Mild head injury—a close relationship between motor function at 1 week post-injury and overall recovery at 3 and 6 months

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Abstract

Based on previous findings of impaired eye and arm motor control after mild closed head injury (CHI), this study examined whether early eye and arm motor function, and the level of post-injury cerebral dysfunction manifested in motor control, relates systematically to recovery at 3 and 6 months after mild CHI.

At 1 week post-injury, we assessed oculomotor function, upper-limb visuomotor performance, and cognitive status in 37 mild CHI patients. Re-examination at 3 and 6 months determined outcome in terms of postconcussional symptoms and performance of everyday tasks, as assessed by the Rivermead Postconcussion Symptoms Questionnaire, the Rivermead Head Injury Follow-up Questionnaire and the SF-36 Health Survey. We then examined the association of early motor function, cognitive status and self-reported health condition with outcome using linear regression.

Motor-based regression models explained a high proportion of the variance in outcome (70–89%), with motor function at 1 week being more closely related to outcome at 3 and 6 months than early psychometric assessment (13–32%) or self-reported health status (54–79%). These motor-based models incorporated subcortical/subconscious motor functions alongside motor functions that are subject to volitional control and are primarily mediated by frontal, parietal and temporal cortical brain regions.

Early assessment of eye and arm motor function may help in improving accuracy of outcome prediction after mild CHI. Such assessment may assist in the better targeting of early health care intervention and help decrease head-trauma-related morbidity and rehabilitation costs.
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1. Introduction

Mild closed head injury (CHI) is a significant cause of morbidity with hospital admission rates of between 100 and 300 cases per year per 100,000 population [1,2] and considerable costs for clinical treatment and care. Although most patients with mild CHI recover relatively soon after the injury and return to work and social activities, a number of patients experience disabling persistent postconcussional complaints of both a physical and psychological nature beyond the first weeks following the injury, and sometimes for months or even years [3–18]. During the first 6 months post-injury, an estimated 20–40% of mild CHI cases suffer such

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consequences [4,7–9,15,19–21]. This impacts significantly on daily life and ability to return to work [3,22] and has financial implications for public health care providers [23].

Many studies have tried to identify early predictors of outcome from mild CHI. In keeping with the prediction techniques applied in the context of moderate-to-severe head trauma, studies aiming to predict outcome after mild CHI have examined clinical measures of trauma severity such as Glasgow Coma Scale (GCS), duration of loss of consciousness (LOC) and degree of post-traumatic amnesia (PTA) [7,15,21,24–29]. Others have employed early symptomatic complaints or biochemical markers [16,21,30–32], and both functional and structural imaging techniques [33–36]. However, all of these approaches are limited in their ability to predict outcome after mild head trauma. Neuropsychological assessment has been frequently applied in mild head trauma to study the functional impact of the injury. More recently, computerised neuropsychological assessment tools aiming to gauge injury status and ability to return to play in sport-related injury have shown promising results in terms of demonstrating impaired cognitive function, tracking functional recovery, and improving acute and post-acute management of athletes who have suffered a mild head injury [37–39]. However, neuropsychological assessment is vulnerable to pre-morbid intelligence and other factors such as age, level of education, state of employment and socioeconomic status, and the application of neuropsychological assessment to predict outcome after mild head injury has proven problematic [25,29,40–43].

We have previously reported that mild CHI impairs the complex cerebral networks for eye and arm motor control at 1 week post-injury, causing deficits in volitional saccades, oculomotor smooth pursuit, and upper-limb visuomotor function [44–47]. These motor deficits occur independently of neuropsychological impairment after mild CHI [46]. The profile of motor deficits, in terms of composition of impaired and preserved motor functions, indicated that the adverse bio-physical impact of closed head trauma on the brain [48,49] manifests in eye and arm movement performance and that motor function relates closely to the functional status of the brain after mild CHI [46].

Based on these findings, we conducted a longitudinal study following patients with mild CHI throughout the first year post-injury in order to examine the recovery profile of such motor deficits. The results showed that motor deficits, compared to healthy controls, are detectable up to a year post-injury [45], independent of psychometric status. A second objective of this study was to examine the association between early motor status and overall recovery, and to see whether there is a systematic relationship between eye and arm motor function at approximately 1 week post-injury and outcome after mild CHI. Based on the view that functionality of the brain at an early stage post-injury may relate to, and be indicative of, the course of recovery in the following months, we hypothesised that it may be possible to use the impact of CHI on the complex cerebral networks for motor control as an objective indicator for the functional status of the brain after mild CHI, and subsequently relate early eye and motor function to later recovery. In addition to motor function, we assessed the relationship of self-reported health condition and neuropsychological status at 1 week post-injury with levels of recovery at 3 and 6 months post-injury. These points in time were chosen in keeping with the notion that most of the recovery following mild CHI is likely to occur within the first 6 months [50] and in line with examples of previous studies aiming to predict and/or assess outcome after mild CHI [7,10,15,16,21,22,25,26,29,32,51–54].

2. Participants and methods

2.1. Participants

Thirty seven subjects (13 female and 24 male) with mild CHI (score on the Glasgow Coma Scale [GCS] 13: 4 cases, 14: 12 cases, 15: 21 cases) were recruited from patients presenting with acute head injury to Christchurch Hospital (the principal hospital for a regional population of over 400,000). Patients had to have a GCS score of between 13 and 15 on first assessment, without falling below 13 at any consecutive assessment at the hospital. At the time of recruitment, no standardised method was in practice to assess duration of post-traumatic amnesia (PTA) in patients presenting with mild head injury to the Emergency Department at Christchurch Hospital and PTA duration was not routinely noted in patient files (apart from brief comments on the lack of recall of the injury-event if applicable). Hence, an iterative process was used to (a) confirm that PTA was less than 24 h (the only required screening criterion) and (b) provide an approximate duration of PTA (the GCS score was the principal factor for CHI classification). At the initial pre-recruitment interview at the hospital, patients were asked about their first memory following the injury. If the remembered event fell within a 24 h period, it was assessed whether the patient remembered being at the scene after the accident/regaining consciousness, being helped by others (e.g., extraction from a vehicle, somebody clearing their bike off the street or calling an ambulance), the arrival of the ambulance (if applicable, standard response time of ambulances within city boarders taken as time approximation), being in the ambulance, arriving at the hospital (time was recorded on admission sheet as was time of accident in the case of MVAs and most sport accidents), treatment events for which the time was noted on the patient chart, and being served a meal (usually dinner or breakfast for patients who stayed overnight). All patients had experienced PTA ranging between 2 min and 22 h (median 15 min) and 32 patients had a confirmed loss of consciousness (LOC, median 2.0 min, range 0.5–15 min). Duration of LOC was, in most cases, established from the available patient records. Most of the patients, in particular those involved in sports and motor vehicle accidents, had a witnessed LOC, with duration recorded in the ambulance/patient notes. Mean age was 29.1 years (SD 12.7, range 15–56 years) and

mean years of education 13.6 (SD 2.56, range 8–19 years). All patients were either employed or attended institutions for secondary or tertiary education and none was involved in litigation. Other potential participants were excluded if there was evidence of any influence of alcohol or psychoactive drugs at time of injury (as the effects of alcohol/drugs may distort scores on the GCS), regular intake of psychoactive drugs or history of drug abuse (risk of GCS distortion; influence of psychoactive medications on eye movement control), central neurological disorder or psychiatric condition (several such conditions are known to affect eye movement patterns in particular), structural brain damage or haematoma on CT head scan (obtained in nine participants and normal in all cases), signs of vestibular dysfunction or oculomotor or somatomotor deficits upon clinical examination, presence of strabismus, visual acuity worse than 6/12, skull fracture, or prior history of mild, moderate or severe head injury with persisting symptoms or complaints. These criteria were consistent with a previous study [46].

Throughout the study, none of the participants was hospitalised or developed secondary health problems related to other causes which could have influenced any of the measures. Subjects were offered compensation for travel costs to attend the testing at the hospital but received no other payment. The project was approved by the Canterbury Ethics Committee and written consent was obtained from all participants.

2.2. Motor assessment

2.2.1. Oculomotor testing

The assessment methods, paradigm parameters, and key measures of motor performance were identical to an earlier study and have been described in detail elsewhere [44,46,55]. Eye movements were recorded using an IRIS infrared limbus tracker (Skalar Medical, BV, Delft, The Netherlands) [56]. We incorporated paradigms for reflexive saccades (44 saccades, stimuli jumping randomly by 5, 10, 15, 20, 25 or 30° in a horizontal direction, at intervals varying pseudorandomly between 1.0 and 1.6 s), antisaccades (32 saccades, stimuli at 5 and 15° off centre, at intervals varying pseudorandomly between 1.0 and 1.6 s, balanced for left and right), memory-guided sequences of saccades (6 different sequences, each with 4 steps, duration of 1.0 s per step, each sequence practised 5 times, then performed once, followed by presentation of the next sequence), self-paced saccades ('do-as-many-as-possible'-self-pacing for 30 s between 2 stationary targets, ±15° off centre) as well as sine and random oculomotor smooth pursuit (sine at 40 and 60°/s peak velocity, and random smooth pursuit, mean peak velocity 80°/s, each task 40 s duration). The only change from our earlier study was the presentation of the antisaccade paradigm by way of video screen using different colours for fixation (red) and antisaccade stimuli (green), rather than by red LED (light-emitting diode) bar.

Mean values of the key measures over all trials in a particular test paradigm were used in analyses. Each paradigm was performed only once by each subject. Before the test proper, subjects were shown an example of each paradigm in order to familiarise them with the task requirements. Several key measures were taken including saccade latency (ms) (reflexive, anti- and self-paced saccades), saccade velocity (°/s) (reflexive, anti- and self-paced saccades), number of self-paced saccades within 30 s, directional errors (antisaccades and memory-guided sequences), and, for all saccadic paradigms, the mean absolute position error of the final eye position ($PE = |(EP_{fin} - SP)/SP| * 100$), and gain (eye position/stimulus position) of the primary saccade ($G_p = EP_{prim}/SP$) and final eye position ($G_F = EP_{fin}/SP$), where EP_{prim} is the eye position after the initial saccade, EP_{fin} is the final eye position and SP is the stimulus position [46]. For memory-guided sequences, an amplitude error (AE) was also derived for all sequence steps [44], based on the view that a sequence of saccades may be perceived as a motor pattern of amplitudes and rhythm performed in an automated manner, irrespective of spatial validation. The AE is based on movement size rather than the absolute size of error between final fixation and stimulus position (AE = mean difference [%] between observed saccadic vs. stimulus amplitude) [44]. An 'absolute time index' (ATI = subject's total response time/duration of the sequence) was also calculated for memory-guided sequences [44]. Key measures for oculomotor smooth pursuit were the average eye peak velocity (°/s) after removal of all saccades from the tracking performance and the tracking lag (ms).

Overall, the oculomotor assessment provided 35 variables (29 variables resulting from the saccadic paradigms and 6 variables from oculomotor smooth pursuit) for the pool of independent measures for the regression analyses.

2.2.2. Upper-limb visuomotor testing

The test set-up and paradigm parameters were identical to our previous study [46], comprising tests of visual acuity, visual perception and resolution, basic arm motor function (movement speed and steadiness) and several one-dimensional (1D) visuomotor tracking tasks (sine and random preview/non-preview and step tracking) [46,57].

Subjects were seated in front of a colour monitor with an eye-to-screen distance of 132 cm [46,57]. The 1D tracking tasks used a steering wheel as subjects' output sensor, which moved a vertical white arrow (16 mm high, 11 mm wide) horizontally on a black background [46,57]. Subjects placed their preferred hand at a fixed position on the steering wheel [46,57]. Key measures for all 1D tracking tasks were the mean absolute error (mm; horizontal distance between arrow head and target) and tracking lag (ms) [46]. The upper-limb visuomotor assessment provided 13 variables for the pool of independent measures for the regression analyses.

2.3. Neuropsychological tests

Attention, working memory, episodic memory and speed of information processing were assessed using the Paced Auditory Serial Addition Task (PASAT) [58], the California

Verbal Learning Test I (CVLT) [59], Symbol Digit Modalities Test (SDMT) [60], and the Trail Making Test A+B (TMT A+B) [61]. General cognitive performance was evaluated with the Vocabulary Test and Matrix Reasoning subtests of the Wechsler Abbreviated Scale of Intelligence (WASI) [62]. Standardised instructions were followed for all tests. The neuropsychological measures provided 27 variables for the pool of independent measures for the regression analyses.

2.4. Health status measures

The study incorporated several health assessment measures to quantify the subjects' current health condition, level of postconcussional complaints and impact of CHI on performance of everyday tasks. These measures were the SF-36 Health Survey (version 2) (SF-36, 8 functional scales and two summary scores) [63], the Rivermead Postconcussion Symptoms Questionnaire (RPSQ, severity of 16 postconcussional symptoms, ranging from zero, i.e., "not experienced at all", to four, i.e., "a severe problem") [64], and the Rivermead Head Injury Follow-up Questionnaire (RHIFQ, specific problems on 10 everyday tasks, rated on a scale from zero, i.e., "no change compared to pre-injury status", to four, i.e., "a severe change compared to pre-injury status") [65]. Summary scores for the RPSQ and the RHIFQ were calculated as the sum of scores on all symptoms or tasks for each questionnaire. Overall, the three health status questionnaires provided 38 variables for the pool of independent measures for the regression analyses.

2.5. Procedures and statistical analysis

Patients were assessed within 1 week of injury (mean 5.5 ± 3.0 days) and then at 3 months (90 ± 5.5 days) and 6 months (182 ± 15 days). Repeated measures-ANOVA was applied to examine whether the CHI group showed an improvement on the applied health status measures during the first 6 months post-injury. Multiple linear regression was applied to explore the relationship of motor function, neuropsychological performance, or health status in the CHI group at 1 week with health status and outcome at 3 and 6 months post-injury. Separate models were calculated for each outcome measure. Outcome measures were the SF-36 Physical summary, SF-36 Mental summary, summary score on the RPSQ, and summary score on the RHIFQ at 3 and 6 months respectively. The outcome measure was defined as the dependent measure in each case. Independent (predictor) variables were the 1-week measures, these being either the measures of motor performance or neuropsychological function, or the patients' 1-week scores on the SF-36 scales and all items on the Rivermead questionnaires. Stepwise-forward regression analysis was used to generate each model. The 'F-to-enter' was 1.0, the 'F-to-remove' 0.5.

The maximal number of steps (i.e., number of independent variables included in each model) for the 3 and 6 months models was limited to 20, in order to help preserve the reliability of the resultant estimates. No models were affected by this limitation, as the number of included variables always fell short of 20 (i.e., in each model, there were less than 20 independent variables that made unique and non-redundant contributions of sufficient power to explaining variance in outcome). The relatively high threshold of 20 variables (i.e., high in terms of 'over-fitting'-risk based on the present number of cases) was chosen due to the nature of the research question asked. It was not the primary aim of this analysis to create models that could unequivocally describe outcome with a minimal number of key independent variables in every new case of mild CHI but to compare the relative capacity of different functional modalities (i.e., motor, psychometric, self-reported health status) at 1 week to relate to and potentially describe outcome. An important element of the comparison between different modalities is the functional diversity that can be captured. This is indirectly expressed in the number of variables that can make useful and independent contributions to the respective models. This comparison is not possible if the number of in-model variables is too restricted.

The interpretation of the strength of association of each model with the respective dependent variable was based on the adjusted R^2, which takes into account the number of independent variables and measures the amount of variance in outcome explained by the in-model variables. The relative contribution of each of the respective in-model variables was quantified by standardised regression coefficients (beta).

Normal-probability plots (plotting the residuals versus their expected normal value) calculated for the regression models showed that the residual values in all models were normally distributed. This confirmed that the distribution of variables in these models was sufficiently normal and that the relationships between the dependent and independent variables was appropriately linear, thereby providing a reliable quantification of the relationship between the respective independent measures and each dependent variable.

3. Results

3.1. Recovery of the CHI group on the applied health status (outcome) measures

The health status of the CHI group improved markedly in the time period between 1 week and 3 and 6 months post-injury. Most of the improvement in health condition was achieved within the first 3 months (Fig. 1). Repeated measures-ANOVA showed that the improvement in health status across the first 6 months was statistically significant on all measures, including the total on the RPSQ [$F(2,72) = 20.61$, $p < 0.00001$], RHIFQ [$F(2,72) = 43.3$, $p < 0.00001$], the SF-36 Physical summary [$F(2,72) = 87.77$, $p < 0.0001$] and the SF-36 Mental summary [$F(2,72) = 16.82$, $p < 0.00001$].

3.2. Association between functional status at 1 week and outcome at 3 months

Overall motor performance at 1 week post-injury showed much stronger associations with levels of recovery at 3 months than early health status or neuropsychological performance (Table 1). The models based on all measures of motor function (i.e., the combined application of oculomotor and upper-limb visuomotor measures) showed the best relationship with outcome, explaining 85–89% of the variance in the scores on the applied health assessment measures. In fact, models incorporating exclusively saccadic measures were almost as good and showed only a small reduction in predictive power compared to mixed eye and arm modalities. Conversely, the ability of only upper-limb visuomotor performance at 1 week to explain variance in outcome was much smaller.

The models based on independent variables from all health assessment measures at 1 week (i.e., all SF-36 scales and all items on the Rivermead questionnaires) related to outcome almost as well as the combined eye and arm or the saccade-based models (Table 1). Yet, the relationships between these models and outcome at 3 months were not quite as strong as those observed for the models based on combined motor measures, and overall health status at

1 week post-injury could only account for 54–79% of the variance in outcome at 3 months.

Neuropsychological status at 1 week showed poor associations with outcome at 3 months (adjusted R^2 13–32%) and only a few neuropsychological measures made any useful contributions to the calculated models (Table 1). For the SF-36 Mental Health summary at 3 months, no model with significant associations could be formulated based only on measures of psychometric status at 1 week.

The number of in-model measures in each model roughly equated to predictive performance. There was no consistent prevalence of any specific motor, neuropsychological or health status measures across the respective models (Tables 2a and 2b) (i.e., no specific measure or clusters of measures within the different modalities showed a universally strong relationship with all outcome measures). Measures of reflexive saccades, antisaccades, memory-guided sequences, and self-paced saccades were found in most models incorporating the contribution of oculomotor measures. These measures covered different motor domains, such as saccadic velocity, latency, accuracy and directional errors. Conversely, measures of oculomotor smooth pursuit featured less frequently. The numbers of in-model measures in the models including only saccadic or only upper-limb visuomotor measures differed considerably from each other, indicating a greater prevalence of eye movement measures able to contribute unique, independent aspects to explaining variance in outcome. The combined models of eye and upper-limb motor measures showed a slightly increased integration of upper-limb visuomotor measures compared to the mono-modal, 'upper-limb-only' models.

In the models based on psychometric status, variables from the WASI, TMT and CVLT were most prevalent. Measures of the PASAT were less common (only present in the model predicting the SF-36 Mental Summary at 3 months), with the SDMT not being represented at all.

The models based on self-reported health status commonly included a number of items from each questionnaire, although the prevalence of variables from certain questionnaires differed slightly depending on the predicted outcome variable.

3.3. Association between functional status at 1 week and outcome at 6 months

As observed with outcome at 3 months, motor performance at 1 week post-injury had the strongest relationship with outcome, showing stronger associations with levels of recovery at 6 months than health status or neuropsychological status at 1 week (Table 1).

The models based on a combined selection of oculomotor and upper-limb visuomotor measures showed the best relationship with outcome and could explain 71–85% of the variance in the scores on the applied health assessment measures. As at 3 months, models incorporating exclusively saccadic measures also showed strong relationships with
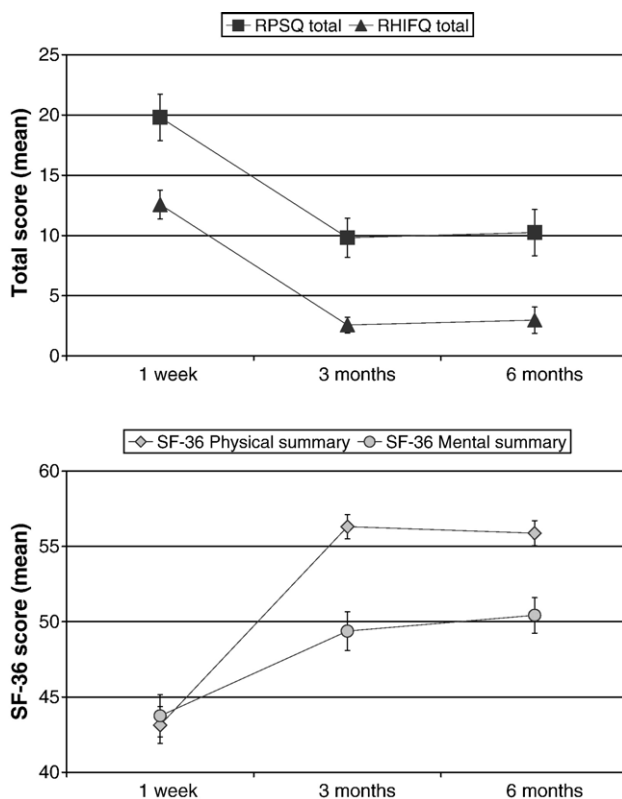

Fig. 1. Improvement on the applied health status measures (dependent 'outcome'-variables in regression analyses) during the first 6 months post-injury (note: low scores on the RPSQ and RHIFQ represent better health status, whereas, on the SF-36, high scores represent better health status). Error bars show standard errors.

Table 1
Stepwise-forward multiple regression: associations between functional status at 1 week and health status at 3 and 6 months

Independent measure pool		Health assessment measures at 3 and 6 months post-injury (dependent variable)														
		SF-36 Physical summary				SF-36 Mental summary				PCS sum (RPSQ total)				Everyday tasks (RHIFQ total)			
		3 months		6 months		3 months		6 months		3 months		6 months		3 months		6 months	
			p-level		p-level		p-level		p-level		p-level		p-level		p-level		p-level
Saccades only	Adjusted R^2	0.78	<0.00001	0.70	0.00003	0.74	0.0002	0.43	0.002	0.70	<0.00001	0.65	<0.00001	0.88	<0.00001	0.82	<0.00001
	Standard error of estimate	2.06		2.97		3.20		5.51		5.44		6.45		1.46		2.72	
	Number of qualifying measures in model	14		10		16		7		8		6		11		10	
Upper-limb visuomotor measures only	Adjusted R^2	0.20	0.02	0.22	0.02	0.08	0.05	0.13	0.13	0.49	0.0003	0.20	0.03	0.63	<0.00001	–	no variables in model
	Standard error of estimate	4.35		4.48		7.42		6.66		7.09		9.50		2.43		–	
	Number of qualifying measures in model	3		4		1		7		7		5		5		0	
Combined eye and arm motor measures (saccades, oculomotor smooth pursuit, upper-limb)	Adjusted R^2	0.85	<0.00001	0.85	<0.00001	0.89	<0.00001	0.73	0.00005	0.86	<0.00001	0.81	<0.00001	0.87	<0.00001	0.71	<0.00001
	Standard error of estimate	1.72		2.06		2.17		3.83		3.83		4.80		1.56		3.33	
	Number of qualifying measures in model	12		15		12		13		10		13		8		10	
Neuropsychological measures	Adjusted R^2	0.32	0.003	0.28	0.01	0.13	0.08	0.24	0.02	0.22	0.02	0.17	0.03	0.24	0.004	0.19	0.06
	Standard error of estimate	4.07		4.38		7.32		6.31		8.73		9.55		3.42		5.46	
	Number of qualifying measures in model	4		6		4		5		4		3		2		7	
Health status measures (all items SF-36, RPSQ, RHIFQ)	Adjusted R^2	0.79	<0.00001	0.70	<0.00001	0.54	0.00001	0.69	<0.00001	0.70	<0.00001	0.68	<0.00001	0.75	<0.00001	0.76	<0.00001
	Standard error of estimate	2.25		2.78		5.24		3.95		5.42		6.00		2.00		2.97	
	Number of qualifying measures in model	16		8		4		9		8		8		14		10	

Table 2a
Stepwise-forward multiple regression (SF-36 at 3 months): in-model measures

Independent measure pool	Health assessment measures at 3 months post-injury (dependent variable)					
	SF-36 Physical summary			SF-36 Mental summary		
		Beta	*p*-level		Beta	*p*-level
Saccades only	Memory-guided sequence amplitude error	1.04	0.0001	Antisaccades final gain	2.02	0.0000
	Latency of self-paced saccades	−0.86	0.0000	Antisaccades absolute position error	−1.96	0.0000
	Peak velocity reflexive saccades — 30°	−0.79	0.0000	Peak velocity reflexive saccades — 5°	1.71	0.0000
	Peak velocity reflexive saccades — 20°	0.72	0.0002	Peak velocity reflexive saccades — 20°	1.35	0.0007
	Antisaccades absolute position error	0.59	0.0001	Peak velocity reflexive saccades — 15°	−1.32	0.0106
	Memory-guided sequence absolute position error	−0.55	0.0136	Peak velocity antisaccades — 15°	1.16	0.0031
	Antisaccades latency	0.52	0.0001	Peak velocity reflexive saccades — 30°	−1.00	0.0002
	Reflexive saccades primary gain	−0.45	0.0006	Correction time directional errors antisaccade task	0.80	0.0001
	Reflexive saccades final gain	0.43	0.0036	Peak velocity reflexive saccades — 10°	−0.76	0.0183
	Peak velocity reflexive saccades — 25°	0.40	0.0209	Reflexive saccades latency	−0.74	0.0000
	Directional errors antisaccade task	0.40	0.0014	Peak velocity antisaccades — 5°	−0.72	0.0559
	Reflexive saccades latency	−0.39	0.0030	Directional errors antisaccade task	−0.69	0.0011
	Directional errors sequence of memory-guided saccades	−0.25	0.0350	Reflexive saccades final gain	−0.60	0.0024
	Erroneous prosaccades latency	0.18	0.1267	Memory-guided sequence primary saccade gain	0.31	0.0187
				Reflexive saccades absolute position error	0.28	0.0334
				Memory-guided sequence absolute time index	0.26	0.0681
Upper-limb visuomotor function only	Upper-limb random preview tracking lag	−1.05	0.0016	Upper-limb movement steadiness	0.33	0.0495
	Upper-limb sine tracking lag	0.64	0.0098			
	Upper-limb sine preview tracking lag	0.57	0.0224			
Combined eye and arm motor measures	Upper-limb step tracking lag	1.76	0.0002	Upper-limb random preview tracking lag	−1.67	0.0000
	Upper-limb step tracking mean absolute error	−1.59	0.0006	Peak velocity reflexive saccades — 15°	−1.03	0.0000
	Upper-limb sine tracking lag	0.66	0.0000	Upper-limb sine tracking mean absolute error	0.99	0.0000
	Upper-limb movement peak velocity	0.65	0.0000	Upper-limb sine preview tracking lag	0.97	0.0000
	Latency of self-paced saccades	−0.65	0.0000	Upper-limb movement reaction time	0.73	0.0000
	Upper-limb random preview tracking mean absolute error	−0.65	0.0021	Upper-limb random tracking lag	−0.63	0.0001
	Lag 40°/s oculomotor smooth pursuit	−0.52	0.0000	Upper-limb sine tracking lag	0.53	0.0001
	Peak velocity reflexive saccades — 30°	−0.48	0.0000	Antisaccades absolute position error	−0.50	0.0000
	Upper-limb sine preview tracking mean absolute error	0.38	0.0134	Peak velocity reflexive saccades — 5°	0.43	0.0017
	Upper-limb movement reaction time	0.22	0.0320	Peak velocity antisaccades — 5°	0.30	0.0011
	Peak velocity reflexive saccades — 5°	0.19	0.0319	Erroneous prosaccades latency	−0.25	0.0042
	Erroneous prosaccades latency	0.11	0.1666	Lag random oculomotor smooth pursuit	−0.24	0.0156
Neuropsychological measures	WASI IQ	0.66	0.0005	TMT B errors	0.49	0.0244
	CVLT trial 1	−0.42	0.0302	TMT B time-to-completion	−0.45	0.0654
	TMT B errors	0.25	0.0885	SDMT (*z*)	−0.39	0.0491
	CVLT serial cluster	−0.24	0.1612	CVLT recall consistency	−0.24	0.1382
Health status measures	Relationship with partner	−0.82	0.0002	Relationship with partner	0.67	0.0001
	Conversation with 1	−0.67	0.0235	Nausea	−0.57	0.0004
	Conversation with 2 or more	0.62	0.0098	SF-36 mental health	0.43	0.0019
	Enjoying previous leisure activities	0.56	0.0021	Finding work more tiring	−0.31	0.0121
	Coping with family demands	0.52	0.0002			
	SF-36 Physical summary	0.51	0.0070			
	Double vision	0.50	0.0036			
	Feeling frustrated	0.46	0.0050			
	SF-36 vitality	−0.42	0.0011			
	Poor concentration	−0.38	0.0088			
	Noise sensitivity	−0.37	0.0077			
	SF-36 bodily pain	0.35	0.0243			
	Irritability	−0.34	0.0138			
	Relationship with previous friends	−0.33	0.0481			
	SF-36 role emotional	0.31	0.0129			
	Routine domestic activities	0.29	0.0486			

Table 2b
Stepwise-forward multiple regression (Rivermead questionnaires at 3 months): in-model measures

| Independent measure pool | Health assessment measures at 3 months post-injury (dependent var.) | | | | | |
| | PCS sum (RPSQ total) | | | Everyday tasks (RHIFQ total) | | |
		Beta	*p*-level		Beta	*p*-level
Saccades only	Peak velocity reflexive saccades — 25°	−0.89	0.0000	Peak velocity reflexive saccades — 20°	−0.92	0.0000
	Memory-guided sequence amplitude error	−0.84	0.0054	Peak velocity reflexive saccades — 15°	0.72	0.0000
	Memory-guided sequence amplitude error primary saccades	0.56	0.0036	Antisaccades latency	−0.69	0.0000
	Memory-guided sequence absolute position error	0.47	0.0484	Antisaccades final gain	−0.50	0.0000
	Peak velocity reflexive saccades — 30°	0.45	0.0020	Directional errors antisaccade task	−0.50	0.0000
	Memory-guided sequence primary saccade gain	−0.39	0.0042	Directional errors sequence of memory-guided saccades	0.49	0.0000
	Latency of self-paced saccades	0.27	0.0292	Latency of self-paced saccades	0.42	0.0000
	Antisaccades latency	−0.22	0.0350	Peak velocity reflexive saccades — 25°	−0.31	0.0114
				Memory-guided sequence amplitude error primary saccades	−0.25	0.0102
				Peak velocity antisaccades — 5°	0.20	0.0603
				Erroneous prosaccades latency	0.19	0.0271
Upper-limb visuomotor function only	Upper-limb random tracking lag	1.81	0.0003	Upper-limb random preview tracking lag	1.30	0.0000
	Upper-limb step tracking mean absolute error	−1.45	0.0399	Upper-limb sine tracking lag	−1.04	0.0000
	Upper-limb random tracking mean absolute error	−1.19	0.0193	Upper-limb sine preview tracking lag	−0.84	0.0000
	Upper-limb step tracking lag	1.10	0.0953	Upper-limb random tracking lag	0.67	0.0009
	Upper-limb sine tracking lag	−0.98	0.0001	Upper-limb step tracking mean absolute error	−0.44	0.0017
	Upper-limb sine tracking mean absolute error	0.85	0.0052			
	Upper-limb movement peak velocity	−0.31	0.0328			
Combined eye and arm motor measures	Peak velocity reflexive saccades — 20°	−0.81	0.0000	Latency of self-paced saccades	1.15	0.0000
	Peak velocity reflexive saccades — 30°	0.67	0.0000	Number of self-paced saccades	0.88	0.0000
	Upper-limb random tracking lag	0.62	0.0002	Antisaccades latency	−0.49	0.0000
	Memory-guided sequence primary saccade gain	−0.57	0.0000	Directional errors sequence of memory-guided saccades	0.39	0.0002
	Peak velocity reflexive saccades — 25°	−0.43	0.0089	Peak velocity reflexive saccades — 25°	−0.39	0.0000
	Lag random oculomotor smooth pursuit	0.36	0.0024	Antisaccades final gain	−0.32	0.0009
	Antisaccades latency	−0.31	0.0009	Upper-limb movement peak velocity	−0.24	0.0076
	Upper-limb random preview tracking mean absolute error	−0.29	0.0486	Upper-limb movement reaction time	−0.17	0.0487
	Peak velocity of self-paced saccades	0.28	0.0183			
	Upper-limb sine tracking mean absolute error	−0.23	0.1300			
Neuropsychological measures	TMT B time-to-completion	0.73	0.0226	PASAT 2.4s pacing (*z*)	−0.49	0.0024
	TMT B errors	−0.62	0.0332	TMT B errors	−0.27	0.0825
	TMT A time-to-completion	−0.36	0.0688			
	CVLT total standard score	−0.34	0.0476			
Health status measures	SF-36 Physical summary	0.63	0.0015	RPSQ total score	−2.78	0.0000
	SF-36 bodily pain	−0.56	0.0011	Dizziness	0.99	0.0000
	SF-36 physical function	−0.42	0.0058	SF-36 physical function	−0.92	0.0000
	Coping with family demands	−0.39	0.0015	Blurred vision	0.70	0.0001
	Relationship with previous friends	0.36	0.0061	Restlessness	0.69	0.0001
	SF-36 general health	−0.34	0.0052	Irritability	0.66	0.0004
	Enjoying previous leisure activities	−0.32	0.0083	Routine domestic activities	−0.58	0.0001
	Restlessness	0.30	0.0072	Noise sensitivity	0.53	0.0127
				Poor memory	0.47	0.0026
				SF-36 role physical	0.43	0.0011
				Poor concentration	0.42	0.0402
				Coping with family demands	−0.38	0.0018
				SF-36 bodily pain	−0.38	0.0069
				Headaches	0.35	0.0127

Table 3a
Stepwise-forward multiple regression (SF-36 at 6 months): in-model measures

Independent measure pool	Health assessment measures at 6 months post-injury (dependent var.)					
	SF-36 Physical summary			SF-36 Mental summary		
		Beta	*p*-level		Beta	*p*-level
Saccades only	Peak velocity reflexive saccades — 30°	−1.25	0.0000	Peak velocity reflexive saccades — 20°	0.84	0.0086
	Peak velocity reflexive saccades — 25°	0.85	0.0009	Peak velocity reflexive saccades — 15°	−0.74	0.0339
	Peak velocity reflexive saccades — 20°	0.76	0.0022	Latency of self-paced saccades	−0.60	0.0008
	Correction time directional errors antisaccade task	0.64	0.0000	Directional errors sequence of memory-guided saccades	0.54	0.0040
	Memory-guided sequence primary saccade gain	0.41	0.0015	Peak velocity reflexive saccades — 30°	−0.52	0.0226
	Antisaccades primary gain	0.40	0.0169	Peak velocity antisaccades — 15°	0.33	0.0513
	Reflexive saccades latency	−0.33	0.0124	Reflexive saccades primary gain	0.25	0.1740
	Peak velocity reflexive saccades — 5°	−0.32	0.0263			
	Reflexive saccades final gain	0.28	0.0660			
	Number of self-paced saccades	0.26	0.0582			
Upper-limb visuomotor function only	Upper-limb random preview tracking lag	−1.15	0.0011	Upper-limb random tracking lag	−1.54	0.0148
	Upper-limb sine preview tracking lag	0.62	0.0158	Upper-limb random tracking mean absolute error	1.44	0.0355
	Upper-limb sine tracking lag	0.52	0.0304	Upper-limb sine tracking lag	0.63	0.0412
	Upper-limb step tracking mean absolute error	0.36	0.0410	Upper-limb sine preview tracking mean absolute error	0.52	0.0383
				Upper-limb random preview tracking lag	−0.46	0.1255
				Upper-limb sine tracking mean absolute error	−0.40	0.2586
				Upper-limb movement peak velocity	0.25	0.1698
Combined eye and arm motor measures	Number of self-paced saccades	1.54	0.0000	Latency of self-paced saccades	−1.10	0.0009
	Peak velocity reflexive saccades — 30°	−1.33	0.0000	Peak velocity reflexive saccades — 20°	1.00	0.0002
	Upper-limb step tracking lag	1.31	0.0086	Number of self-paced saccades	−0.94	0.0032
	Latency of self-paced saccades	1.25	0.0002	Peak velocity reflexive saccades — 30°	−0.82	0.0001
	Upper-limb step tracking mean absolute error	−1.24	0.0156	Upper-limb random tracking lag	−0.80	0.0004
	Peak velocity reflexive saccades — 25°	1.22	0.0000	Upper-limb sine tracking mean absolute error	0.70	0.0004
	Correction time directional errors antisaccade task	0.75	0.0002	Peak velocity reflexive saccades — 25°	−0.68	0.0073
	Lag 40°/s oculomotor smooth pursuit	−0.62	0.0000	Lag random oculomotor smooth pursuit	−0.49	0.0009
	Upper-limb sine preview tracking lag	0.48	0.0017	Directional errors sequence of memory-guided saccades	0.43	0.0043
	60°/s sinusoidal smooth pursuit average peak velocity	0.47	0.0036	Directional errors antisaccade task	−0.41	0.0059
	Erroneous prosaccades latency	−0.30	0.0540	Memory-guided sequence primary saccade gain	0.41	0.0045
	Memory-guided sequence primary saccade gain	0.28	0.0091	Peak velocity antisaccades — 15°	0.36	0.0183
	Upper-limb movement steadiness	0.24	0.0134	40°/s sinusoidal smooth pursuit average peak velocity	−0.20	0.1134
	Directional errors antisaccade task	0.21	0.0500			
	Antisaccades latency	0.15	0.2371			
Neuropsychological measures	CVLT trial 1	−0.71	0.0050	PASAT 1.6 s pacing (*z*)	−0.72	0.0077
	CVLT total standard score	0.70	0.0322	CVLT trial 1	0.64	0.0052
	WASI Verbal T	0.49	0.0154	PASAT 1.2 s pacing (*z*)	0.53	0.0485
	CVLT recall consistency	−0.36	0.0816	CVLT serial cluster	0.51	0.0208
	CVLT recall discriminability	−0.32	0.0564	CVLT list B	−0.44	0.0235
	TMT B errors	0.27	0.0826			
Health status measures	Relationship with previous friends	−0.69	0.0000	Feeling depressed	0.59	0.0011
	Relationship with partner	−0.56	0.0000	Noise sensitivity	−0.57	0.0001
	Enjoying previous leisure activities	0.47	0.0032	SF-36 mental summary	0.52	0.0031
	Conversation with 2 or more	0.47	0.0003	SF-36 mental health	0.45	0.0120
	Sleep disturbance	−0.46	0.0000	Enjoying previous leisure activities	−0.40	0.0081
	Routine domestic activities	−0.38	0.0069	Double vision	0.38	0.0070
	SF-36 role physical	0.31	0.0068	Routine domestic activities	0.31	0.0265
	Coping with family demands	0.26	0.0354	Feeling frustrated	−0.28	0.0289
				Dizziness	0.26	0.0437

Table 3b
Stepwise-forward multiple regression (Rivermead questionnaires at 6 months): in-model measures

Independent measure pool	Health assessment measures at 6 months post-injury (dependent var.)					
	PCS sum (RPSQ total)			Everyday tasks (RHIFQ total)		
		Beta	p-level		Beta	p-level
Saccades only	Peak velocity reflexive saccades — 30°	1.10	0.0000	Peak velocity reflexive saccades — 20°	−1.28	0.0000
	Peak velocity reflexive saccades — 20°	−1.02	0.0001	Peak velocity reflexive saccades — 30°	1.04	0.0000
	Peak velocity reflexive saccades — 25°	−0.60	0.0074	Memory-guided sequence primary saccade gain	−0.65	0.0002
	Memory-guided sequence primary saccade gain	−0.46	0.0006	Peak velocity reflexive saccades — 10°	0.48	0.0005
	Peak velocity reflexive saccades — 10°	0.40	0.0165	Antisaccades final gain	−0.40	0.0008
	Correction time directional errors antisaccade task	−0.29	0.0344	Correction time directional errors antisaccade task	−0.36	0.0013
				Peak velocity reflexive saccades — 25°	−0.34	0.0464
				Memory-guided sequence final saccade gain	0.34	0.0278
				Number of self-paced saccades	−0.29	0.0042
				Memory-guided sequence absolute time index	0.27	0.0064
Upper-limb visuomotor function only	Upper-limb random preview tracking mean absolute error	0.63	0.0150	No variables in model		
	Upper-limb sine preview tracking lag	−0.59	0.0038			
	Upper-limb sine tracking lag	−0.42	0.0546			
	Upper-limb movement peak velocity	−0.33	0.0523			
	Upper-limb step tracking lag	−0.33	0.0670			
Combined eye and arm motor measures	Peak velocity reflexive saccades — 10°	0.83	0.0000	Memory-guided sequence absolute time index	0.74	0.0000
	Upper-limb movement reaction time	−0.81	0.0000	Peak velocity reflexive saccades — 10°	0.72	0.0002
	Peak velocity reflexive saccades — 25°	−0.66	0.0009	Peak velocity reflexive saccades — 25°	−0.62	0.0004
	Antisaccades absolute position error	0.50	0.0001	Upper-limb movement reaction time	−0.58	0.0001
	Memory-guided sequence absolute time index	0.44	0.0005	Peak velocity of self-paced saccades	−0.42	0.0308
	Lag random oculomotor smooth pursuit	0.42	0.0043	Peak velocity reflexive saccades — 30°	0.42	0.0063
	Latency of self-paced saccades	0.39	0.0013	Memory-guided sequence amplitude error primary saccades	0.41	0.0022
	Peak velocity antisaccades — 5°	−0.36	0.0023	60°/s sinusoidal smooth pursuit average peak velocity	−0.27	0.0196
	Peak velocity reflexive saccades — 30°	0.36	0.0397	Lag 40°/s oculomotor smooth pursuit	0.25	0.0247
	Correction time directional errors antisaccade task	−0.31	0.0133	Reflexive saccades final gain	−0.15	0.2421
	Reflexive saccades latency	−0.29	0.0165			
	40°/s sinusoidal smooth pursuit average peak velocity	0.20	0.0692			
	Upper-limb step tracking mean absolute error	−0.15	0.1567			
Neuropsychological measures	WASI IQ	4.75	0.0223	TMT B time-to-completion	0.63	0.0699
	WASI Verbal T	−3.64	0.0119	CVLT trial 5	−0.58	0.0280
	WASI Matrix T	−1.77	0.0474	CVLT long delay free recall	0.54	0.0412
				WASI Verbal T	−0.51	0.0198
				TMT B errors	−0.48	0.1208
				TMT A time-to-completion	−0.42	0.0536
				CVLT trial 1	0.39	0.0679
Health status measures	Enjoying previous leisure activities	−0.57	0.0004	Conversation with 2 or more	−0.85	0.0002
	Participating in previous social activity	0.43	0.0045	RPSQ total score	−0.66	0.0214
	Relationship with previous friends	0.36	0.0040	Conversation with 1	0.64	0.0054
	Sleep disturbance	0.33	0.0031	Slowed thinking	0.62	0.0015
	Coping with family demands	−0.30	0.0208	Light sensitivity	0.54	0.0020
	SF-36 general health	−0.30	0.0125	Nausea	0.45	0.0023
	Relationship with partner	0.29	0.0252	Relationship with previous friends	0.43	0.0017
	SF-36 mental health	−0.28	0.0211	Sleep disturbance	0.37	0.0008
				Blurred vision	−0.33	0.0240
				SF-36 mental health	−0.31	0.0121

outcome at 6 months (adjusted R^2 43–82%) (Table 1), although their power to predict 6-month outcome was generally not as high as that observed for the 3-month outcomes.

The ability of upper-limb visuomotor function to predict outcome at 6 months was substantially smaller than that of measures of oculomotor function. The corresponding models

incorporated only a few measures and no relationship was seen between upper-limb visuomotor function at 1 week and problems on everyday tasks as reported on the RHIFQ at 6 months. However, the combined use of oculomotor and upper-limb measures identified independent contributions from upper-limb visuomotor function for predicting problems on everyday tasks and other outcome measures, this being evident from the integration of upper-limb measures into the combined models, even for the RHIFQ (Tables 3a and 3b).

The models based on independent variables from all health assessment measures at 1 week (i.e., all SF-36 scales and all items on the Rivermead questionnaires) were weaker than the models based on combined eye and arm motor function (Table 1), with early post-injury health status explaining 68–76% of the variance in outcome.

Psychometric status at 1 week did not usefully explain variance in 6-month outcomes. Neuropsychological performance as assessed by the neuropsychological tests deployed in this study could account for only 17–28% of the variance in the applied outcome measures.

The motor-based models continued to include measures from different tasks and functional domains, such as movement velocity, latency, motor accuracy and directional errors of antisaccades and memory-guided sequences (Tables 3a and 3b).

Each model based on the combined application of the SF-36 scales and items from both Rivermead questionnaires incorporated measures from all questionnaires. However, as observed in the motor-based models, the pattern of independent measures and strength of their contribution to the respective models varied according to the dependent variable, and no specific measure showed a consistently strong relationship with all outcome measures (Tables 3a and 3b).

Models based on neuropsychological measures tended to incorporate a higher number of independent measures than observed in the 3-month models but were generally weaker in their predictions.

4. Discussion

The present study indicates a close association between early motor function and levels of recovery and outcome at 3 and 6 months after mild CHI. Motor performance at 1 week related closely to outcome as assessed by the scores on the SF-36 summary scales and each of the Rivermead questionnaires at 3 and 6 months post-injury. Across all regression analyses, the models based on combined eye and arm motor functions consistently showed the strongest associations with outcome measures. This effect of a relative advantage of motor function in relation to outcome was present both at 3 and 6 months. These findings suggest that post-injury motor function, and in particular eye movement performance, may have potential in providing useful indications of outcome, and that early assessment of eye and arm motor function may contribute to a prospective quantification of functional re-

covery at 3 and 6 months following mild CHI, independently of measures of patient self-report and assessment of psychometric status.

The models based on the combined measure pool of SF-36 scales and all scores on postconcussional symptoms and complaints on the two Rivermead questionnaires at 1 week produced models with predictive power that was slightly weaker than that of models based on motor function. The association of the 'symptom/complaint'-based models with outcome was, however, reasonably strong, and much stronger than that of the models based on psychometric status. This indicates that quantification of early postconcussional symptoms and measures of performance on everyday tasks may be preferable to neuropsychological assessment in providing prospective indications of recovery after mild CHI. The finding of associations between the self-reported health status at 1 week and level of recovery at 3 and 6 months post-injury appears to be largely consistent with earlier evidence of an association between early symptomatic complaints and outcome [4,16–18,21,53], although the strength of these associations is variable across studies.

The poor ability of models based on psychometric status (i.e., the pool of 27 measures derived from PASAT, SDMT, CVLT, TMT A and B, and WASI) at 1 week to relate to and predict outcome in the current study may be due to multiple reasons. It was apparent that the neuropsychological tests applied in our study were unable to produce a sufficient number of measures showing significant correlations with outcome at 3 and 6 months, providing unique non-redundant contributions to the respective models. It is possible that this may have been due to the specific selection and limited number of neuropsychological tests. However, all of the tests applied in our study are known to be sensitive to mild head trauma and have been used in numerous other studies to measure attention, short-term, working and episodic/declarative memory, speed of information processing, general cognitive and 'executive' function after mild CHI. Yet, performance on the applied tests incorporates elements of most of these functions, and, therefore, the resulting measures may have been, due to this overlap, too closely related and lacking the diversity needed to provide a sufficient number of measures making unique contributions to the respective models. However, results from earlier studies [7,15,29,53,66] suggest that the use of other neuropsychological tests is not likely to improve the predictive power of neuropsychological assessment.

A crucial factor contributing to the low ability of the psychometric models to relate to outcome may have been the susceptibility of neuropsychological testing to pre-morbid factors such as compensatory abilities, intelligence, educational background, and sociodemographic factors such as employment or socioeconomic status [25,29,40–43,67], resulting in inconsistent relationships between the initial injury severity and the extent of cognitive impairment. This inconsistency is likely to distort the relationship between head-trauma-related cerebral dysfunction and the reflection

of such dysfunction in the neuropsychological test results [40,67]. The dissociation between neuropsychological assessment and the presence of cerebral dysfunction resulting from this distortion is likely to adversely affect the capacity of psychometric assessment to project on outcome.

The higher number of in-model variables in the models based exclusively on saccades compared to the upper-limb models, indicates less redundancy amongst the measures of oculomotor (saccadic) function, and that the eye movement measures were able to make more independent contributions to outcome prediction. In turn, this suggests that the assessment of eye movement function may provide measures able to detect a wider spectrum of independent nuances in brain function than the upper-limb tracking tasks.

Interestingly, the motor-based regression models repeatedly showed contributions of motor measures representing subconscious low-level motor functions (e.g., saccadic velocities, measures of oculomotor smooth pursuit and ballistic upper-limb movement peak velocity). These functions represent basic accessory elements of the functional mainframe underlying cerebral motor output and are mediated by deeper subcortical structures, brainstem, and cerebellum [68–71]. Consistent with the centripetal model of neural dysfunction in CHI [49,72] and evidence of an association between persistent postconcussional complaints and subcortical dysfunction after mild CHI [35,73,74], MRI evidence has shown that the depth of parenchymal lesions is directly related to the severity and duration of LOC and that the depth of lesion is predictive of the recovery level on the Glasgow Outcome Scale at 6 months post-injury [75]. Consequently, it is an intriguing finding of this study that motor measures assessing the function of 'deeper' brain structures, the functional integrity of which is a factor in deciding outcome, are indeed associated with level of recovery. In all motor-based models, these 'subconscious' motor functions featured alongside motor functions that are more influenced by aspects of volitional control (e.g., directional errors, latencies, motor accuracy), primarily mediated by frontal, prefrontal, parietal and temporal cortical motor areas [46,47,68,76]. Due to the complex functional neuroanatomy employed for eye and arm motor processing, motor testing is able to simultaneously sample cortical and subcortical brain function. Taking into account the composition of motor measures in the motor-based regression models, the current results indicate that it is possible to integrate the functional 'make-up' resulting from this sampling process into a model able to describe key aspects of both cortical and subcortical function and relate the corresponding motor performance at 1 week to levels of recovery in the months post-injury.

Our current findings suggest that measures of subconscious and subcortical functioning may be an important element in obtaining a complete picture of the functional integrity of the brain after mild CHI and their inclusion in outcome prediction may be crucial in providing accurate projections on recovery after head trauma. Appropriately,

50% of the models based on early health status featured nausea or dizziness, symptoms which might imply involvement of structures caudal to the grey and white matter junction. Similarly, De Kruijk et al. [16] found the presence of headaches, nausea and dizziness early after mild CHI to be indicative of the presence of postconcussional symptoms 6 months later, this being consistent with the results of other studies showing the association between the early presence and degree of these symptoms and later levels of recovery throughout the first year after mild CHI [4,17,18,21].

Given the strength of the associations between early motor assessment and outcome that emerged in the current mild CHI group, it is likely that our findings describe an effect which is present in the majority of mild CHI patients. It has to be kept in mind, however, that the current models were based on a limited sample size of 37 patients. While this sample size was sufficient to examine deficits in eye and arm motor function during the first year post-injury [45] and compare the association of different functional modalities at 1 week with later outcome, it may be insufficient to support an expectation that the principle of a motor-based outcome prediction will be applicable to the general mild CHI population. Validation of the current models and the relationships between early motor function and outcome in a larger cohort of mild CHI patients is essential before any clinical use of this method can be considered. If future studies confirm the utility of instrumented motor assessment as applied in the present study to predict outcome after mild head trauma, it should be possible to develop a clinical application of this method via a portable laptop-based test instrument making use of compact, video-based eye trackers already commercially available. Instrumented oculomotor assessment has the best potential for the development of a portable and easy-to-use test-kit based on commercially available equipment, and would involve only a small reduction in predictive power compared to an instrument based upon both eye and arm motor measures. Any clinical application of such testing will have to be computerised and fully automated, ready to be used by clinical staff. Preliminary assessments by our group have confirmed the technical feasibility of such a computerised clinical test-kit.

In conclusion, our current findings indicate a strong association of early post-injury motor function with health status and level of recovery during the first 6 months after mild CHI. Instrumented motor testing may provide an objective, quantitative assessment able to improve prediction of outcome while having the advantage of being entirely independent from patient self-report. This, in turn, may benefit patients with mild CHI and help to reduce long-term morbidity resulting from mild head trauma due to the better targeting of early health care intervention.

Acknowledgements

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