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ARTICLE

Corticomotor correlates of somatosensory reaction time and variability in individuals with post concussion symptoms

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ABSTRACT

Persistent post concussion symptoms (PPCS) describe the condition when an individual experiences chronic symptoms, particularly fatigue, beyond the expected time of recovery. The aim of this study was to quantify the effect of fatigue and related ongoing symptoms on somatosensory and corticomotor pathways using reaction time (RT) testing, and single-pulse and paired-pulse transcranial magnetic stimulation (TMS). Eighty-three participants (nine female, mean age 37.9 ± 11.5 years) were divided into two groups (persistent symptoms versus asymptomatic) following self-report based upon previously published clinical symptom scores. All participants completed somatosensory and visuomotor RT testing, as well as corticomotor excitability and inhibition measurements via TMS. Participants in the persistent symptom group ($n = 38$) reported greater number of previous concussions ($t = 2.81$, $p = 0.006$) and significantly higher levels of fatigue and related symptoms in the asymptomatic group ($n = 45$; $t = 11.32$, $p < 0.006$). Somatosensory RT showed significant slowing and increased variability in the persistent symptoms group ($p < 0.001$), however no significant differences were observed between groups for visuomotor RTs. Transcranial magnetic stimulation revealed differences between groups for intracortical inhibition at all stimulus intensities and paired pulse measures. The results indicate that somatosensory and corticomotor systems reflect on-going fatigue. From a practical perspective, objective and simplistic measures such as somatosensory and corticomotor measures can be used in the assessment of PPCS and gauging the efficacy of post concussion rehabilitation programmes.

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Concussion; somatosensory reaction time; visuomotor reaction time; transcranial magnetic stimulation

Introduction

Concussion is a complex neurological injury. Heterogeneous signs and symptoms represent underlying neurophysiological disruption following impact-causing deformation of axonal membranes and the opening of membrane-associated sodium-potassium channels (Giza and Hovda 2001, 2014; Stillman et al. 2017). The acute signs and symptoms of concussion can result in a rapid onset of transient neurological impairments that can resolve spontaneously (McCrory et al. 2017). However, as concussion is described as an evolving injury where symptoms can change rapidly, or conversely be delayed, it is suggested that full recovery for a concussion takes between 10 (McCrory et al. 2017) to 28 days (Collins et al. 1999; Broglio and Puetz 2008; Martini and Broglio 2017). A more recent paper reported concussion recovery can take up to >29 days (D'Lauro et al. 2018). In a minority of people, symptoms may continue beyond the expected time frame of recovery. Termed persistent post concussion symptoms (PPCS), approximately 10% of concussed individuals experience chronic symptoms that may continue for a number of months (or longer)(Ryan and Warden 2003; Guinto and Guinto-Nishimura 2014) and include, but are not limited to, headaches, vertigo/dizziness, irritability, emotional labiality or irritability, cognitive difficulty (e.g., concentration), sleep disturbance and/or depression and anxiety (Broshek et al. 2015). Persistent fatigue is one of the most common symptoms reported by sufferers with PPCS, however, it is often under-acknowledged or overlooked in clinical assessments (Johansson and Rönnbäck 2014).

Despite the potentially debilitating impact of PPCS and the continuing demand for objective tools to confirm PPCS status and recovery, assessment options that are reliable and cost-efficient in objectively quantifying PPCS is limited (Heitger et al. 2006). Clinical imaging is expensive, and quantifying structural abnormalities in those with PPCS is not currently achievable (Heitger et al. 2006; McCrory et al. 2017). Application of neuropsychological and cognitive testing to quantify PPCS are the most common techniques. Interestingly, meta-analyses of studies of patients with PPCS (minimum of three months) compared to controls show non-significant differences and small effect sizes (Cohen's

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$d = -0.11$ – 0.04) in cognitive testing outcomes (Binder et al. 1997; Schretlen and Shapiro 2003; Belanger et al. 2005; Frencham et al. 2005a; Oldenburg et al. 2016). However, a recent scoping review suggested that prior work might have been limited in detection via standard assessments, reflecting lack of sensitivity in methods (McInnes et al. 2017).

Conversely, it has been suggested that assessing the sensorimotor system may be useful in objectively quantifying continued symptoms in those with PPCS (Heitger et al. 2006; Pearce et al. 2019). Indeed, interest in somatosensory and motor systems in quantifying on-going concussion symptoms has emerged over the last decade (De Beaumont et al. 2007; De Beaumont et al. 2011; Pearce et al. 2014; Pearce et al. 2015). Examining the motor system, both from a functional and physiological perspective, as an independent functional biomarker encompasses the established knowledge on motor control, its complex functional neuroanatomy and physiology, and the paradigms to assess motor function (Graziano et al. 2002; Heitger et al. 2006; Pearce 2016).

Components of motor testing include reaction time (RT) and reaction time variability (RTv). RT is simply the time measured from the presentation of a sensory stimulus to completion of the motor response, reflecting processing of sensory stimuli, and time for execution of the response (Alibazi et al. 2019). RT can be classified into either 'simple', where there is only one presented stimulus requiring one type of motor response; or 'choice' where there are two or more possible stimuli presented and requiring the appropriate or correct motor response. A generalised measure of cognitive function for over a century, (Merkel 1885; Carter 1938) single and choice RT tasks provides a reliable proxy measure of attention or cognitive control, (Weissman et al. 2006) as the motor response still requires elements of perception, decision making, and response preparation (Botwinick and Thompson 1966; Alibazi et al. 2019). Intra-individual RTv refers to inconsistency in an individual's speed of motor responses following a given stimulus, and has been argued to reflect a subset of abnormally delayed motor responses during reaction time tasks (Kofler et al. 2013). Once thought of as 'data noise' or 'test error', RTv is now believed to reflect an inability to engage cognitive and motor control effectively (Cole et al. 2018). In healthy individuals, homogenous responses (i.e., low RTv) reflect focussed attention towards completing the task. Conversely, high RTv has been observed in the range of neurological impairments including concussion (Stuss et al. 1989; Segalowitz et al. 1997; Favorov et al. 2019; Pearce et al. 2019).

Currently, the neurophysiological mechanisms for PPCS require further elucidation. One non-invasive neurophysiological technique, transcranial magnetic stimulation (TMS), is effective in understanding the corticomotor excitatory and intracortical inhibitory circuits. Stimulating the primary motor cortex (M1), motor evoked potentials (MEPs) provide an understanding of neurophysiological mechanisms in context with functional observation assessments (Hallett 2000; Kobayashi and Pascual-Leone 2003; Pearce and Maller 2018). First developed in 1985 (Barker et al. 1985, 1986) single and paired-pulse TMS has demonstrated reliability, and gained popularity, in measuring the physiology of the central nervous system in both healthy and diseased populations, (Hallett 2000; Kobayashi and Pascual-Leone 2003). The use of TMS has been reported in acute concussion effects and recovery, (Pearce et al. 2015) and the long-term sequelae of multiple concussions (De Beaumont et al. 2009; Pearce et al. 2014; Pearce et al. 2018). As a result, the most recent consensus statement included TMS as a research tool in understanding the physiology of concussion (McCrory et al. 2017). More recently Pearce et al. (2019) utilised TMS to investigate the neurophysiology of PPCS, reporting in those with ongoing symptoms, an association with reduced intracortical excitability and cognitive performance decrements. Extending on this work, the aim of this study was to specifically compare, between those with PPCS reporting persistent fatigue and related ongoing concussion symptoms to those without ongoing post concussion symptoms, the somatosensory, visuomotor, and motor system responses via RT and single-pulse and paired-pulse TMS measures respectively. A secondary aim was to associate RT data with corticomotor responses from TMS. We hypothesised that those with PPCS, who show increased fatigue symptoms would demonstrate slower, less accurate, and more varied RT responses. Further, we also hypothesised that those with PPCS would show increased corticomotor inhibition.

Methods

Following public announcement highlighting the study and calling for volunteers, 83 participants (9 female, 74 male; mean age 37.8 ± 11.5 years) were recruited. Pre-screening inclusion for the study involved participants being 18 years or older, and with the exception of concussion(s), free of upper limb musculoskeletal injury, neurological or psychiatric disorders. Inclusion criteria required participant's ongoing concussion symptoms to be for a minimum of three months, as diagnosed by a clinician (American Psychiatric Association 2013). Control group participants were those who had previously sustained a concussion(s), for a minimum of three months, but without ongoing symptoms (see 'Symptom self-report' section). Participants were excluded if they suffered a moderate or severe TBI, brain injury from a blast explosion, and/or a skull fracture.

Prior to testing, all participants provided written informed consent and were pre-screened for suitability to TMS (Rossi et al. 2011). All testing procedures were completed in one laboratory visit taking approximately 45 min. All procedures were approved by the Institutional Review Board prior to commencement of testing (HREC18005) following the principles of the Declaration of Helsinki.

Symptom self-report

All participants completed questionnaires regarding their concussion injury history (Pearce et al. 2014) and self-assessment of fatigue and related symptoms from the previous four weeks (Johansson et al. 2009). The questionnaire

required participants to respond to each question via a rating scale from 0 to 3, in 0.5 increments with higher scores reflecting greater severity for each symptom-related question. As recommended by the authors (Johansson and Rönnbäck 2014) we used a cut-off score of 10.5 to distinguish between 'symptomatic' PPCS and 'asymptomatic' control groups. Johansson and Rönnbäck (2014) have previously reported that those who scored above 10.5 were also above the 99th percentile for control groups and correlated to significant impacts on activities of daily living.

Reaction time and variability testing

Somatosensory and visuomotor RT was measured using two computer-based applications in randomised order to reduce potential serial effects. Visuomotor testing was completed using CogState online computerised testing programme (CogState, Melbourne, Australia). Participants completed a simple reaction time test ('detection test') where the individual was instructed to respond as quickly as possible by pressing a keyboard key as soon as the card had turned 'face up'. If the individual pressed the key prior to the card being turned face up, this was recorded as an error and contributing to the accuracy metric. The task was completed when 25 correct responses were recorded or the maximum time allowed for the test had elapsed (Maruff et al. 2009). Participants then completed a choice RT test ('identification test') where the subject was required to press a keyboard key representing the 'yes' button if the card was red in colour, or another keyboard key representing the 'no' button if the card was black in colour. If the individual pressed the incorrect response, this was recorded as an error and contributing to the accuracy metric. Similar to the simple RT, the test was completed when 25 correct responses were recorded or the maximum time had elapsed (Maruff et al. 2009).

Somatosensory RT was undertaken utilising a portable vibro-tactile stimulation device (*Brain Gauge*, Cortical Metrics, USA). The instrument, similar in size and shape to a standard computer mouse, comprises of two small cylindrical prods (ø5 mm) positioned at the front of the device to stimulate the region of the distal phalanx for the participant's D2 (index) and D3 (middle) digits (Tommerdahl et al. 2016). Somatosensory RT involved participants, using their dominant hand, to respond to the pulse delivered by the prod, by pressing the same prod as quickly as possible (Holden et al. 2019). No visual stimulus was given on a computer screen. Following familiarisation trials, 20 stimuli were provided at randomised intervals (Tommerdahl et al. 2016).

Surface electromyography (sEMG) and transcranial magnetic stimulation (TMS)

Single and paired pulse TMS was applied over the M1 contralateral to the participant's dominant hand. Surface electromyography (sEMG) activity was recorded using bipolar Ag/AgCl electrodes positioned over the first dorsal interosseous (FDI) muscle at an intra-electrode distance of 2 cm with the ground electrode placed over a bony prominence on the wrist (Wilson et al. 1993b; Pearce and Kidgell 2009, 2010; Pearce et al. 2013). sEMG signals were amplified (×1,000), band pass filtered (high pass at 13 Hz, low pass at 1,000 Hz), digitised online at 2 kHz, recorded (500 ms; 100 ms pre-trigger, 400 ms post-trigger), and analysed using Power Lab 4/35 (ADInstruments, USA). All sEMG methods conformed to the Non-Invasive Assessment of Muscles (SENIAM) guidelines for sEMG (Hermens et al. 1999).

Single pulse monophasic motor evoked potentials (MEPs) were obtained using a Magstim 200^2 stimulator (Magstim Co, UK) with a 70 mm figure of eight coil (Magstim Co, UK). For reliability of coil placement during testing, participants wore a snug-fitted cap with markings of 1 cm spacing in a latitude-longitude pattern (EasyCap, Germany). The cap was positioned with reference to the nasion-inion and inter-aural lines (Pearce et al. 2000).

Determination of the 'optimal site', where the largest MEP amplitude could be observed following supra-threshold TMS, was determined during a controlled, low-level tonic contraction (5% of maximal voluntary contraction) of the FDI muscle, which provides a greater reliability of the MEP than compared to the muscle at rest (Kamen 2004). Identification of the active motor threshold (aMT) was determined by stimulating at very low intensities and gradually increasing the stimulus, at 5% of stimulator output steps, then 1% steps closer to threshold, until an observable MEP of at least 200 μV and associated cSP could be measured in 50% of ten stimuli (Wilson et al. 1993a).

Single pulse MEPs were completed at intensities of 130%, 150% and 170% above the individual's aMT (Pearce et al. 2013). At each intensity 20 stimuli, in four sets of five, were presented at random intervals between 7–10 s. A rest of 30 s was provided after each set and after each intensity level to reduce any potential effects of muscular fatigue.

Paired-pulse TMS was delivered using two Magstim 200^2 stimulators coupled by the BiStim system (Magstim Co, UK). SICI and LICI MEPs was delivered at random intervals between 8–10 s using an interstimulus interval (ISI) of 3 ms and 100 ms respectively. Following previously published TMS protocols in concussion (Pearce et al. 2014; Pearce et al. 2015), SICI MEPs were measured using a conditioning stimulus of 80% aMT and test stimulus of 130% aMT. LICI MEPs were quantified with suprathreshold conditioning and test stimuli at 130% of aMT (Pearce et al. 2014). For both SICI and LICI measures, 15 stimuli, in three sets of 5 pulses, were delivered at random intervals between 8–10 s, with a 30 s break between each set to avoid muscular fatigue.

Data and statistical analyses

Self-report symptom score was totalled from responses from 14 of 15 questions. Twenty four hour variations in sleeping patterns question was not included as only 'yes' or 'no' responses were recorded (Johansson et al. 2009).

The primary outcome measure for visuomotor and somatosensory RT tasks were the speed of responses in milliseconds. CogState accuracy metric was calculated as a

percentage of correct responses divided by the total number of trials. Reaction time variability was calculated as the standard deviation of the reaction time. This method has been previously reported (Zhang et al. 2011; Favorov et al. 2019).

Single pulse active MEP latency was determined from the stimulus pulse to the onset of the MEP amplitude. MEP amplitudes were measured from the peak-to-trough difference of the waveform. Duration of the cSP was calculated from the onset of the MEP waveform to the return of uninterrupted EMG (Wilson et al. 1993a). As it is well acknowledged, the most influencing confounding factor on SP duration is the preceding MEP (Škarabot et al. 2019), thus, we compared cSP:MEP ratio between groups to reduce between-subject variability and reflect a balance between excitatory and inhibitory mechanisms (Orth and Rothwell 2004).

Paired-pulse SICI measures were quantified as a ratio of the paired-pulse test stimulus MEP to a monophasic single pulse MEP at 130% aMT (McGinley et al. 2010; Pearce et al. 2014; Pearce et al. 2015). LICI (Figure 2(b)) was calculated as a ratio of suprathreshold conditioning and test stimuli at 130% of aMT (Pearce et al. 2014).

All data were tested for normality using Shapiro-Wilks tests. As the dependent variables were found to be not-normally distributed we used log-transformed data to compare between groups for fatigue symptom scores, RT variables, and SICI and LICI using independent t-tests. Cohen's *d* was utilised to compare effect sizes between groups with <0.5 (small), 0.50–0.79 (moderate), and ≥ 0.80 (large) used to describe the magnitude of effects (Cohen 1988). A between groups mixed model repeated measures ANOVA were utilised to compare between multiple stimulus intensities (130%, 150% and 170% aMT) for cSP:MEP ratios. Where ANOVA detected differences, post-hoc paired comparisons using Bonferroni adjustment were employed. Associations between depended variables were undertaken using Pearson's *r*. Data is presented as mean and 95% confidence intervals (CI), and all statistical analyses were conducted using SPSS V25 (SPSS Inc., USA) using a significant level of $\alpha < 0.05$.

Results

All participants completed testing with no adverse effects. Table 1 illustrates descriptive data between groups. There was no difference in age ($t = 1.29$, $p = 0.21$; $d = 0.28$). However, the PPCS group self-reported more concussions compared to the asymptomatic control group ($t = 2.81$, $p = 0.006$; $d = 0.63$). The symptomatic group were significantly higher in self-reported fatigue and related symptoms in the previous four weeks ($t = 11.32$, $p < 0.001$; $d = 3.42$), compared to the asymptomatic group.

Reaction time

Reaction time testing revealed mixed results (Table 2). Significant differences and large effect sizes were observed for somatosensory RT ($t = 4.78$, $p < 0.001$; $d = 0.96$) and somatosensory RTv ($t = 3.73$, $p < 0.001$; $d = 0.88$). No significant differences, and small to moderate effect sizes, were observed between groups for visuomotor simple ($t = 1.31$, $p = 0.19$; $d = 0.36$) and choice RT ($t = 0.96$ $p = 0.34$; $d = 0.25$), or simple RT accuracy ($t = -0.80$, $p = 0.42$; $d = 0.16$) and choice RT accuracy ($t = -0.65$, $p = 0.51$; $d = 0.14$).

Table 1. Participant demographics: age, number of previous concussion reported, and self-reported symptom scores (all mean [± 95% CI]).

	PPCS	Asymptomatic
Age (years)	39.71 [35.25–44.16]	36.33 [33.48–39.18]
Previous concussions (mean)	4.07 [2.95–5.20]$^{+}$	2.13 [1.26–3.01]
Fatigue and related symptoms score (Johansson et al. 2009)	20.17 [18.08–22.25]$^{+}$	3.18 [2.25–4.11]

$^{+}p < 0.01$.

Table 2. Reaction time data between groups (all mean [± 95% CI]).

	PPCS	Asymptomatic
Somatosensory RT (ms)	300.04 [268.16–321.92]$^{+}$	230.30 [220.02–240.58]
Somatosensory RTv (ms)	25.60 [20.15–31.04]$^{+}$	14.67 [12.87–16.46]
Visuomotor simple RT (ms)	337.81 [312.99–362.63]	315.04 [301.42–328.67]
Visuomotor simple RT accuracy (% correct)	98.02 [97.11–98.94]	98.44 [97.72–99.16]
Visuomotor choice RT (ms)	454.42 [430.99–477.85]	437.63 [418.65–456.61]
Visuomotor choice RT accuracy (% correct)	94.96 [93.68–96.23]	95.63 [94.03–97.24]

RT: reaction time; RTv: reaction time variability.
$^{+}p < 0.001$.

Transcranial magnetic stimulation

No differences between groups in motor threshold we observed (PPCS: 34.81 [32.75–36.92] vs Asymptomatic: 35.52 [33.20–37.79], $t = -0.21$, $p = 0.83$) or latency (PPCS: 23.76 [23.14–24.37] vs Asymptomatic: 23.27 [22.77–23.77], $t = 1.27$, $p = 0.21$). Comparison of cSP:MEP ratios across three TMS stimulus intensities (Figure 1) between groups showed an interaction effect ($F_{2,162} = 3.73$; $p = 0.02$). Post-hoc pairwise comparisons revealed significant differences in ratios at all intensities (130%: $p = 0.016$; 150%: $p < 0.001$; 170%: $p < 0.001$), with increased intracortical inhibition observed in the symptomatic group (Figure 2). Significant differences were also found for paired-pulse TMS between groups for SICI ($t = -5.27$, $p < 0.001$; $d = 1.11$, Figure 3(a)) and LICI ($t = -4.56$, $p < 0.001$, $d = 1.12$, Figure 3(b)).

Correlations between variables

Correlation analyses on transformed data identified significant correlations between fatigue and related symptoms scores and somatosensory RT ($r = 0.39$, $p = 0.001$) and RTv ($r = 0.32$, $p = 0.006$), cSP:MEP ratios (130%: $r = 0.24$, $p = 0.04$; 150%: $r = 0.38$, $p = 0.001$; 170%: $r = 0.37$, $p = 0.001$), SICI ($r = -0.35$, $p = 0.003$) and LICI ($r = -0.22$, $p = 0.04$). Conversely, no correlations were identified between the number of concussions previously reported with the aforementioned variables. Somatosensory RT showed significant correlations between RTv ($r = 0.74$, $p < 0.001$) and 150% cSP:MEP ratio ($r = 0.25$, $p = 0.02$), SICI ($r = 0.33$, $p = 0.002$),

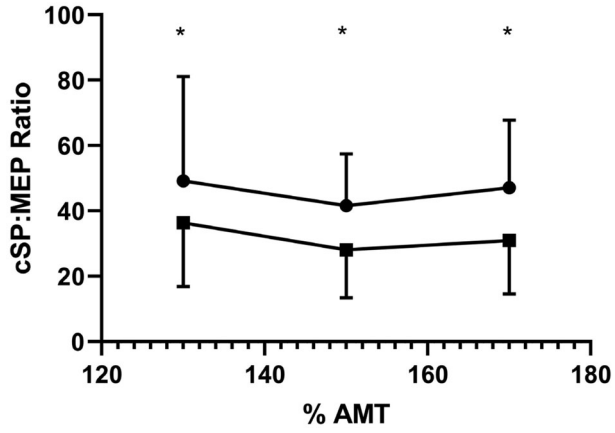

Figure 1. Comparison between groups (circles for symptomatic, squares for asymptomatic) for cSP:MEP ratio at 130%, 150% and 170% above active motor threshold. The higher the ratio, the greater the intracortical inhibition. (*$p < 0.05$).

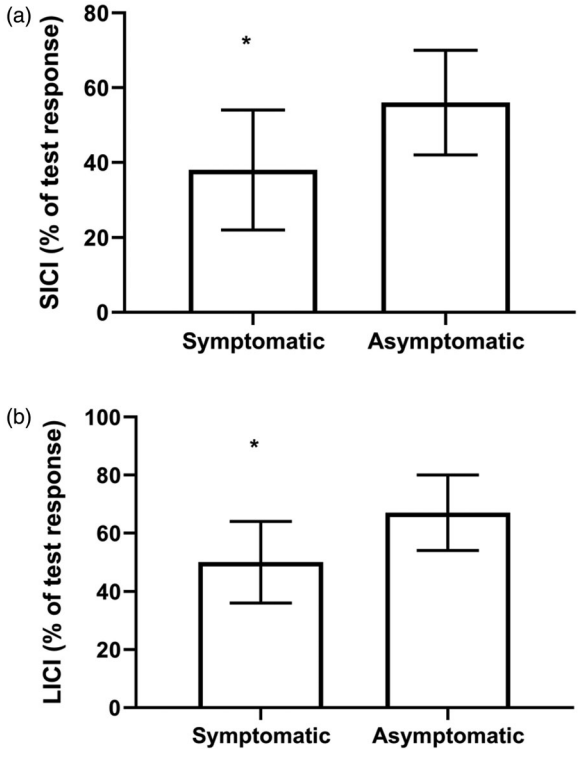

Figure 2. Paired pulse measures for SICI (a) and LICI (b) between symptomatic and asymptomatic groups. (*$p < 0.05$).

and LICI ($r = 0.25$, $p = 0.03$). However, RT did not show significant correlations with 130% and 170% cSP:MEP ratios (both $r = 0.20$, $p = 0.07$). In contrast, somatosensory RTv showed significant correlations with cSP:MEP ratios (130%: $r = 0.22$, $p = 0.04$; 150%: $r = 0.32$, $p = 0.004$; 170%: $r = 0.28$, $p = 0.01$), SICI ($r = -0.25$, $p = 0.02$) and LICI ($r = -0.23$, $p = 0.03$).

Discussion

The aim of this study was to describe RT and neurophysiological responses in a cohort of individuals with persistent post concussion symptoms (PPCS) compared to asymptomatic age match control participants. The data showed that in the symptomatic group who showed high fatigue and related symptom scores, somatosensory RT was slowed and RTv was greater. Conversely simple and choice visuomotor RT showed small to moderate differences between groups, but was not statistically different. Neurophysiological measures showed significantly increased intracortical inhibition in the PPCS group, with correlations to symptoms scores and somatosensory RTv.

While recent work demonstrated neurophysiological changes, along with cognitive impairments, in those with persistent post concussion symptoms (Pearce et al. 2019), this study specifically aimed to investigate the somatosensory, visuomotor, and motor systems in those who report high levels of post concussion fatigue. It is well described that concussion induces a neurometabolic cascade that transiently disrupts neurophysiological function (Giza and Hovda 2001, 2014) with recovery generally between 10 and 28 days. However, Johansson and Rönnbäck (2014) have suggested that if these physiological systems are not fully recovered, neural transmission will be inhibited. The mechanisms of persistent fatigue may reflect abnormal neurometabolic functioning, such as down-regulation of astrocyte glutamate transporters and cerebral sodium/potassium (Na-K) ATPase activity (Rönnbäck and Hansson 2004; Frencham et al. 2005b; Rönnback and Johansson 2012; Block et al. 2013; Johansson and Rönnbäck 2014). Previous research has demonstrated changes in cSP and Na-K ATPase. For example, Placidi et al. (2013) showed reduction in cSP duration and increased Na-K ATPase, reflecting increased cortical activity, associated with loss in REM sleep (which has an antiepileptogenic role). Conversely the results from this study suggest that the increased cSP duration and SICI and LICI reflecting increased inhibited cortical activity from reduced Na-K ATPase activity. However, stronger lines of evidence from previous TMS research suggest that increased corticomotor inhibition such as that seen in this study, reflect altered γ-aminobutyric acid (GABA) activity. Studies have demonstrated that individuals with higher levels of M1 GABA had reduced RT performance (Stagg et al. 2011). Specifically with TMS, previous evidence in a cohort of concussion participants, that measures cSP duration increased, for SICI and LICI is reduced in those with PPCS compared control participants and those to those who had fully recovered (Pearce et al. 2019); however, in this study the association with RT and TMS is less clear. Correlation analyses showed only 150% aMT correlated with slowed RT performance. Conversely, associations between the variability in RT and intracortical inhibition was found at all TMS stimulation intensities. Whilst limited in the number of studies, nearly three decades of research has shown increased variability in those with concussion or mild traumatic brain injury (Stuss et al. 1989; Rabinowitz and Arnett 2013; Cole et al. 2018). Moreover, Segalowitz et al. (1997) demonstrated RT variability was related to underlying electrophysiological changes via electroencephalography P300 amplitude changes following mTBI. This is the first study to show associations with RTv and intracortical inhibition in those with ongoing concussion symptoms.

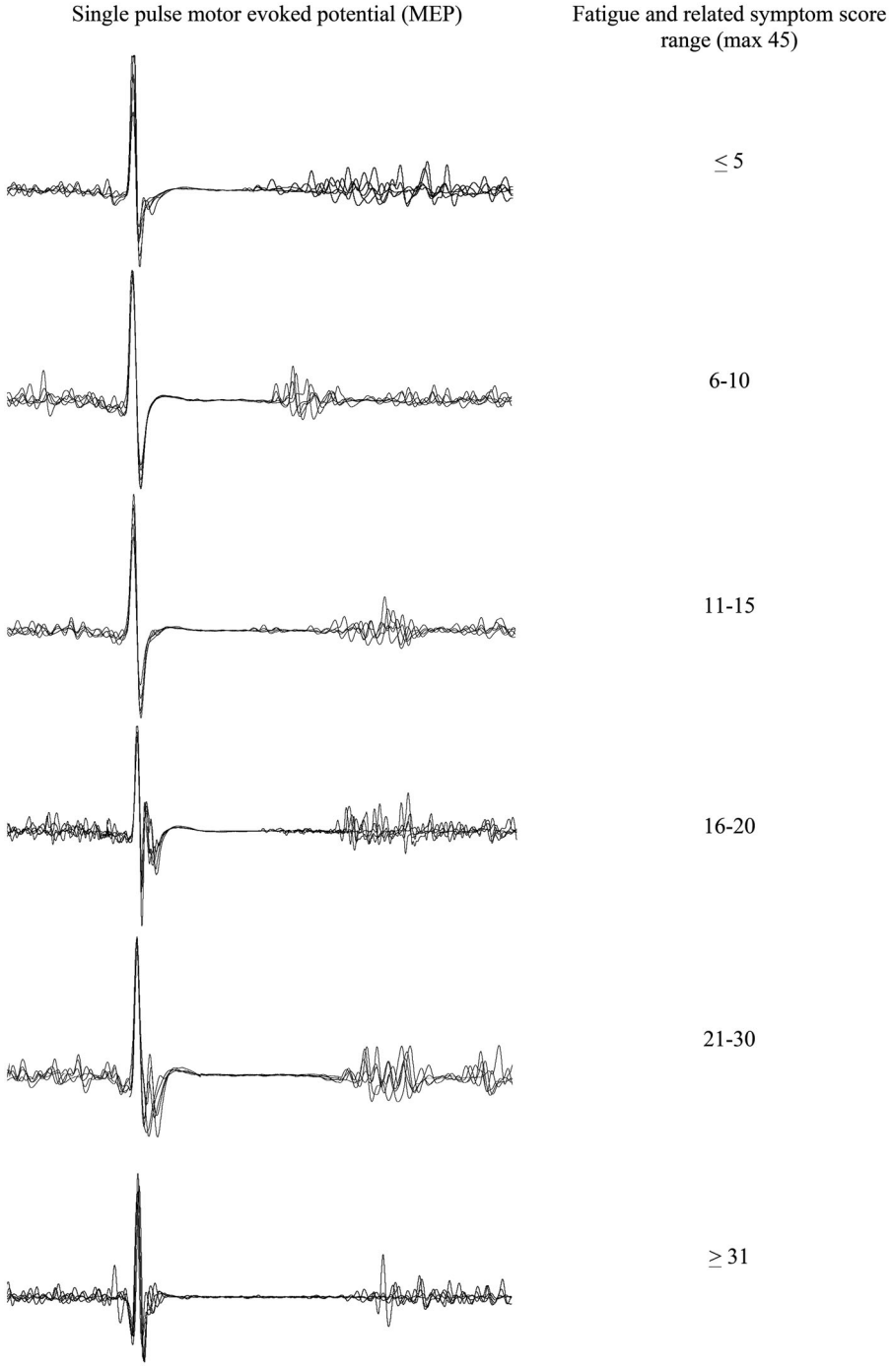

Figure 3. Example of raw TMS sweeps for fatigue and related symptom score 'bins'.

There are two possible reasons why visuomotor RT did not show differences between the groups. However, questions on computer based cognitive assessments that rely on timing (for example with RT) are being raised given overall slowing in timed performance since RT studies first appeared in the 19th Century (Woodley et al. 2013). It has been suggested that the slowing in RT performance may not be due to human competency, but rather increased delays in commercial-grade computer software cognitive programmes, and hardware systems they are being run off (Holden et al. 2019). Moreover Holden et al. (2019) have posited that computer RT testing, requiring a presented stimulus and a mechanical response, has inherent latencies and inconsistencies that may be introduced to the measure by both hardware (computer monitor and keypad or mouse) and software (operating system). These inconsistencies may impact on testing error, increasing the chances of false negative results. Using a tactile stimulus, delivered by a dedicated hardware device designed to store the interval between stimulus delivery and stimulus response (Cortical Metrics, USA), has reduced the potential for software and hardware errors, and this may explain the difference in detecting differences via somatosensory RT task and the visual RT tasks in this study. Holden et al. (2019) demonstrated that visual RT tasks could, depending on the computer systems that they are run on, introduce variability errors on the order of 40 to 80 msec.

Such an error could explain the differences in somatosensory RT/RTv and visual RT/RTv data observed in this study.

It was interesting to observe the correlation of symptoms scores to RT, RTv and intracortical inhibition whereas the number of concussions showed no difference between groups and by proxy, no association to dependent variables. However, as concussion history and symptom severity were self-reported, this should be considered a limitation of the study. Similarly, while we used the suggested cut off of 10.5 on the fatigue and related symptom score (Johansson and Rönnbäck 2014) to compare between groups, this represents that a true randomisation of participants did not occur. However, previous research showed no differences in cognitive and TMS measures between fully recovered concussion participants and age-matched controls (Pearce et al. 2019), we are confident that these findings are not due to sampling error.

In conclusion, the findings of this study suggest the robustness of the somatosensory and motor pathways in detecting persistent fatigue in those with suspected post concussion symptoms. Using non-invasive somatosensory and neurophysiological techniques, we observed slowed reaction times, increased reaction time variability and increased intracortical inhibition to support self-reporting of constant fatigue and related symptoms. Using a multi-modality approach combining both objective measures with patient symptom reporting can assist with current challenges in clinical assessment and progressive measures to assess effective rehabilitation in those with PPCS.

Disclosure statement

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