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ABSTRACT

This study aimed to describe the 24-hour composition of movement behaviors, including sleep, sedentary behavior, and physical activity (PA), among pediatric sports-related concussion (SRC) patients over their recovery period, assess the association between movement compositions and recovery time, and understand feasibility of 24-hour accelerometry in the study population. A cohort of 50 pediatric SRC patients were asked to wear a wrist-worn accelerometer continuously for the duration of their recovery. Among all enrolled participants, the sample was primarily 14 or 15 years of age (65%), female (55%), and recovered in under 28 days (88%). Accelerometer compliance was moderate; 35 participants (70%) were compliant with the protocol. Compositional analysis was used to address time-use objectives in 33 participants who provided adequate data for inclusion. Overall, participants spent an average of 50% of their 24-hour day sedentary, 33% sleeping, 11% in light intensity PA, and 6% in moderate or vigorous intensity PA. The 24-hour composition of movement behaviors was not associated with recovery time ($p = .09$–$.99$). However, the limited sample size may have contributed to null findings. Given recent evidence supporting the effects of sedentary behavior and PA on concussion recovery, future studies should aim to further validate these findings in a larger sample.

KEYWORDS

Concussion; compositional analysis; movement behavior; time-use

Introduction

Sport-related concussions (SRC[s]) are a significant public health concern in the United States (US) (Rivara & Graham, 2014). The prevalence rate of SRCs among US children (<18 years) is between 1,400 and 2,400 per 100,000 children, amounting to 1.9 million cases in 2013 (Bryan et al., 2016). Pediatric SRCs increase the risk of short-term health problems including neurobehavioral changes (e.g., fatigue, nervousness/irritability), cognitive impairment (e.g., slowed reaction times, difficulty concentrating), sleep disturbances, somatic symptoms (e.g., nausea, vomiting, dizziness), and/or emotional symptoms (Willer & Leddy, 2006), and long-term health problems including psychosocial outcomes (e.g., hyperactivity, inattention), psychiatric disorders and premature mortality into adulthood (Sariaslan et al., 2016). However, there is evidence that treatments to decrease symptom severity and reduce recovery time will reduce the effect of short-term health problems, and possibly, longer-term health outcomes (Iverson & Gioia, 2016; McKinlay et al., 2002). Therefore, there is a need to find the most effective treatment protocols to minimize SRC symptom severity and reduce recovery time.

Although historical SRC clinical treatment guidelines prescribe physical rest and adequate sleep until symptoms subside (McCrory et al., 2013), recent evidence has emerged that exercise during the acute phase is safe and potentially more effective than rest for reducing recovery time and minimizing symptom severity (Grool et al., 2016; Leddy et al., 2010; 2019; Majerske et al., 2008; McCrory et al., 2017). Specifically, it has been found that completing sub-symptom threshold (increasing exercise intensity until symptoms present) or submaximal (based on 80% of the participants aged based maximum heart rate) aerobic exercise at any time within the first 7-days of injury, and continuing until fully recovered, leads to fewer and less severe symptoms, and a shorter recovery time (Grool et al., 2016; Leddy et al., 2010).

Aside from exercise, it is also understood that sleep is integral to the SRC recovery process (Jaffee et al., 2015). The majority of athletes suffering from a SRC report sleep dysfunction or disturbances during recovery (Hoffman et al., 2017; Makdissi et al., 2017). This may manifest as shorter or longer sleep duration than pre-injury (Hoffman et al., 2017), difficulty falling asleep or maintaining sleep (Alla et al., 2012), or a diagnosed sleep disorder (Allan et al., 2017; Willer & Leddy, 2006). Additionally, sleep dysfunction is independently associated with many of the same neurobehavioral problems (Paiva et al., 2015; Sadeh et al., 2002), cognitive impairment (Curcio et al., 2006; Kopasz et al., 2010), somatic symptoms (e.g., headaches, dizziness) (Guidetti et al., 2014; Paiva et al., 2015), and/or emotional symptoms (Baum et al., 2014; Gregory & Sadeh, 2012) experienced during SRC recovery. This shared symptomology makes it difficult to discern whether symptoms are related to one or both conditions, or if sleep dysfunction during SRC recovery is exacerbating symptom severity and prolonging recovery (Hoffman et al., 2017). Indeed, sleep dysfunction during SRC recovery may result in greater symptom severity and some cognitive impairments (i.e., reaction time) (Hoffman et al., 2017).

The interrelated and complementary nature of sleep and physical activity may produce stronger recovery effects than their independent effects. In studies on the effect of sleep and physical activity on body composition, aerobic fitness, and blood lipid profile, the combined or concurrent effect of sleep and physical activity appears to be stronger than the independent effect of either sleep or physical activity (Carson et al., 2016; Chastin et al., 2015; Dulloo et al., 2017; Saunders et al., 2016). This suggests there may be an interactive relation between sleep and physical activity (VanderWeele, 2009), which should be measured and tested concurrently for their role in the SRC recovery process.

Aside from the potential effects of sleep and physical activity on SRC recovery, the third movement behavior occurring during a 24-hour cycle, sedentary time, must also be considered. A recent study aimed to understand the effect of screen-time on concussion recovery and found that a reduction of screen-time (approximately 500 median minutes per day) resulted in a faster recovery time (Macnow et al., 2021). It is important to note that there is considerable evidence that screen time is associated with sedentary time to such a degree that it is often considered to be a proxy estimate for sedentary time (Tremblay et al., 2017).

Few studies have used a compositional data approach to investigate the effects of sleep, physical activity, and sedentary time in a 24-hour activity cycle on SRC recovery. Compositional data analysis, while commonplace in the fields of geology, biology, and other scientific fields, has only recently been applied to the health sciences, including epidemiology (Clifford Astbury et al., 2020; Dumuid et al., 2018). This statistical approach yields results that are appropriately adjusted for the codependent nature of movement behaviors, where other more customary procedures fail to do so.

Additionally, few studies have investigated the effects of movement behavior on concussion recovery in a free-living setting. Of the studies investigating the effect of an exercise protocol on concussion recovery, few utilize a device-based objective estimate of activity but rather rely on self-reports of activity levels and completion of the exercise protocol. There are two main limitations with this approach: (1) self-reports of physical activity, even when using a prescribed exercise protocol, are prone to bias (i.e., response, recall, social desirability) (Shephard, 2003); and (2) self-report methods fail to capture total daily physical activity, which includes physical activity occurring during the exercise protocol in addition to any other physical activities occurring during the 24-hour period (i.e., incidental daily movement) (Westerterp, 2009). Finally, while randomized controlled trials (RCTs) assessing the effects of an exercise and screen-time restriction protocol on SRC recovery are important, the field also needs to be informed by larger, free-living settings and assessments. Moreover, RCT results often fail to be relevant, appropriate, and of importance to patients in real-world settings due to their small and unrepresentative samples (Heneghan et al., 2017), This hinders the translation of gold-standard clinical trial data to a clinical best practices model, and ultimately fails to provide patients with evidence-based care.

Therefore, the purpose of this study was (i) to describe the composition of movement behaviors including sleep, sedentary behavior, and physical activity, among pediatric SRC patients during the recovery period and (ii) to assess the association of the composition of these behaviors with recovery time in days. We hypothesized that a normal recovery duration would be associated with higher levels of physical activity and sleep, and lower levels of sedentary time.

Methods

Participants

Data from this prospective observational study were collected from a specialty outpatient sports medicine and concussion clinic from 2020 to 2021. To be eligible to participate, those presenting to the clinic must have been aged 14–17 years at the time of enrollment, must have received a diagnosis of SRC upon exam, and must have been injured within the past 7-days of the initial exam. Exclusion criteria included those who (1) were already taking part in another study that measures their physical activity, sleep, or is related to concussion or musculoskeletal injury; (2) had a clinician diagnosed condition known to affect sleep (e.g., sleep apnea, narcolepsy, depressive or bipolar disorder, etc.); (3) had a clinician-diagnosed neurological disorder; (4) had a co-existing musculoskeletal injury that impacted their ability to be physically active during recovery; or (5) had a sibling or other person living in their household that was already participating in the study. Participants with a diagnosed neurodevelopmental disorder, such as ADHD or a learning disability, were included to increase generalizability.

Data sources

Data were collected at three time points during the study including the initial clinic visit/enrollment, during the recovery period at the patient's home, and at the final clinic visit following clearance to resume all normal activities. At the initial clinic visit, participants were asked to self-report their sex, age, date of injury, sport participating in at time of injury, pre-injury sleep patterns and physical activity (14-days prior to SRC), relevant medical history (i.e., concussion history, migraines, psychological disorders), presence of acute symptoms (i.e., dizziness, headache, vision problems, amnesia), socioeconomic status, and pubertal development (Petersen et al., 1988). Pre-injury sleep patterns were assessed using the Children's Report of Sleep Patterns (CRSP) (Meltzer et al., 2013). Pre-injury physical activity was assessed using the modifiable activity questionnaire for adolescents (MAQ-A) (Delshad et al., 2015; Kriska et al., 1990). Baseline symptom severity was assessed by certified athletic trainers and/or specialty trained neuropsychologists in the treatment and management of concussions using a battery of validated measures for the age group under study. These included the Post-Concussion Symptom Scale (PCSS) (McLeod & Leach, 2012) the vestibular ocular motor screening (VOMS) (Mucha et al., 2014), King-Devick test (Galetta et al., 2015, 2016), and Trails A and B from C3 Logix (Allen et al., 2012).

During the recovery period and while the patient was at home, the 24-hour movement behaviors (physical activity, sleep, sedentary time) were measured using a wrist-worn ActiGraph GT9X Link activity monitor (ActiGraph, LLC, Pensacola, FL) (Hibbing et al., 2018). ActiGraph monitors have been extensively validated in laboratory and free-living conditions to monitor physical activity, sleep, and sedentary time (Ried-Larsen et al., 2012). Only participants whose accelerometer data were considered valid were included in the time-use analysis. Four valid accelerometer wear-days were required for accelerometer data to be considered reflective of average activity levels (Cain et al., 2013); a valid wear-day was defined as having at least 16 hours of valid data. As this study was conducted as a pilot, feasibility of 24-hour wrist-worn accelerometry in a pediatric SRC population was assessed in addition to other study objectives.

At the final clinic visit, when the participant was medically cleared to resume all normal activities, a final self-reported questionnaire was administered. This questionnaire assessed activities and behaviors that may have interfered with sleep during the recovery period using the Children's Report of Sleep Problems (CRSP) (Meltzer et al., 2013).

Definition of exposure: composition of 24-hour time use

Time-use analysis aims to describe the amount of time spent engaging in three distinct behaviors: (i) sleep, (ii) sedentary, and (iii) physical activity. In this analysis, we partitioned physical activity into light physical activity (LPA) and moderate to vigorous physical activity (MVPA) due to the distinct relevance of each to SRC recovery. Inherent to the 24-hour activity cycle, which has a constant denominator of 1440 minutes, is the mutual exclusivity and codependency of time spent in each of the three movement behaviors; time spent in one behavior (sleeping) inherently displaces time in another behavior (sedentary, physical activity). For this reason, it has been proposed by compositional analysts that time-use studies must adjust for the relative changes in time spent in each movement behavior to be statistically sound (Dumuid et al., 2018). Compositional data analysis achieves this goal by using Aitchison geometry to bound the 24-hour activity cycle (the whole) into a closed simplex of vectors (proportions that sum to the whole). Therefore, the composition of proportions of the day spent in each distinct movement behavior serves as the exposure variable.

Definition of outcome: recovery time

The primary outcome of interest was time to SRC recovery. This was estimated as the number of days between the date of injury and the date of full medical clearance. Descriptive estimates were analyzed using a binary outcome, calculated by categorizing participants' time to recovery in days as a recovery of expected length (<28 days) or as protracted recovery (≥28 days). A licensed professional (physician, neuropsychologist, or nurse practitioner) determined medical clearance and was defined as the participant's date of return to unrestricted physical activity and academics participation. This included continuous full days of school without limitations or accommodations and tolerance of physical activity at the level the athlete previously endured (e.g., full contact practice without limitations).

Statistical analysis

Prior to enrollment, a power analysis was conducted to determine the sample size necessary to detect differences in time-use between recovery groups ($n = 272$). All variables of interest used in the univariate analyses and subsequent models to evaluate the effect of a composition of movement behaviors occurring during a 24-hour period on recovery time were assessed for missing data and normality when appropriate. Participant characteristics were evaluated using frequencies and percentages, means and standard deviations (SD), and medians and interquartile ranges (IQR), depending on the variable's distribution. Chi-square and Mann-Whitney tests for differences in frequencies and medians between the normal and protracted recovery time groups were applied, respectively.

While compositional data accounts for the codependent nature of the variables, it renders typical statistical techniques such as linear regression unapplicable. In order to apply these techniques to compositional data, the data must be transformed in a way that allows them to function as absolute values. This analysis uses the isometric log-ratio (ilr) transformation, as proposed by Hron et al., which is recommended for use with linear regression and in analyses that aim to describe the relationship between individual component parts (movement behaviors) and the outcome (Hron et al., 2012). Four linear regression models were used to estimate the association between each type of movement behavior and days to SRC recovery, while adjusting for time spent in other behaviors.

All analyses were conducted using STATA 16.1 (StataCorp. 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LLC) and the open-source software R (Version 3.6.1, R Foundation for Statistical Computing, Vienna, Austria) including internal packages designed for ActiGraph and compositional data analysis such as GGIR and Compositions.

Results

The final sample included 50 adolescents, of whom 44 (88.0%) recovered within 28 days and 6 (12.0%) experienced a protracted recovery. The mean (SD) age was 15.8 (1.2) years, and the majority of the sample was female (52.0%), non-Hispanic race/ethnicity (68.0%), had no concussion history (58.0%), and had no other diagnosed neurodevelopmental disorder (82%). There were no statistically significant differences in these patient characteristics when comparing those who recovered normally to those who experienced a protracted recovery ($p > .05$). See Table 1 for complete descriptive statistics of all enrolled participants ($n = 50$).

Based on the clinical evaluations of the patients, there were no statistically significant differences among those who recovered normally and those who experienced a protracted recovery ($p > .05$) (Table 2). However, those who experienced a protracted recovery did measure a higher median (IQR) score for vestibular-ocular motor dysfunction (normal recovery = 9.0 [3.0–17.0] vs protracted recovery = 17.0 [1.0–37.0], $p = .48$), mean convergence (normal recovery = 2.7 [3.0–17.0] vs protracted recovery = 17.0 [1.0–37.0], $p = .45$), and post-concussion symptom severity (normal recovery = 20.0 [13.0–33.0] vs protracted recovery = 35.5 [15.0–46.0], $p = .24$). On average, patients were seen in-clinic a median (IQR) 2.0 (1.0–4.0) days following the initial injury and this median time did not differ between the recovery groups ($p = .64$).

Descriptive statistics on the participants' physical activity, sleep, and sedentary time are derived from self-report survey data (completed at the initial clinic visit and at the final clinic visit) and accelerometry (collected during the recovery period) (Table 3). Based on accelerometry, the participants demonstrated acceptable accelerometer protocol compliance. Overall, 70% ($n = 35$) of participants provided sufficient accelerometer data (≥4 valid days) to be included in the time-use analysis. Of the rest, 16% ($n = 8$) provided no valid days and 14% ($n = 7$) provided less than four valid days of data. However, among all valid wear days (≥16 hours of wear), the median wear time was 98.8%, indicating that among valid wear days the vast majority of the day was measured. An additional two participants were lost to follow up, yielding a final analytic sample of 33 participants (normal recovery, $n = 29$; protracted recovery, $n = 4$) included in the compositional analysis. As would be expected, those who recovered normally wore the accelerometer for a median (IQR) 6.0 (5.0–9.0) days while those who experienced a

Table 1. Descriptive statistics of pediatric patients presenting to a specialty sport-related concussion clinic, 2019–2021.

		SRC Recovery time, *n* (%)		
Characteristic	Overall, *n* (%)	Normal recovery	Protracted recovery	*p*
RTP (days), median (IQR)	13.0 (11.0–19.0)	11.5 (10.5–17.0)	33.5 (32.0–51.0)	.009
Age, mean (SD)	15.8 (1.2)	15.8 (1.2)	16.1 (1.2)	.63
Sex				
Male	24 (48.0)	20 (45.5)	4 (66.8)	.41
Female	26 (52.0)	24 (54.6)	2 (33.3)	
Race/ethnicity				
NH White	34 (68.0)	28 (63.6)	6 (100.0)	.55
NH Black/AA	5 (10.0)	5 (11.4)	0 (0)	
Hispanic/Latino	5 (10.0)	5 (11.4)	0 (0)	
Other[a]	6 (12.0)	6 (13.6)	0 (0)	
History of concussion				
No	29 (58.0)	27 (61.4)	2 (33.3)	.30
Yes	20 (40.0)	16 (36.4)	4 (66.7)	
Behavioral diagnosis				
No	41 (82.0)	37 (84.1)	4 (66.7)	.34
Yes	8 (16.0)	6 (13.6)	2 (33.3)	

Note. SRC = sport-related concussion, RPT = return to play; IQR = interquartile range; SD = standard deviation; NH = non-Hispanic; AA = African-American. [a]Other race/ethnicity includes patients who identified as Asian, American Indian, Alaska Native, Native Hawaiian or other Pacific Islander.

Table 2. Concussion related clinical measures at initial consultation.

		SRC Recovery time, median (IQR)		
Clinical measures	Overall ($n = 50$)	Normal recovery ($n = 44$)	Protracted recovery ($n = 6$)	p^a
VOMS score[c]	10.0 (3.0–19.0)	9.0 (3.0–17.0)	17.0 (1.0–37.0)	.48
Convergence	3.0 (1.0–6.2)	2.7 (1.0–6.3)	4.7 (3.0–6.0)	.45
PCSS score	21.0 (13.0–35.0)	20.0 (13.0–33.0)	35.5 (15.0–46.0)	.24
Time from injury to clinic, days	2.0 (1.0–4.0)	2.0 (1.0–4.0)	2.5 (1.0–4.0)	.64

[a]Wilcoxon rank-sum (Mann-Whitney) test applied to assess for differences between groups.

Note. SRC = sport-related concussion, IQR = interquartile range; VOMS = vestibular ocular motor screening; PCSS = post-concussion symptom scale.

Table 3. Descriptive estimates of physical activity, sleep, and sedentary time during SRC recovery.

		SRC recovery, median (IQR)		
	Overall ($n = 33$)	Normal recovery ($n = 29$)	Protracted recovery ($n = 4$)	p
Accelerometer wear				
Valid day non-wear time, % mdn (IQR)	0.9 (0.2–3.8)	0.9 (0.2–3.8)	1.0 (0.5–5.2)	.80
Valid days worn, days	7.0 (5.0–10.0)	6.0 (5.0–10.0)	21.0 (12.0–25.5)	.01
Physical activity				
Avg PA h wk^{-1}, mdn (IQR)	28.5 (25.4–35.8)	27.9 (25.4–35.2)	34.4 (28.6–37.4)	.41
LPA m d^{-1}, mdn (IQR)	158.4 (130.8–187.6)	150.5 (128.6–185.4)	185.8 (165.2–190.4)	.29
MVPA m d^{-1}, mdn (IQR)	91.7 (73.1–122.6)	91.1 (73.1–116.0)	109.1 (78.4–132.2)	.47
Sedentary				
Sedentary time m d^{-1}, mdn (IQR)	706.0 (642.0–748.8)	708.1 (642.0–748.8)	684.7 (634.5–739.1)	.54
Sleep				
Sleep time m d^{-1}, mdn (IQR)	481.1 (455.3–506.5)	483.9 (463.8–506.5)	451.0 (429.4–510.6)	.38
CSRP score, mdn (IQR)	34 (30–39)	34 (29–39)	35 (32.5–38)	.92
% sleep eff., mdn (IQR)	85.8 (82.8–88.8)	85.2 (82.8–88.6)	89.0 (78.9–92.1)	.47
Median sleep onset, mil. time	23:02	23:17	22:41	.50
Median wake onset, mil. time	07:33	07:33	07:32	.69

Note. SRC = sport-related concussion, IQR = interquartile range; mdn = median, PA = physical activity; h = hours; wk = weeks; LPA = light physical activity; m = minutes; d = days; MVPA = moderate to vigorous physical activity; CSRP = Children's Report of Sleep Problems; eff. = efficiency; mil. = military.

protracted recovery wore the accelerometer for a median (IQR) 21.0 (12.0–25.5) days ($p = .01$). Among participants with valid accelerometer wear-time, the median (IQR) time spent physically active, as estimated by accelerometry, was 57.6 (29.5–141.6) hours per week overall. There were no differences in the overall time spent active among those who recovered normally versus those who had a protracted recovery ($p = .47$). However, those who recovered slower spent a greater amount of time engaged in MVPA (median = 109.1 [IQR = 78.4–132.2] minutes per day) and LPA (medial = 185.8 [IQR = 165.2–190.4] minutes per day) compared to those who recovered normally (MVPA: median = 91.1 [IQR = 72.8–119.2] minutes per day; LPA: median = 150.5 [IQR = 128.2–185.4] minutes per day; $p = .47$ and .25, respectively). Similarly, those who recovered normally spent slightly more time sedentary (708.1 [642.0–804.0]) compared to those who had a protracted recovery (684.7 [634.5–739.1]), but this was also not a statistically significant difference ($p = .53$). Finally, among the sleep estimates, both those derived from self-report (CRSP) and accelerometry, there were no statistically significant differences when comparing the recovery groups. Overall, participants reported a median (IQR) score of 34 (30.5–39) on the CRSP, and an 85.9% (82.8–89.1) median (IQR) sleep efficiency.

Results from the compositional linear regression models evaluating the association of each 24-hour movement behavior on SRC recovery time, while controlling for time spent in all other behaviors, are shown in Table 4. Sleep and MVPA were positively associated with recovery time in days (sleep: $B = 0.02$; MVPA: $B = 0.03$), while sedentary time and LPA were negatively associated with recovery time in days (sedentary: $B = -0.04$; LPA: $B = -0.01$), though these findings were not statistically significant. The mean variations of the pairwise log-ratios, indicating the average variation in the natural log of the combination of behaviors under study, are shown in Table 5. Results indicate that MVPA and LPA, and sedentary and sleep time, did not tend to displace each other. Additional MVPA time most frequently displaced sedentary time. Overall, the findings indicate that the 24-hour composition of movement behaviors among adolescents recovering from SRC did not affect recovery time.

Table 4. Compositional regression estimates of movement behavior pivot coordinates against recovery time in days among $n = 33$ pediatric concussion patients.

Pivot	Estimate	SE	t	p
Sleep vs. remaining	0.02	0.04	0.46	.65
Sedentary behavior vs. remaining	−0.04	0.03	−1.14	.26
LPA vs. remaining	−0.01	0.05	−0.10	.92
MVPA vs. remaining	0.03	0.04	0.85	.40

Note. SE = standard error; LPA = light physical activity; MVPA = moderate to vigorous physical activity. Model is adjusted for age and sex.

Table 5. Mean variations of the pairwise logratios among $n = 33$ pediatric concussion patients.

	Mean variation of the pairwise logratios		
24-hour movements	LPA	SB	Sleep
Overall			
MVPA	0.098	0.331	0.253
LPA		0.220	0.167
SB			0.062
Protracted recovery			
MVPA	0.103	0.345	0.265
LPA		0.236	0.181
SB			0.064
Normal recovery			
MVPA	0.048	0.138	0.131
LPA		0.039	0.021
SB			0.041

Note. LPA = light physical activity; SB = sedentary behavior; MVPA = moderate to vigorous physical activity.

Discussion

The purpose of this study was to describe the 24-hour composition of movement behaviors, including sleep, sedentary behavior, and physical activity, among pediatric SRC patients over their recovery period and to determine if the composition of these behaviors was related to recovery time. We found that those who recovered on time and those who took longer to recover did not significantly differ in accelerometer-measured physical activity, sleep, or sedentary time. The adolescents who recently suffered a SRC in this sample spent most of their time engaged in sedentary behaviors (over 50% of the 24-hour day), 33% of their time sleeping, 11% in light intensity physical activity, and 6% in MVPA. Those with protracted recovery spent a greater proportion of time in LPA and MVPA compared to those who experienced a normal recovery time (LPA: protracted = 12.9% vs. normal = 10.4%; MVPA: protracted = 7.6% vs. normal = 6.3%) and a smaller proportion of time sedentary (47.5% vs. 49.2%). Interestingly, this potential association of LPA and MVPA with recovery time is absent in the compositional linear regression model, which found neither LPA or MVPA to be associated with recovery time. This exemplifies the value of compositional analysis and accounting for relative changes in other movement behaviors. Importantly, the accelerometer protocol compliance among the sample was moderate; thirty percent of the sample was excluded from analysis due to insufficient data. Wear-time patterns suggest that adolescents tend not to take the watch off frequently, but rather, forget to put it back on after removing it. This finding may assist in giving appropriate participant education in future studies using accelerometry in this population. With water-resistant accelerometers, compliance may improve if participants are instructed to always wear the watch, including during bathing.

Overall, these results differ from what others have found. In an observational study among 20 SRC patients, Sufrinko et al. (2018) found, using accelerometry, that several measures of physical activity and sleep were related to worse clinical measures at follow-up appointments, however this exploratory study did not evaluate the patterns and combinations of physical activity, sleep and sedentary time over the entire recovery period to determine the potential effect on protracted recovery (Sufrinko et al., 2018). Randomized trials on this topic have demonstrated strong evidence on the effect of exercise and sedentary behavior protocols on recovery time. Most recently, Macnow and colleagues found that restricting screen-time had a positive effect on SRC recovery time (Macnow et al., 2021). Those instructed to reduce their screen-time for the first 48-hours following the injury had a median recovery time approximately 4.5 days shorter than those who were not given any specific instructions to reduce screen-time. As has been shown in other areas of time-use epidemiology, and in the study of sedentary behaviors, screen-based behaviors are the primary source of sedentarism for adolescents. Therefore, in effect, this study was an evaluation of a treatment to reduce sedentary time. Similarly, Leddy and colleagues found that completing 30 minutes low intensity aerobic exercise daily during the first 7-days of recovery, and continuing until fully recovered lead to a shorter recovery time (J. J. Leddy et al., 2019). Although these findings are compelling, some have pointed out that the interrelatedness of sedentary time and physical activity requires a more complete measurement of these behaviors to account for the displacement of one for the other (Knell et al., 2022). For instance, it is possible that when adolescents are asked to limit their screen-time, they will replace that time with a physically active behavior. In fact, this has been proven in other contexts (Lizandra et al., 2019). Therefore, it is difficult to know whether the screen-time restriction was the primary mechanism explaining the effect on recovery time in the Macnow study, or if the screen-time restriction resulted in greater levels of physical activity which was the primary mechanism explaining the effect. Although the current study was not able to offer any further insight into these potential mechanisms, this was the first to describe the composition of these 24-hour behaviors in the context of a SRC recovery period. Future studies should aim to further expand on this work and the work of others by evaluating 24-hour movement behavior patterns among those recovering from a concussion.

Application of compositional data analysis to the study of pediatric concussion is novel and offers advantages to clinical care. Future research may aim to explore challenges with patient compliance with physical activity and behavioral recommendations that clinicians in this field often face. While patients frequently return to specialty clinics or to their primary care provider within several days to weeks post-injury, little is known about a patient's compliance with prescribed interventions between visits. A reliable tool for obtaining 24-hour movement behavior data could prove useful for determining areas to target with further treatment, particularly in cases of protracted concussion recovery. Although previous studies have shown reduction of recovery time with controlled physical activity (Leddy et al., 2019) and adequate sleep (Hoffman et al., 2017), to our knowledge, an effective and practical way to objectively track compliance with these recommendations has yet to be implemented in clinical practice.

This study is not without limitations. Primarily, an *a priori* power analysis found that the current analysis would need a total of 272 participants to detect significant differences in the composition of behaviors between the recovery groups. The COVID-19 pandemic severely limited the number of patients seen in the clinic (and therefore the potential pool of participants) but also on recruitment efforts, particularly in the early stages of participant recruitment and data collection. To this point, due to the time frame of participant enrollment, the activity pattern captured during this study period may have been influenced by disruptions to available activities during the pandemic. However, the sample size was relatively large for a clinic based observational sample who were asked to wear an accelerometer for an extended period of time. This study demonstrated the feasibility of such an approach. Aside from the limited power in the analysis, this study also was observational in nature and was therefore limited in its ability to determine any causal relations between the 24-hour movement behaviors patterns/composition and recovery time. Future studies should aim to similarly utilize accelerometry while recommending varying randomized behavioral treatments (subthreshold exercise, sleep, sedentary time/screen-time restrictions) to evaluate the effects on recovery time.

Conclusions

The findings of this pilot study suggest no association of time-use with recovery time in adolescents who have recently suffered a SRC. Due to the conflict of these results with the currently available literature, and considering the limitations of this study, additional studies that aim to quantify the relationship between time-use and SRC recovery are warranted. Previous studies have found the independent effects of physical activity, sedentary behaviors, and sleep on SRC recovery. However, it is important to continue to study these behaviors as a composition, rather than as independent effects given the highly interrelated nature of each. This requires the use of accelerometry to fully capture these behaviors. The use of accelerometry to measure 24-hour movement behaviors was successful and provides some preliminary evidence on the feasibility of this approach for future studies and potentially within clinical practice. Ultimately, this body of research will help to formulate best clinical practices for acute and sub-acute SRC treatment and management.

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Authors' contributions

RB was responsible for data collection, data analysis, interpretation of the results and drafting of the manuscript. AP, CJ and CE contributed to the acquisition of the data; drafting and revision of the manuscript. SB contributed to the drafting and revision of the manuscript. GK was responsible for the concept, design, oversight of the data collection, and drafting of the manuscript.

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