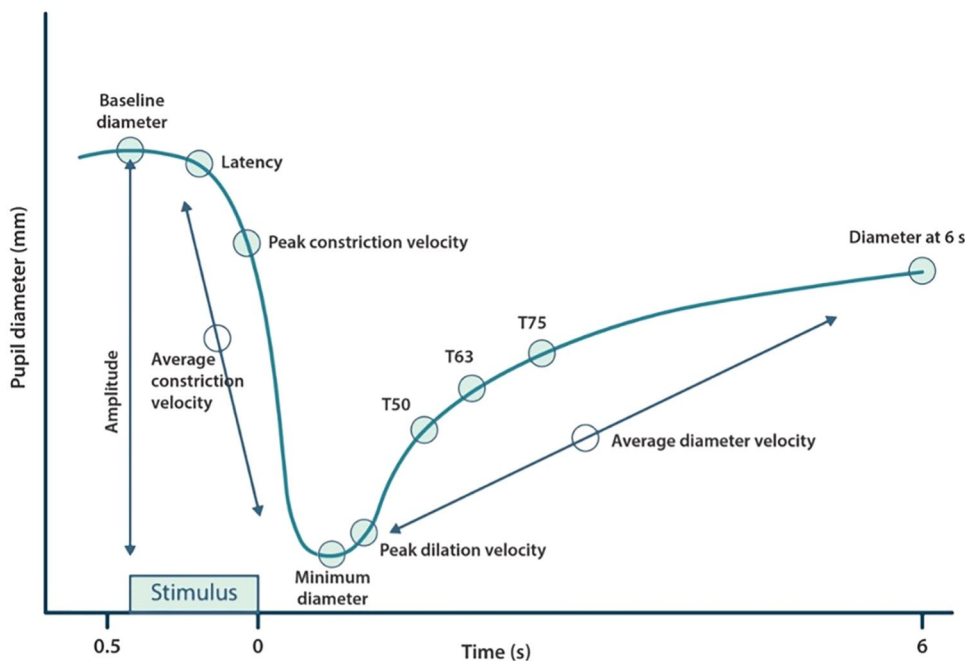
Table 1 Pupil light reflexes metric description and unit of measurement

Outcome measure	Description	Unit of measurement
Max. diameter (mm)	Baseline maximum pupil diameter	Millimetres
Min. diameter (mm)	Minimum pupil diameter at the point of maximal constriction	Millimetres
Percent constriction (%)	Maximum pupil diameter − minimum pupil diameter/maximum pupil diameter × 100	Percentage
Constriction latency (ms)	The time taken for the pupil to initially constrict in response to the bright light stimulus	Milliseconds
ACV (mm/s)	The average/rate at which the pupil constricts from the point of initial constriction to the maximal constriction	Rate of millimetres per second
PCV (mm/s)	The peak constriction speed is the fastest constriction speed recorded	Rate of millimetres per second
ADV (mm/s)	The average/rate at which the pupil dilates from the point of initial dilation to maximal dilation	Rate of millimetres per second
PDV (mm/s)	The peak dilation speed is the fastest dilation speed recorded	Rate of millimetres per second
75% recovery time (s)	The point at which the pupil returns to 75% of its baseline diameter after maximum constriction	Seconds

PLR pupillary light reflex, *ACV* average constriction velocity, *PCV* peak constriction velocity, *ADV* average dilation velocity, *PDV* peak dilation velocity

Table 2 Summary statistics of the female field hockey participants clinical characteristics

Participants, n		33
Age, y, mean ± SD		24.78 ± 4.2
History of concussion, n (%)		
	No	21 (64%)
	Yes	12 (36%)
Number of concussions, n (%)		
	1	6 (18%)
	2	3 (9%)
	>2	3 (9%)
Time since most recent concussion, n (%)		
	<2 weeks	0 (0%)
	>2 weeks <3 months	2 (16%)
	>3 months <1 year	2 (16%)
	>1 year	8 (68%)

n- number; y-years; %-percentage; SD- standard deviation

one previous diagnosis of concussion, of which, $n = 6$ had suffered two or more. Time since the most recent concussion ranged from 2 weeks to 3 months ($n = 2$), > 3 months to < 1 year ($n = 2$), with most ($n = 8$) sustaining their concussion more than 1 year previously.

Reliability

Table 3 summarises *ICC* values for intratester reliability; these ranged between moderate (PDV), good (latency, ACV, MCV, ADV and T75%) and excellent (maximum pupil diameter, minimum pupil diameter and percent constriction). PDV which was the least reliable metric, had MDC (95 CIs) scores ranging from 0.5 to 0.7 mm/s, equivalent

Table 3 Reliability and minimum detectable change for each PLR parameter

PLR parameter	Left eye						Right eye					
	Mean	SD	(95 CI)	SEM	MDC, 95%	% grand mean	Mean	SD	(95 CI)	SEM	MDC 95%	% grand mean
Max. diameter (mm)	6.30	0.82	0.99	0.08	0.23	3.62	6.34	0.79	0.98	0.11	0.32	4.97
Min. diameter (mm)	4.49	0.77	0.99	0.08	0.22	4.79	4.56	0.79	0.97	0.14	0.39	8.52
Percent constriction (%)	28.91	4.56	0.96	0.95	2.63	9.09	28.50	4.59	0.93	1.29	3.57	12.54
Constriction latency (ms)	0.21	0.02	0.76	0.01	0.03	13.28	0.21	0.02	0.80	0.01	0.03	14.53
ACV (mm/s)	− 3.76	0.44	0.90	0.15	0.41	11.01	− 3.70	0.47	0.86	0.20	0.54	14.72
PCV (mm/s)	− 4.84	0.60	0.89	0.22	0.60	12.44	− 4.84	0.60	0.86	0.25	0.69	14.28
ADV (mm/s)	0.99	0.20	0.78	0.11	0.31	31.09	0.99	0.25	0.87	0.10	0.28	27.90
PDV (mm/s)	1.53	0.58	0.68	0.17	0.50	31.60	1.59	0.72	0.61	0.24	0.70	42.20
75% recovery time (s)	2.96	0.87	0.78	0.48	1.34	45.32	3.06	0.88	0.78	0.49	1.37	44.72

PLR pupillary light reflex, *ACV* average constriction velocity, *PCV* peak constriction velocity, *ADV* average dilation velocity, *PDV* peak dilation velocity, *SEM* standard errors of measurement, *MDC* minimal detectable change

to 31.6%–42.2% of the grand mean scores. By contrast, the MDC (95 CIs) scores for minimum diameter values were 0.23–0.32 mm, or 3.6%–5% of the grand mean scores.

PLR (Concussion History vs. Control)

There were no statistically significant ($P > 0.05$) differences between the right and left eye within each group for each PLR metric based on dependent *t*-test. The data were combined as planned [4, 13, 31, 32], with mean scores (right and left eyes) used for between group comparisons (concussion history vs. controls). Table 4 shows mean (SD) for all PLR metrics split by group. Effect sizes were small, and there were no statistically significance differences ($P > 0.05$) between the groups for any of the metrics.

To examine if time from diagnosis affected PLR metrics, we undertook an exploratory analysis comparing athletes ($n = 2$) with a recent concussion (> 2 weeks < 3 months post injury) to the rest of the group ($n = 31$). We observed slower (Cohen's d effect size); latency (0.53), ACV (0.99), PCV (0.52) and ADV(1.41) in participants with a recent history of concussion (Fig. 3a–e).

Discussion

This study demonstrates the NeurOptics PLR-3000 as a reproducible tool in assessing PLR in elite female hockey athletes however its accuracy has not been demonstrated in this study. Comparisons of athletes with a history of concussion and those without a history of concussion did not show any statistically significant differences. An exploratory analysis showed athletes who sustained a concussion within the previous three months had slower PLR, when compared to all other athletes who had either a history of concussion over three months or no concussion history. Our study extends the current body of research to support the reliability (*ICC*s) of the PLR-3000 and potential use of PLR in diagnosing SRC while supporting the use of a pupilometer as a safe and easy to use tool for the assessment of PLR.

Reliability of PLR-3000

Previous research demonstrated the pupilometer as a reliable tool for assessing PLR metrics [1, 29, 36]. This study found good (0.76–0.90; latency, ACV, PCV, ADV and T75%) to excellent (0.91–0.99; max. pupil diameter, min. pupil diameter and percent constriction) reliability for the PLR metrics derived from the PLR-3000. Excellent reliability is unsurprising in static pupillary metrics such as pupil diameter where data is captured at a single point in time, whereas, the dynamic pupillary metrics (latency, ACV, PCV, ADV, PDV, T75) list them) demonstrated good reliability. The dynamic

Table 4 Between group comparisons: history of concussion vs. controls

PLR parameter	History of concussion ($n=12$)		No history of concussion ($n=21$)		Effect size	Mann–Whitney
	Mean	SD	Mean	SD	SMD (95% CI)	P
Max. diameter (mm)	6.38	0.72	6.29	0.85	0.1 (-0.6 to 0.8)	0.96
Min. diameter (mm)	4.58	0.71	4.49	0.81	0.1 (-0.6 to 0.8)	0.84
Percent constriction (%)	28.42	4.53	28.87	4.60	-0.1 (-0.8 to 0.6)	1.00
Constriction latency (ms)	0.21	0.02	0.21	0.02	0.0 (-0.7 to 0.7)	0.99
ACV (mm/s)	-3.72	0.46	-3.73	0.45	0.0 (-0.7 to 0.7)	0.79
PCV (mm/s)	-4.83	0.65	-4.84	0.57	0.0 (-0.7 to 0.7)	0.85
ADV (mm/s)	0.95	0.21	1.01	0.23	-0.2 (-0.9 to 0.5)	0.37
PDV (mm/s)	1.56	0.36	1.56	0.24	0.0 (-0.7 to 0.7)	0.78
75% recovery time (s)	3.09	0.80	2.97	0.91	0.1 (-0.6 to 0.8)	0.97

PLR pupillary light reflex, *ACV* average constriction velocity, *PCV* peak constriction velocity, *ADV* average dilation velocity, *PDV* peak dilation velocity

metrics may be affected by more measurement noise, as the machine must capture and calculate changing metrics over time. A ninth metric; PDV must be calculated from raw data exported from the PLR-3000. This metric was the least reliable (0.61–0.68). This may be due to differences in how the machine calculates the automated metrics when compared to manual calculations; for example, how data was smoothed, however, no previous research has investigated the reliability of PDV for comparison.
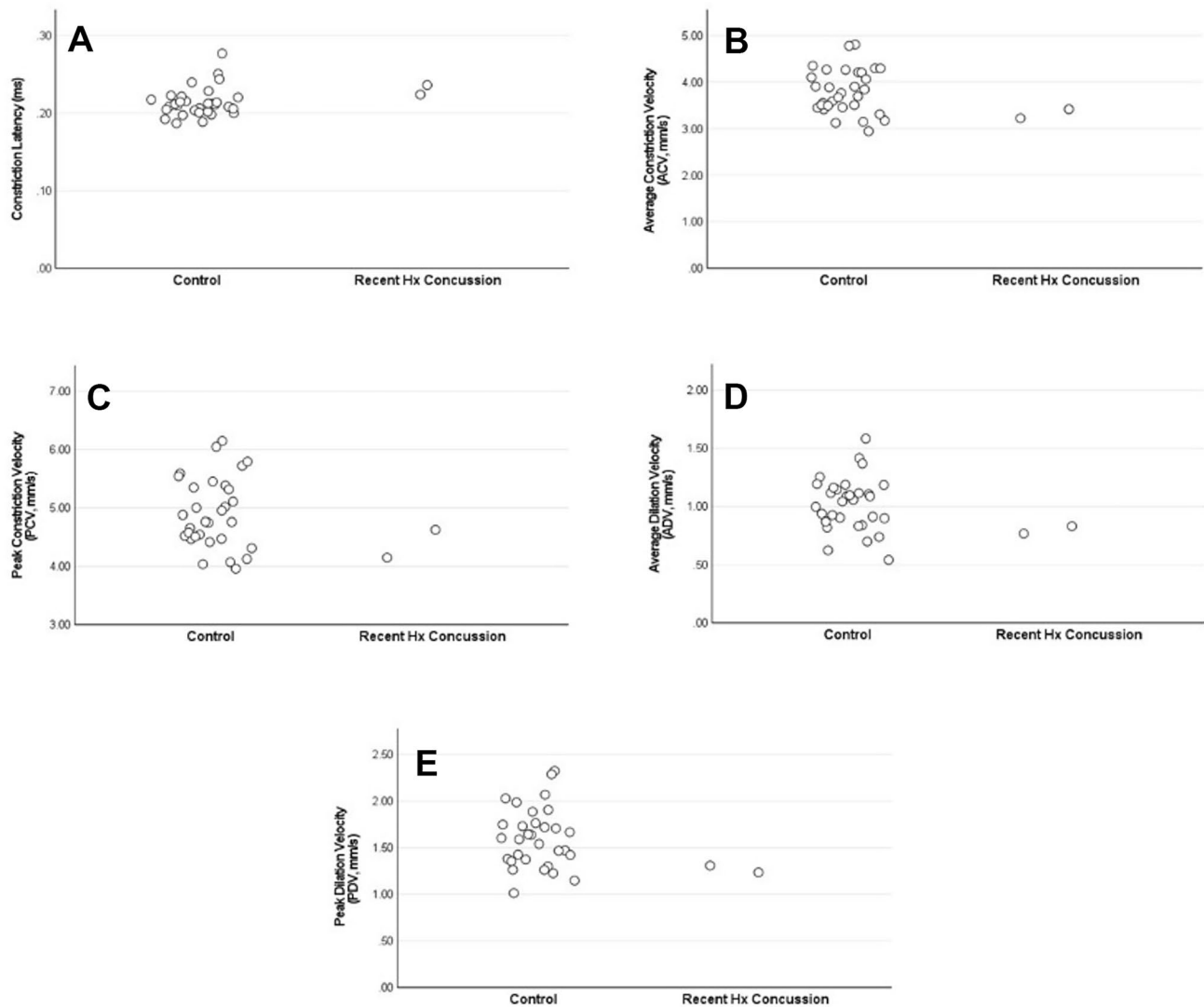
History of Concussion and PLR

Existing evidence suggests the clinical resolution of symptoms after concussion is premature to physiological recovery of the brain and there are concerns that residual neurological deficits may exist [12, 20, 21]. This highlights the importance of undertaking serial assessment of objective outcomes, such as PLR, throughout the chronic phases post-SRC. Previous research suggests that patients with a history of mTBI have slowed PLRs compared to controls [31, 32]. In contrast, we recorded no between group differences. Primarily, this could be due to our relatively small number of cases, coupled with a heterogeneous concussion history. Some cases reported having a concussion more than ten years ago, with most ($n=8/12$) sustaining a concussion more one year prior to testing; it is likely that these injuries were fully resolved at the time to testing [20].

There were some discrepancies among athletes who '*felt they had concussions in the past*' but they went undiagnosed. For the purpose of this study we separated the groups based on SRC diagnosed by trained personnel. However, given the sport is amateur in this country with no doctor present at any national training sessions and the majority of national games and no doctor or physiotherapist present at club level training or matches, it is possible previous concussions were missed, which would reclassify some of the control subjects, potentially skewing the results. There is another possibility where athletes could have been misclassified into the control group. Supposably athletes in this group had sub concussive injuries or repeated head trauma or head acceleration events, without symptoms, they would have gone unreported and may account for discrepancies between this research and previous research. Comparison of our subjects who had a known history of concussion to a control group who are age and sex matched, in a not sporting population may have been a better evaluation.

Recent Concussion and PLR

In our exploratory analysis, we found that a subgroup of athletes ($n=2$) who had sustained a recent concussion (<3 months), were most likely to have slowed constriction latency, ACV, ADV and PDV. Previous research in acute and sub-acute mTBI patients supports these findings of slowed PLRs [3]. Interestingly, a study in high-school football athletes found a change in PLR metrics with high-acceleration head impacts without symptoms, when compared to their baseline [14], highlighting the potential consequences of sub-concussive impacts in the absence of concussion symptoms. This could be underpinned by afferent processing delay in the PLR pathway and neural circuity disruption along the parasympathetic and sympathetic pathways [15]. Although the exact mechanisms at play between SRC and ANS dysfunction is yet to be fully understood it is worth

Fig. 3 **A–E** Comparing PLR metrics in athletes with a recent concussion (< 3 months) to controls (no recent history of concussion). **A** Constriction latency (ms), **B** ACV (mm/s), **C** PCV (mm/s), **D** ADV (mm/s) and **E** PDV (mm/s)

noting the largest differences in our study involved constriction latency and ACV which suggests delayed visual processing and reduced parasympathetic activity. Previous research attempts to explain reduced ACV, which is a consistent finding across studies [4, 31, 32]. PCV demonstrates initial and rapid neurological response to stimulus while ACV is an expression of the remaining slower response component averaged out over time [32]. This suggests deficiency in the neural feedback loop mechanism of PLR. Due to heterogeneity in current research, the type and extent of any effect on PLR metrics post-SRC remains unclear. Testing at each phase of insult (acute, sub-acute, chronic) is necessary to determine specific phase dependant PLR defects.

Sex and PLR

Existing studies suggest that females are more susceptible to concussion [6] and are slower to recover compared to males [8]. Some studies have examined if PLR response is moderated by biological sex, but findings are conflicting [5, 19, 23, 30, 33]. Two studies [5, 19] recorded sex-based differences in PLR, with both studies demonstrating females with prolonged T75 compared to age-matched males post SRC. Carrick et al., [5] also reports sex differences across maximum and minimum pupil diameter (males recorded smaller diameters in both concussed cases and controls) and PCV (female controls recorded quicker PCV than males). Our study

Table 5 Pupillary light reflexes in mild traumatic brain injury and sports related concussion studies summarised

Study	Subjects	Sex	Age	Mechanism of injury	Stage of concussion	PLR findings (bright white light)
mTBI						
Capó-Aponte et al. [4]	20 subjects 20 controls	Undefined	19–44 years	Blast-induced	Subacute 15–45 days	Slowed ACV, ADV, increased latency, longer T75
Thiagarajan and Ciuffreda [31]	17 subjects 15 controls	12 females 20 males	24–44 years	Varied (mostly RTA, falls)	Chronic > 1 year	Slowed ACV, PCV, ADV, smaller pupil diameters
Truong and Ciuffreda [32]	32 subjects 40 controls	Undefined	21–60 years	Varied (mostly RTA, falls)	Chronic > 45 days	Slowed ACV, ADV, PDV, smaller pupil diameters
Capó-Aponte et al. [3]	100 subjects 100 controls	166 males 34 females	19–44 years	Varied (airborne training, falls, RTA)	Acute < 72 h	Slowed ACV, ADV, longer T75
SRC						
Master et al. [19]	98 subjects 134 controls	99 males 133 females	12–18 years	SRC	Subacute < 28 days	Faster ACV, PCV, ADV, PDV, reduced latency, faster T75, larger pupil diameters
Joseph et al. [14]	13 subjects compared to baselines	13 males	17–18 years	Sport, sub concussive SRC	Acute < 1 h of HHI	Slowed PCV, ADV, percentage change in pupil diameter
Hsu et al. [13]	92 subjects normative data	36 males 56 females	7–17 years	Mostly SRC > falls > RTA	Acute, subacute, chronic < 15 days > 365 days	Faster ACV, PCV, ADV, faster T75

mTBI mild traumatic brain injury, *SRC* sports related concussion, *PLR* pupillary light reflex, *ACV* average constriction velocity, *PCV* peak constriction velocity, *ADV* average dilation velocity, *PDV* peak dilation velocity, *HHI* high acceleration head impact (defined as impact that simultaneously achieved linear acceleration of > 95 g and a rotational acceleration of > 3760 rad/s^2 with SRC symptoms/diagnosis)

shows greater maximum pupil diameter (6.29 mm ± 0.85) in female controls when compared to age-matched male controls [5]. Our study shows similar values in female controls for, minimum pupil diameter (4.49 mm ± 0.81), latency (0.21 ms ± 0.02), PCV (− 4.84 mm/s ± 0.57) and T75 (2.97 mm/s ± 0.91) when compared to age matched males [5].

Age and PLR

Age appears to effect PLR [5, 34]. Carrick et al. [5] reported decreased maximum and minimum pupil diameters, PCV and latency over the lifespan (0–100 years), regardless of concussion history. Our sample consisted of elite athletes aged 19 to 34 years, but we did not observe any deterioration within this age range. In our study, latency (0.21 ms ± 0.02) and ACV (− 3.72 mm/s ± 0.45) data each compared well to normative age matched data recorded in other adult populations, Capo-Aponte et al. [4] (19–44 years; latency 0.21 ms ± 0.01; ACV − 4.11 mm/s ± 0.44), Capo-Aponte et al. [3] (19–44 years, latency 0.22 ms ± 0.01; ACV − 4.05 mm/s ± 0.53) and Thiagarajan and Ciuffreda [31] (24–44 years, latency 0.21 ms ± 0.0; ACV

− 4.40 mm/s ± 0.1) (Table 5). Latency and ACV in this study are also comparable to normative data in younger populations in the study from Hsu et al. [13] [7–17 years (mean 15 years), latency 0.23 ms ± 0.03; ACV − 3.70 mm/s ± 0.74] (Table 5).

Limitations

Important components for this reliability study were met; patients were stable between repeated measures, testing conditions were similar (lux room, same instrumentation and examiner), and *ICC*, SEM and MDC were calculated. Our sample size was 31. Although this is above average for reliability studies in the sports science field (where sample size interquartile range is 13–32) [2] a priori sample size calculation is recommended. The *ICC*s and corresponding precision estimates reported in the current study can inform future sample size estimation in PLR reliability research. Based on our findings, the true *ICC* for minimum diameter metrics can be estimated at 0.95; if we set a minimal *ICC* value (null) of 0.85, then participants (*n* = 25) is recommended (assuming 2 testing points, a significance level of 0.05 and power of 80%). Although this figure compares favourably

to our current sample size, larger numbers of participants would be required to retain adequate power when quantifying reliability in other metrics. For example, lower *ICC*s were reported for dilation/constriction; if we estimate the true *ICC* for these metrics to be 0.8 and set a minimal *ICC* of 0.70, then at least 150 participants are recommended (again, assuming 2 testing points, a significance level of 0.05, and power of 80%) [2].

We acknowledge that optimal time interval between repeated measures is unclear; some suggest that a 1 min period may be more suitable to allow consensual response to return to baseline after bright white light stimulus [25]. Similarly, the optimal amount of time to accommodate to the lux of the room is unclear. It has been suggested that 10 min is needed to allow for visual adaption [25] which is slightly longer than we used in our study. All testing was undertaken by a single examiner, using a standardised protocol, however they were not blinded to the athlete's concussion history which could influence bias. As case-controlled designs are retrospective, there may have also been discrepancies with athletes' recall. Although we used a standardised definition of concussion that necessitated medically verification, as field hockey is an amateur sport Ireland, it is possible that some control athletes had a previous concussion, which were missed or misdiagnosed.

Conclusion

This research does not support previous research that the PLR-3000 is an accurate instrument for distinguishing between those with and without a history of concussion. However, the *ICC* values for intratester reliability were good to excellent for most PLR metrics, with data comparing favourably to normative values previously reported from other populations. This suggests that our control subjects that have not reported a history of concussion might have had a concussion or sub concussive repetitive trauma that results in a similarity between the PLRs of reported and non reported sports related concussion. As such, playing elite field hockey may result in changes in the PLR of participants suggesting a concussive event without symptoms or history of a sport related concussion. Further comparison between elite field hockey players and non athletes will be necessary to further explore this phenomenon. Some PLR metrics may distinguish between distinct group of female athletes (recent history of concussion), but the sample size is small and exploratory in nature. Larger studies are required to confirm its validity and responsiveness.

Declarations

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