Concussion in the Wild: Clinical Utility of Mobile Monitoring of Symptoms and Avoidance Behavior in Adolescents and Adults with Concussion

Kori Durfee - PhD Candidate

Introduction

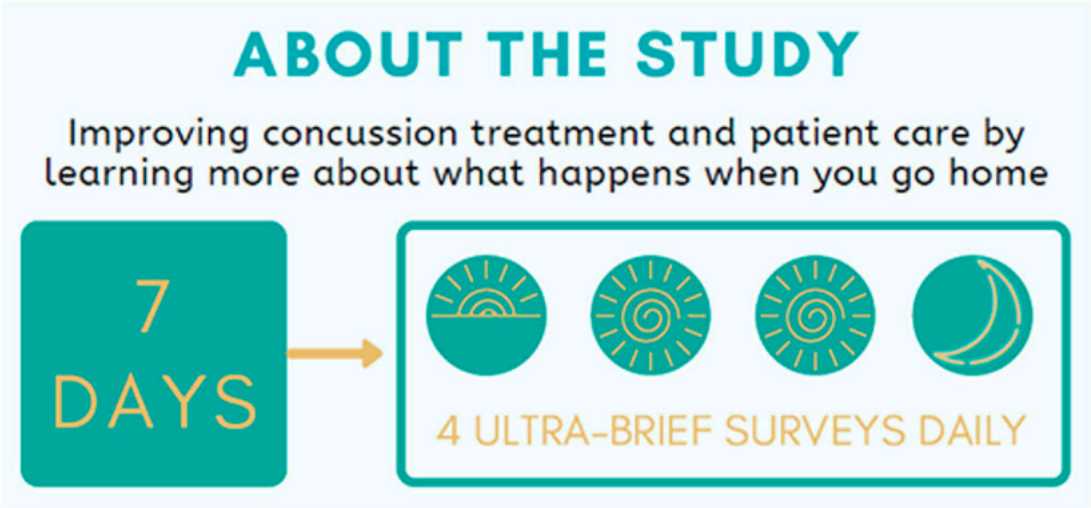
Determining how concussion responds to exposures and behaviors throughout the course of a patient's everyday life is a central focus of concussion assessment and clinical interview (Kontos et al., 2019; Reynolds et al., 2014) and a key criterion for determining recovery (e.g. absence of symptoms in response to activity) (Patricios et al., 2023). Modern ambulatory approaches, including ecological momentary assessment (EMA) hold promise to reduce the burden of gathering this information and increase the accuracy of patient reports by allowing for real-time symptom capture as patients go about their daily lives (Patricios et al., 2023). Critically, few studies have leveraged EMA to monitor concussed patients (Corwin et al., 2021; Sufrinko et al., 2019a; Trbovich et al., 2021; Worthen-Chaudhari et al., 2017) and there remains a relative paucity of information about the clinical utility of EMA approaches in this space.

There is adequate evidence for EMA's ability to help guide clinical care by providing more accurate and comprehensive information, rather than relying on retrospective reports and single-episode performance. Sufrinko and colleagues (2019) not only confirmed that EMA-based symptom ratings correspond well with in-clinic assessments, but they also provided preliminary evidence that EMA-derived ratings have clinical utility. Aligning with previous findings on clinical symptom assessments (i.e., PCSS) (Meehan et al., 2013), brief EMA symptom reports in the first week of recovery was a significant predictor of recovery time, with every 1-point increase in total symptom score resulting in a 2.2-day increase in recovery time. Additionally, they found that summary measures of total symptom response derived from EMA items administered throughout their protocol (>2 weeks of observation) was a better predictor of recovery than gold-standard (PCSS) symptom inventories administered during initial and follow-up clinic visits.

The Mobile Neurocognitive Health (MNCH) Project:

This project leveraged an ecological momentary assessment approach (EMA) to capture symptom severity, environmental exposures, and cognitive performance in concussed patients from a concussion specialty clinic. EMA has the ability to guide clinical care by providing more accurate and comprehensive information, rather than relying on retrospective reports and single-episode performance. Participants were asked to respond to four EMA survey notifications daily, for a one week (i.e., 7 days) following their initial clinic visit, resulting in a total of 28 surveys administered to participants throughout the study. Surveys were scheduled during four 2.5-h time windows throughout each day (i.e., 7:30 AM, 10:30 AM, 3:00 PM, and 8:00 PM).

- The MNCH protocol extends previous ambulatory concussion research in several ways:
  - 1) we included a more comprehensive inventory of symptom ratings and included an item that asked participants to rate how much completing the brief cognitive assessment provoked symptoms
  - 2) we asked participants to report on their exposure to symptom-provoking environments and the degree to which they may have avoided symptom-provoking environments
  - 3) we administered 3 ultra-brief, performance-based cognitive assessments



Please see the MNCH Methods manuscript for more details on the methodology and outcomes utilized in this project.

Study Objectives:

Overall Objective: Describe the clinical utility of the MNCH protocol to support further use and integration into clinical concussion research

- **Aim 1:** Document EMA outcomes (i.e., symptom scores, avoidance behavior, and symptom reactivity) gathered from the MNCH protocol.
- **Aim 2:** Describe the degree of correspondence between the EMA-based symptom ratings derived from the MNCH protocol and clinic-based symptom assessment.
- **Aim 3:** Provide initial evidence for the clinical utility of the MNCH protocol for predicting protracted recovery from concussion ($\geq$28 days).

Methods

Study Design

A prospective, repeated measures design was used for the current study.

Data

This study includes clinical data from our concussion clinic in Fairfax, VA (Inova Concussion Program) and data derived from the MNCH project. As purpose of this study is to document the validity and clinical utility of this tool, rather than documenting daily changes in outcomes, this study will utilize participant's weekly averages for each EMA outcome.

Participants

- Inclusion Criteria:
  - 13-25 years of age
  - diagnosed with a sport or non-sport related concussion by clinical neuropsychologist within 7 days of the injury
  - no history of concussion within the last 6 months
  - willing to use a personal smart phone for data collection
- Exclusion Criteria:
  - evidence of a more severe brain injury (e.g., positive neuroimaging finding, loss of consciousness $\geq$20 min)

– had significant visual impairments that prevented the use of a smart phone

Outcome Measures

In addition to demographics (i.e., age, gender) and health histories, we will be analyzing 6 of outcomes:

- **EMA Data (weekly averages):**
  - **Symptom Assessment:** consist of 15 symptoms that participants rate their current status on a scale of 0 (none) - 100 (worst it could be) (*NOTE: total symptom score was converted to a scale of 0-150 to match scoring of in-clinic symptom assessment)*
  - **Symptom Reactivity:** participants rate their increase/worsening of symptoms after they complete a short neurocognitive assessment (higher score = symptoms worsened after assessments)
  - **Avoidance Behavior:** participants rate on a scale of 0 to 100 (completely avoided) how much they have actively avoided environments/situations that they thought would increase their symptoms
- **In-Clinic Data (from the fist clinical visit):**
  - **Post-Concussion Symptom Scale (PCSS):** consist of 32 symptoms that participants rate their current status on a scale of 0 (none) to 6 (severe) (*NOTE: participants complete this assessment during their clinical exam at the concussion clinic)*
  - **Recovery Time:** the number of days between the date of injury (i.e., date that the patient self-reported that the injury happened) and the day that the patient received medical clearance from their injury by their medical provider
  - **Recovery Groups:** patients with a recovery time lasting longer than 28 days are considered to have a protracted recovery, or a recovery that is lasting longer than expected based on average recovery times reported in the literature

Table 1: **Variables derived from the MNCH study that were utilized in the current study**

EMA Data	In-Clinic Data
- EMA Total Symptom Score (0-150pts)	- PCSS Total Symptom Score (0-132pts)
- EMA Symptom Reactivity (0-1,500pts)	- Recovery Time (days)
- EMA Avoidance Behavior (0-100pts)	- Recovery Groups: *Normal & Protracted*

Data Analysis

Statistical significance was set at $p \leq .05$ for all analyses. All analyses were conducted using R (version 4.5.0), with data manipulation and visualization performed using the **dplyr, tidyr,** and **ggplot2** packages.

Describing the Sample:

- Descriptive statistics (e.g., means, medians, standard deviations, frequencies) were used to describe participant demographics, health history, and injury details

Aim 1:

- Descriptive statistics (e.g., means, medians, standard deviations, frequencies) were used to describe EMA (total symptom scores, avoidance behavior frequency, and symptom reactivity), and in-clinic symptoms (i.e., PCSS) data.

Aim 2:

- A series of Pearson's Product Moment correlations were performed to examine associations between EMA and in-clinic data.

Aim 3:

- Recovery time was calculated for participants with available medical clearance dates in their EMR and used to create NORMAL (<28 days) and PROTRACTED ($\geq$28 days) recovery groups. Recovery group equivalence on demographics, health history, EMA (symptom, avoidance behavior frequency, and symptom reactivity), and in-clinic (PCSS symptom score) data was examined with a series of independent samples t-tests and chi-squares.
- Logistic Regressions (LRs) for EMA Symptoms, in-clinic symptoms, and recovery groups:
  - Separate LRs were used to examine the relationship between PCSS total symptom score and protracted recovery group, as well as EMA total symptom score and protracted recovery group.
  - A multiple LR was performed with both EMA and PCSS total symptom score as predictor variables and recovery group as the outcome.
- Logistic Regressions (LRs) for EMA outcomes:

- A series of LRs were performed to examine the relationship between avoidance scores and recovery group and symptom reactivity scores and recovery group.
- A multiple LR was conducted to identify the unique, and potentially additive, contribution of avoidance behavior and symptom reactivity scores over and above EMA total symptoms for identifying protracted recovery.

Results

Participant Demographics

A total of 110 participants completed the MNCH Study. Given the goal of establishing the clinical utility of these measures, participants with less than 10 surveys completed were excluded from the data analysis (N=16; 14%; 16/115). Further, in-clinic symptom scores (i.e., PCSS) was not available for 10 of the participants (10%, 10/99) and were also excluded from the current study. The final sample included 89 participants:

- mean age of 16.00 years (D=2.92 yrs) and was 67% female (60/89)
- 74% (66/89) of sample sustained a sport-related concussion and 19% (23/89) had a non-sport mechanism of injury (i.e., MVA, fall)
- On average, participants completed 71% (20/28; M=19.94; SD=5.00) of the surveys throughout the one-week period
- Participant demographics and data for clinical and EMA assessments are presented in Table 1

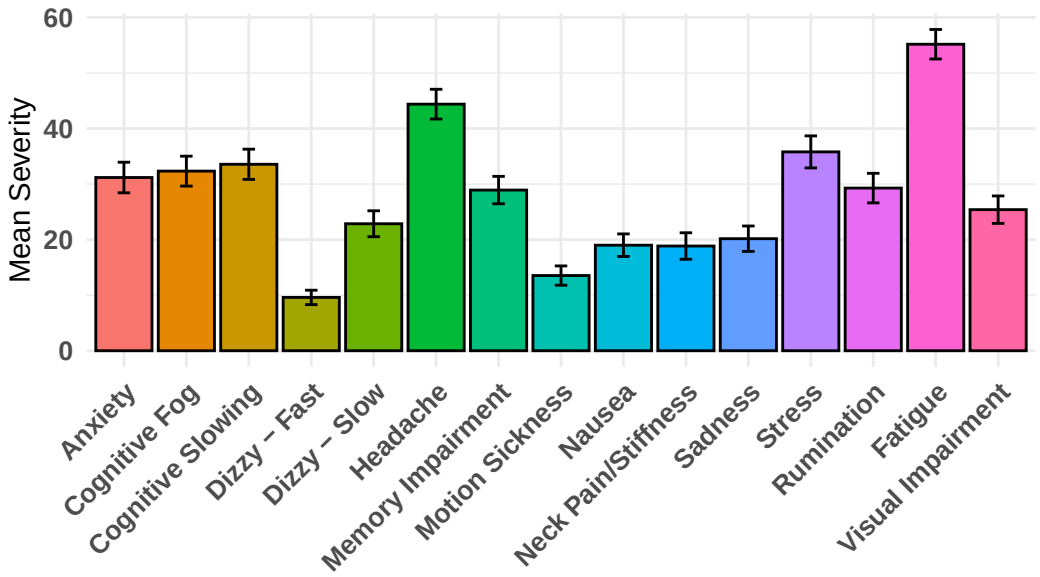
Among the 15 symptoms that were assessed in the MNCH project, on average, participants in the current sample reported the highest symptom severity for "fatigue", "headache", "stress" and "cognitive slowing" and the lowest symptom severity for "fast spinning dizziness" and "motion sickness" (see Figure 1).

Table 2: **Participant health history, in-clinic assessment, and EMA assessment data (N=89)**

	Mean ($\pm$SD) or n (% Within Sample)
Health History:	
Concussion	31 (35%)
Migraine	24 (27%)
Anxiety	31 (38%)
Depression	31 (24%)
ADHD/LD	5 (6%)

	Mean (±SD) or n (% Within Sample)
EMA Data:	
EMA Total Symptom Score	42.0 (±27.1)
EMA Symptom Reactivity	34.2 (±23.4)
EMA Avoidance	26.6 (±20.3)
In-Clinic Data:	
PCSS Total Symptom Score	33.2 (±20.1)

Figure 1. Mean Symptom Severity and Error Bars for EMA Symptoms (N=89)



Associations Between EMA Data and In-Clinic Symptom Scores

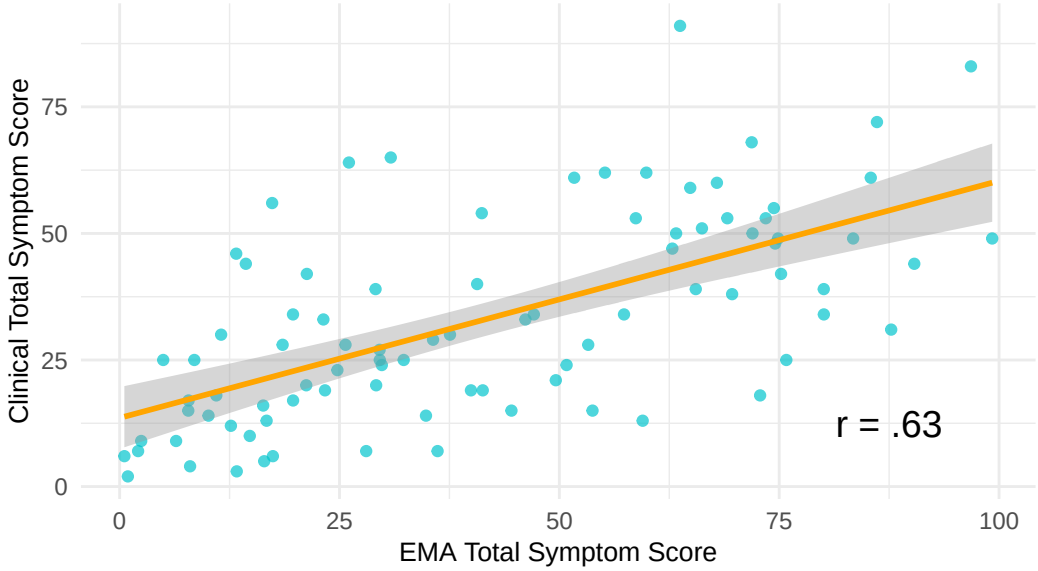
- Total symptom scores from EMA and PCSS were positively related (r=.63; $p < .001$) (see Figure 2)
- EMA total symptom score, symptom reactivity and avoidance behavior were both significantly correlated (see Table 3)

Table 3: **Correlations between EMA and clinical data (N=89). *p<.01**

	1	2	3	4
1. **PCSS Total Symptom Score**	-			

	1	2	3	4
2. **EMA Total Symptom Score**	.63*	-		
3. **EMA Avoidance Behavior**	.55*	.56*	-	
4. **EMA Symptom Reactivity**	.43*	.73*	.50*	-

Figure 2. Association Between EMA and Clinical Symptom Scores



Exploring the Clinical Utility of EMA for Predicting Protracted Recovery

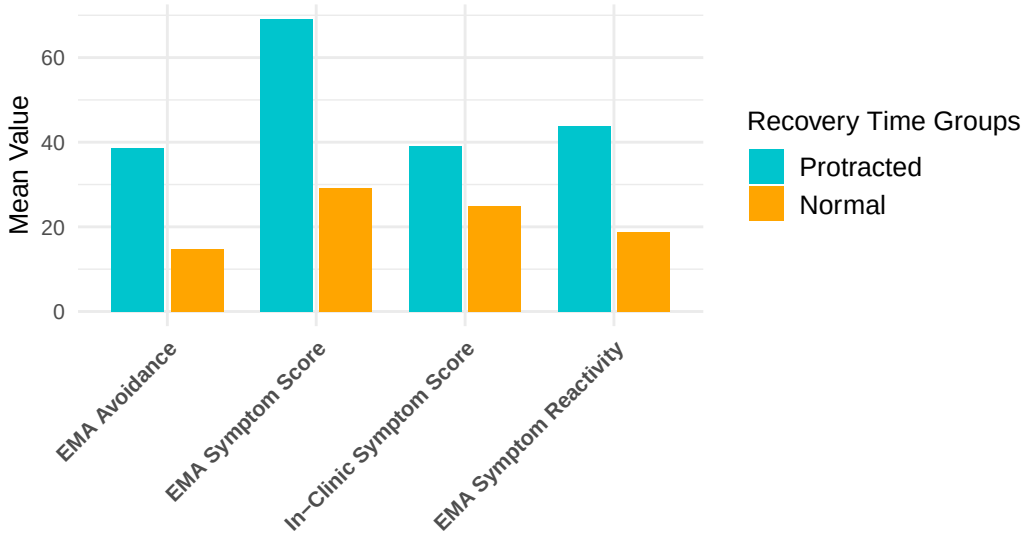
- Recovery time was available for 83% (74/89) of participants
  - Average recovery time of 24 days (SD=15.9; Range: 4-102 days)
    - 55 (74%) participants in the NORMAL recovery group
    - 19 (26%) participants in the PROTRACTED recovery group
- Recovery groups did not differ on demographics or health histories *(see Table 2)*
- However, the PROTRACTED group exhibited significantly higher *(see Table 2 and Figure 3)*:
  - EMA total symptoms ($p = .002$)

- In-Clinic symptom scores ($p = .02$)
- EMA Symptom Reactivity ($p = .04$)
- EMA Avoidance ($p = .02$)

Table 4: **Means and Frequencies for participant demographics, health histories, clinical symptoms, and EMA outcomes for NORMAL (n=55) and PROTRACTED (n=29) recovery groups (N=74). *$p \leq .05$**

	NORMAL Mean Score / Freq.	**PROTRACTED Mean Score / Freq.**	***p***
Demographics:			
Gender (% Female)	64%	68%	.92
Age	15.16	16.68	.09
Health Hx (% Yes):			
Concussion	35%	32%	1.00
Migraine	22%	26%	.93
Anxiety	33%	53%	.20
Depression	20%	37%	.24
ADHD/LD	7%	0%	.54
EMA Data:			
EMA Total Symptom Score	34.82	57.04	.002*
EMA Reactivity	29.97	42.50	.04*
EMA Avoidance	21.14	34.59	.02*
In-Clinic Data:			
PCSS Total Symptom Score	29.56	40.42	.02*

Figure 3. Mean Scores for PROTRACTED (n=19) and NORMAL (n=55) Recovery Groups on EMA and In−clinic Data



- Results from the LRs revealed that total EMA symptoms (p =.003) and total PCSS symptoms (p = .05) both independently predicted protracted concussion recovery (see Figure 4 and 5 for distribution of EMA and in-clinic symptom scores between recovery groups, respectively).
  - However, when both predictors were entered into a multiple LR, EMA total symptoms (p = .02) emerged as the only significant predictor of protracted recovery, not PCSS total symptoms (p = .95).

Figure 4. Distribution of EMA Symptom Scores Between NORMAL (n=55) and PROTRACTED (n=19) Recovery G

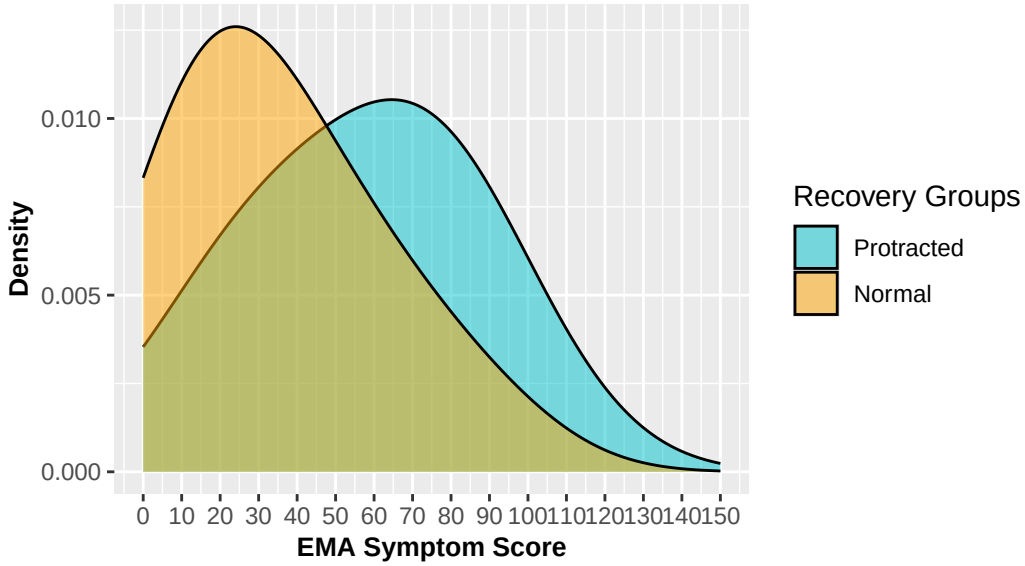
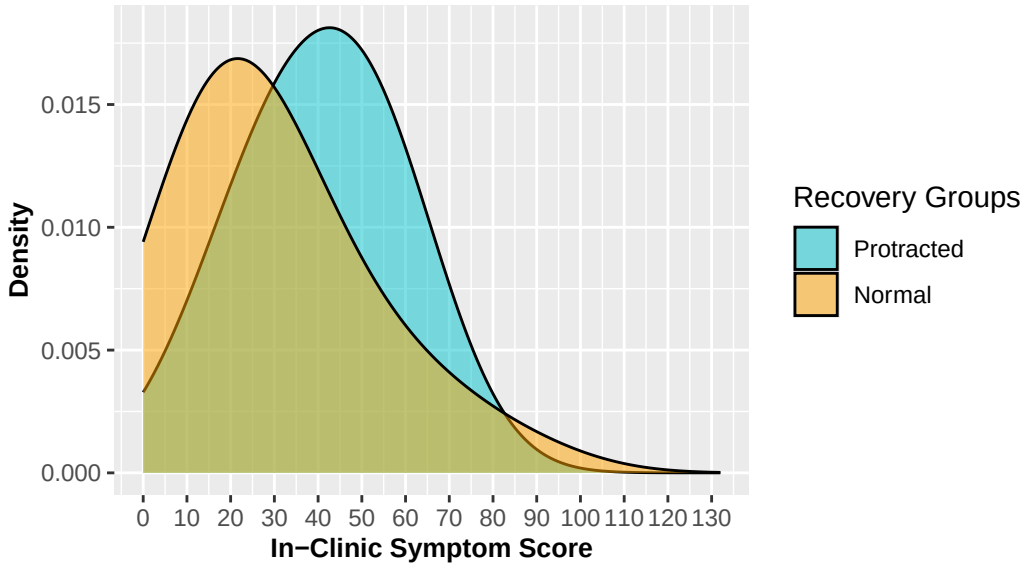


Figure 5. Distribution of In−Clinic Symptom Scores Between NORMAL (n=55) and PROTRACTED (n=19) Re



- Both EMA avoidance behavior ($p = .01$) and symptom reactivity ($p = .05$) were independent predictors of protracted concussion recovery
- Independent LR models examining the risk of protracted recovery associated with avoidance behavior and symptom reactivity showed that avoidance behavior ($p = .01$) and symptom reactivity ($p = .05$) each independently predicted protracted recovery status

- However, when EMA avoidance behavior (p = .24) and symptom reactivity (p = .86) were entered into separate models with EMA total symptom score, EMA total symptom score emerged as the only significant predictor of protracted recovery (p = .04 and .03, respectively).
- This is likely due to the high degree of shared variance between these 3 scores/ratings as seen in the result for the correlations (*r:* .56 - .73) (see Table 3)

Discussion

Study Purpose and Summary of Findings

This study provided an overview and description of the EMA data generated by the MNCH project in a sample of adolescents and young adults by examining the degree to which EMA symptoms corresponded with in-clinic symptoms and by exploring if EMA symptoms corroborates the well-documented prognostic utility of the commonly used in-clinic symptom measure (PCSS) predicting protracted concussion recovery.

- EMA symptoms are significantly correlated with in-clinic symptoms (PCSS)
- EMA Symptoms are a better predictor of protracted recovery than symptom scores derived from the in-clinic assessment

Using EMA Symptoms to Predict Recovery

Consistent with previous reports (Sufrinko et al., 2019), the current study found that symptom reports collected via EMA exhibited greater sensitivity to protracted recovery than symptom scores derived from the in-clinic assessment. When compared head-to-head in a MLR, EMA symptom score accounted for nearly all the predictive variance of the PCSS and ***EMA symptom score contained unique predictive information over and above the PCSS***. This suggests that sampling symptom intensity and burden in real-time, throughout many contexts (including different times of day) results in a more detailed and accurate representation of the state of the injury, which may be useful especially in cases where a patient's symptoms vary considerably across different contexts. For example increased symptoms in busy environments for someone with vestibular/ocular motor impairments). Supporting this, density plots examining the distribution of EMA and in-clinic symptom scores among recovery groups showed a larger distribution of EMA symptom scores across both recovery groups, potentially reflecting inaccurate and minimized retrospective reporting of symptoms during the clinical examination.

Measuring Avoidance Behavior and Symptom Reactivity

The MNCH protocol included continuous monitoring of two novel states/behaviors that have not been explored in previous research, real-time avoidance of symptom-provoking environments and symptom-reactivity to neurocognitive testing. We observed recovery group differences in ratings on both items, although, neither item contained unique information predictive of protracted recovery above and beyond EMA symptom reports suggesting that they indicate a common underlying vulnerability. That is, patients who are experiencing greater symptom intensity in everyday life (and are therefore at greater risk of protracted recovery) may also be more avoidant of symptom-provoking environments and reactive to cognitive exertion. However, it is notable that a single-item rating of avoidance performed similarly to the 15-item symptom rating in its ability to predict protracted recovery.

Clinical Utility of EMA in Concussion

Ambulatory approaches hold the potential to increase access to concussion clinical care and rehabilitation by providing access to difficult to reach populations (Elbin, Womble, et al., 2022). Ambulatory assessments provide additional information about how concussion symptoms and patients with concussion behave in everyday environments (i.e. 'in the wild') and insights into novel aspects of patient experience and behavior that could improve clinical care by exposing features of the injury that are not easily obtained through in-clinic assessments.

Limitations

- Participants were required to have their first in-clinic visit within seven days of their injury to be enrolled in the study. This seven-day enrollment window resulted in an inconsistent collection of data from the in-clinic visit and the start of the EMA data collection window
- The current study included EMA symptom and cognitive assessments only for the first week (i.e., acute) following concussion, which limits the generalization of these findings to other sub-acute and chronic recovery time frames
- The current study excluded participants who completed less than 36% (10/28) MNCH surveys, which are similar to those used in other EMA studies

Future Directions

- Further work is needed to determine whether the MNCH or similar protocols could be used as a standalone tool to support delivery of clinical care (whether in-person or telehealth)

- Future studies that are focused on validating data collected via EMA methodology with in-clinic visits should include other forms of assessments such as the CP Screen (Kontos et al., 2020), Vestibular/Ocular Motor Screen (VOMS) (Mucha et al., 2014), and mood assessments (e.g., anxiety/depression).
- Further research is necessary to better understand how instrumental ratings of avoidance and avoidance behavior might be in understanding concussion recovery and recovery timelines.

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