Moving for Recovery: Using time-use compositions to Explore Physical Activity and Sleep in Sports-Related Concussion

Authors:
Mayan J. Bedggood[1], Tom Stewart[2], Josh McGeown[1,3,4], Stephen Kara[5,6], Alice Theadom[1], Mangor Pedersen[1], Scott Duncan[2]
Correspondence:
Mayan Bedggood: mayan.bedggood@aut.ac.nz
Institutions:
1. Traumatic Brain Injury Network, Auckland University of Technology, Auckland, NZ
2. Human Potential Centre, Auckland University of Technology, Auckland, NZ
3. Mātai Medical Research Institute, Gisborne, NZ
4. Department of Anatomy and Medical Imaging, University of Auckland, Auckland, NZ
5. Axis Sports Medicine, Auckland, NZ
6. High Performance Sport, Auckland, NZ

This manuscript is a preprint

Example citation:
Bedggood, M. J., Stewart, T., McGeown, J., Kara, S., Theadom, A., Pedersen, M., & Duncan, S. (2025). Moving for recovery: Using time-use compositions to explore physical activity and sleep in sports-related concussion. *SportRxiv*, 2025-05.

Abstract

Sports-related concussions are a prevalent and often misunderstood form of traumatic brain injury worldwide. While earlier clinical guidelines advocated for strict physical and cognitive rest until full symptom resolution, a growing body of evidence now supports the inclusion of physical activity (PA) as a critical component of effective concussion recovery. To date, much of the research has examined the role of PA in isolation, without accounting for the inherently interdependent nature of daily movement behaviours. Time-use composition frameworks address this limitation by analysing how time is proportionally distributed across various activities and how reallocating time among these behaviours can influence health outcomes. To the author's knowledge, this is the first study to employ Compositional Data Analysis (CoDA) to assess the relative contributions of four key movement behaviours - sedentary behaviour, light PA, moderate-to-vigorous PA, and sleep - on concussion recovery. Using a homogeneous sample of 35 male athletes with acute sports-related concussion and 45 matched healthy controls, the study explored group differences in time-use composition, optimal behavioural distributions for recovery, and the impact of reallocating time among behaviours. While no statistically significant differences or associations were observed across most movement behaviours, sleep emerged as a positive predictor of recovery time in the unadjusted model. Additionally, although not statistically significant, the compositional isotemporal substitution analysis suggested that reallocating 60 minutes per day to either light or moderate-to-vigorous PA could theoretically shorten recovery duration by approximately four days. These findings demonstrate the potential of CoDA to provide nuanced insights into how the relative distribution of daily activities and sleep may influence concussion recovery. Future research with larger and more diverse samples is warranted to enhance clinical applicability and guide evidence-based treatment recommendations.

Key words: Physical activity, movement, exercise, concussion, mTBI, TBI, brain injury, recovery, CoDA, compositional data analysis, time-use epidemiology

Introduction

Concussion and Physical Activity

Sports-related concussion (SRC) is a type of traumatic brain injury resulting from direct or indirect biomechanical forces to the head, neck or body during sports or exercise (Alam et al., 2020; Patricios et al., 2023; Verboon et al., 2021). These forces - such as rapid acceleration, deceleration, or rotational movement - can be transmitted to the brain, leading to cellular disruption, potential axonal injury, altered cerebral blood flow, and inflammation (Patricios et al., 2023). SRC can be seen as an “invisible injury” with no external signs of damage, yet they can result in a wide variety of symptoms. These include headaches, difficulty concentrating, sleep disturbances, balance problems, nausea, and heightened sensitivity to light or noise (Alam et al., 2020; Di Battista et al., 2020; Markovic et al., 2021; Verboon et al., 2021). While a variable number of individuals recover within 14 days, approximately 10–30% experience persistent symptoms that can severely affect daily life (Kara et al., 2020; McInnes et al., 2017; Verboon et al., 2021). The variability in recovery trajectories remains poorly understood, presenting challenges for clinicians in managing a patient’s return to everyday activities (McGeown et al., 2020). This underscores the urgent need for further research into whether specific interventions or activity modifications during the acute phase can positively influence recovery outcomes.

Since the first International Conference on Concussion in Sport in 2001, the standard recommendation for managing sports-related concussion has been physical and cognitive rest until full symptom resolution (Howell et al., 2019; Leddy et al., 2019; Markovic et al., 2021; Micay et al., 2018; Willer et al., 2019). However, recent research has questioned the effectiveness of prolonged rest and has even identified potential risks associated with it (Dobney et al., 2017; Lawrence et al., 2018; Leddy, 2025; Leddy et al., 2019). Evidence now suggests that resting for more than three days offers minimal benefit for adult recovery (Leddy et al., 2016; Silverberg & Iverson, 2013). For example, Thomas et al. (2015) found that individuals prescribed five days of strict rest reported more symptoms and slower recovery. Similarly, Schneider et al. (2017) concluded that an initial rest period of 24–48 hours followed by gradual re-engagement in activity yields better outcomes. Reflecting this evolving evidence base, instead of advocating strict rest until all symptoms resolve, the 2022 Concussion Consensus Statement now supports a brief period (24–48 hours) of relative rest - including basic daily activities and limited screen exposure - followed by a gradual return to light physical activity, such as walking, as long as it is well tolerated. Activity intensity can then be progressively increased, provided any symptom exacerbation is mild and short-lived.

These updated recommendations are supported by a growing body of research indicating that PA plays a significant role in recovery from SRC. Numerous studies have shown that PA can shorten recovery time and reduce post-concussion symptoms (Buckley et al., 2022; Chizuk et al., 2022; Coslick et al., 2020; Grool et al., 2016; Leddy, 2025; Leddy et al., 2021; Seehusen et al., 2021). The approach to measuring the impact of PA varies across studies. Some have focused on structured aerobic exercise programs (e.g., Leddy et al., 2021), while others have examined naturalistic, daily-life activity levels (e.g., Grool et al., 2016; Seehusen et al., 2021). Research has also explored the role of different intensity levels - ranging from mild-to-moderate PA (e.g., Buckley et al., 2022) to moderate-to-vigorous PA (e.g., Coslick et al., 2020) - as well as the importance of adherence to PA regimens in promoting recovery (e.g., Chizuk et al., 2022). Importantly, no adverse events have been reported as a result of initiating PA, even when started within days of injury and in highly symptomatic individuals as young as 13 years old (Chizuk et al., 2022; Leddy et al., 2021). This highlights not only the efficacy but also the safety of early, appropriately dosed PA following SRC. Recent systematic reviews further support the positive effects of PA on concussion recovery (Art et al., 2023; Leddy et al., 2023; Reid et al., 2022), reinforcing its role as a valuable component of post-concussion care.

A significant limitation in the current literature on PA and concussion recovery lies in the methods used to assess PA. Many studies have relied on subjective self-report measures (Boisgontier et al., 2020; Buckley et al., 2022; Coslick et al., 2020; Grool et al., 2016; Howell et al., 2016; Krainin et al., 2021; Majerske et al., 2008; Remigio-Baker et al., 2019, 2020; Wilson et al., 2020). Self-reported data are prone to various inaccuracies, including social desirability bias, where participants may overestimate their activity levels to align with perceived expectations (Van de Mortel, 2008). In the absence of objective validation, PA levels may also be unintentionally under- or over-reported. Moreover, self-report measures often lack precision in capturing the timing, duration, and intensity of activity, and they can impose a significant burden on participants (Buckley et al., 2021; Lawrence et al., 2018; Lishchynsky et al., 2019; Remigio-Baker et al., 2020; Seehusen et al., 2021; Wilson et al., 2020). Given these limitations, there is a clear need for future research to prioritise the use of objective PA tracking technologies. Doing so will enhance the accuracy, consistency, and interpretability of findings related to PA and SRC recovery.

A New Way to Look at Physical Activity: Compositional Data Analysis

Most existing research has examined PA outputs in isolation, typically exploring whether higher or lower levels of PA correlate with specific outcomes. Some studies have gone further by categorising daily behaviours into light PA, moderate-to-vigorous PA, sedentary behaviour, and sleep, in order to evaluate their individual effects on health-related outcomes (Grgic et al., 2018). However, because each day consists of a fixed 24-hour period, these behaviours are inherently interdependent - an increase in one necessarily results in a corresponding decrease in at least one of the others (Pedisic, 2017). Given this interdependence, changes in activity behaviours should be considered within the context of the entire 24-hour day. For example, increasing light PA could unintentionally reduce sleep or increase sedentary time, potentially diminishing the intended health benefits. As such, evaluating PA, sedentary behaviour, and sleep as *proportions* of a whole offers a more comprehensive framework for understanding their combined influence on health and recovery (Dumuid et al., 2021).

To address this complexity, Dumuid et al. (2018) introduced a novel statistical approach for predicting changes in continuous outcome variables based on **relative**, rather than **absolute**, changes in behaviour compositions. Compositional Data Analysis (CoDA) was developed specifically to analyse data constrained within a constant-sum structure (such as time-use data), which traditional statistical models are not well equipped to handle (Dumuid et al., 2020). CoDA uses log-ratio transformations to convert data from a constrained simplex space into an unconstrained real space, enabling the use of conventional statistical techniques while preserving the interdependent relationships among behaviours (Dumuid et al., 2018; Dumuid et al., 2020; Liangruenrom et al., 2023; Mellow et al., 2023).

Time-use epidemiology investigates how time is distributed across various daily activities, its influence on health outcomes, and how optimising this allocation can enhance overall well-being. Time-use is considered one of the most relevant and modifiable behavioural risk factors in many health-related contexts (Pedisic, 2017). The primary components of time-use research - PA, sleep, and sedentary behaviour - are collectively referred to as *movement behaviours* (Dumuid et al., 2020). Emerging evidence suggests that health outcomes are influenced not merely by changes in individual behaviours, but by the reallocation of time among them. For instance, substituting sedentary time with light or moderate-to-vigorous PA has been associated with improved cardiometabolic biomarkers (Grgic et al., 2018). Traditional analytical approaches that evaluate these behaviours independently fail to account for their compositional nature, since time spent on one activity inherently affects time available for others (Pedisic, 2017). CoDA offers a more robust framework for addressing this issue by examining the relative distribution of time across behaviours. It allows researchers to identify optimal time-use patterns tailored to specific populations and to generate evidence-based, actionable recommendations for improving health (Dumuid et al., 2021; Grgic et al., 2018).

Recent research on PA has emphasised the significance of how the *relative* contributions of various movement behaviours influence overall health within a fixed timeframe, typically a 24-hour day (Dumuid et al., 2021; Hedayatrad et al., 2022). These studies underscore the interconnected nature of movement behaviours and highlight the importance of tailoring time-use recommendations to specific health goals, rather than relying on a uniform, one-size-fits-all approach. Although time-use epidemiology and CoDA techniques have been applied in a limited number of studies involving other neurological populations, such as individuals recovering from stroke (Ezeugwu & Manns, 2024; Hooker et al., 2022; Orme et al., 2020), to the author's knowledge, this is the first study to employ CoDA to examine recovery following SRC. The present study aims to objectively compare movement behaviour patterns between individuals with acute SRC and healthy controls using CoDA methodology. Specifically, it seeks to: (1) determine whether the 24-hour time-use composition of movement behaviours differs between the two groups; and (2) explore the relationship between time-use composition and the number of days to concussion recovery.

Methods

Participants

We recruited two groups between 16 and 35 years of age. The first group consisted of 35 male sports players (M = 21.71 years, SD = 5.10) in the acute (≤ 14 days) phase post-SRC. Participants for this group were included if their injury occurred in a sports game or training and was diagnosed by a physician. Diagnosis was based on a combination of (1) clinical history with plausible mechanism, (2) Sport Concussion Assessment Tool (SCAT-5) or Brain Injury Screening Tool (BIST) symptoms scores, (3) clinical examination to exclude any neurological or intracranial abnormalities, (4) review of video if available, and (5) eye-witness accounts if available. The second group consisted of 45 healthy male controls (M = 23.13 years, SD = 4.34). These were a mix of athletes and non-athletes who had not suffered a concussion in the last 12 months, had not suffered more than five total concussions in their lifetime and did not have lingering symptoms from a previous concussion (to minimise potential confounding effects of cumulative damage and/or chronic inflammation). Participants for either group were excluded if they had an existing significant neurological condition or were contraindicated for an MRI scan (e.g., certain metal implants, or braces).

The concussion participants were recruited at their initial consultations at Axis Sports Concussion Clinics in Auckland, New Zealand and via community links (e.g. physiotherapists, word of mouth, digital and print advertisements). The control group were recruited via convenience sampling from the general population through print advertisements at the Auckland University of Technology and The University of Auckland, as well as social media advertisements. Participant data collected for this study has been de-identified to protect participant confidentiality. All participants were provided with a participant information sheet and consent form and the study was conducted in accordance with the ethical standards of the Declaration of Helsinki. Ethics approval was obtained from the Health and Disability Ethics Committee (HDEC – 2022 EXP 11078), New Zealand.

Materials and Procedure

All participants were fitted with an Axivity AX3 physical activity tracking device immediately following recruitment (within 14 days following their concussion for the concussion group) to wear on either of their wrists (see Figure 1). The device is a data logger and features MEMS 3-axis accelerometer and flash based on-board memory. It is designed to be worn at all times, which enabled the collection of continuous 24/7 movement behaviour data. Using the Open Movement Software (OMGUI, version 1.0.0.43, Open Movement, Newcastle University, UK), each device was initialised to record for 15 days (to enable 14 full days of data to be extracted after allowing for the participants to be fitted with the devices at varying times of the day) at 50 Hz sampling frequency, with a range of ± 8g.

Participants were not asked by researchers to alter their physical activity in any way. The concussion participants recruited through Axis Sports Concussion Clinics underwent extensive clinical examination by a Sport and Exercise Physician. They received verbal and written education regarding physical loading to address their symptoms and were scheduled for a follow up consultation approximately 14 days post-injury (Kara et al., 2020; McGeown et al., 2020). Following the 15-day wear-time, researchers collected the devices from participants at a location convenient to them. If the participant was recruited from Axis Sports Concussion Clinics, then clinical recovery was determined by their physician (as per previous publications; Kara et al., 2020; McGeown et al., 2020) and their date of discharge was used to calculate clinical recovery time (in days). For those participants recruited through the community, their clinical recovery time was calculated using the date that their follow up BIST scores were ≤ 20.

Figure 1

Axivity AX3 Wrist-Worn Device

Measurements

Time-Use Behaviours

Time-use behaviours were extracted from the Axivity AX3 accelerometer devices. Firstly, raw data from each device was downloaded via the *OMGUI* software in the form of .cwa files and then the *GGIR* package in R (Migueles et al., 2019) was used to determine device wear time and extract time use behaviour variables. The variables of interest were daily time spent in sedentary behaviour, light intensity PA, moderate intensity PA, vigorous intensity PA, and sleep (recorded in minutes). The gravity-based acceleration unit (*g*) thresholds used to determine these intensities were 40*g* for light PA, 100*g* for moderate PA and 400*g* for vigorous PA (Hildebrand et al., 2014; Hildebrand et al., 2016). The minutes of moderate and vigorous intensity PA were combined into moderate-vigorous PA. Additionally, the sleep duration was calculated based on accumulated nocturnal sustained inactivity within a sleep period window that is identified using a Heuristic Algorithm looking at Change of Z-angle (HDCZA) (van Hees et al., 2018). All participants with at least three days of 24-hour wear time were included in the analyses, and minutes in each behaviour of interest were averaged across valid days. The derivation of time use variables was performed in R software (version 4.2.2).

Covariates

Age (years) and initial symptom burden (total BIST scores) were included as covariates to rule out the possibility of them confounding the primary association of interest for the second analysis.

Statistical Analyses

Time-use behaviours were treated as compositional data (i.e., all behaviours sum to 24 hours) and analysed using the *compositions* (Van den Boogaart & Tolosana-Delgado, 2008) and *deltacomp* (github.com/tystan/deltacomp) R packages. No zero imputation was required as there were no missing values in the dataset. All statistical analyses were performed in R and the code can be found in the Supplementary Materials.

Analysis One: Group Comparison Concussions versus Controls

The average time spent in each movement behaviour were reported as geometric means, which were normalised to 1440 minutes (i.e., minutes in 24 hours) in order to calculate compositional means. Compositions were created for each of the four movement behaviour variables (minutes of sedentary behaviour, light PA, moderate-vigorous PA, sleep) using the *comp* function in the compositions package in R. The movement behaviour compositions were then expressed as isometric log-ratio coordinates, which allows compositional data to be analysed using traditional statistical methods (Dumuid et al., 2018; Dumuid et al., 2020; Liangruenrom et al., 2023). To compare the time-use-composition of the concussion group to healthy controls, a compositional multivariate analysis of variance (MANOVA) was conducted with group as the independent variable with two levels (concussion, control) and the movement behaviour isometric log ratios as the dependent variables (Martín Fernández et al., 2015). Partial eta squared (η_p^2) was calculated as an indication of effect size for the model.

Analysis Two: Time-Use-Composition Association with Recovery

To estimate the ideal time-use-composition for optimising clinical recovery time following concussion, a compositional isotemporal substitution analysis was performed (Grgic et al., 2018). This process consists of creating a specific set of isometric log ratio coordinates from the time-use behaviour composition and fitting a series of linear regression models. Firstly, sequential binary partition (SBP) matrices were created for the sedentary behaviour, light PA, moderate-vigorous PA and sleep variables (see Table 1) which are used as a series of instructions for constructing isometric log ratios (ilr).

Table 1
Sequential Binary Partition Matrices for all Movement Behaviours

(A) SBP for Sedentary Behaviour

	sed	*lpa*	*mvpa*	*sleep*
ilr1	+1	-1	-1	-1
ilr2	0	+1	-1	-1
ilr3	0	0	1	-1

(B) SBP for Light PA

	sed	*lpa*	*mvpa*	*sleep*
ilr1	-1	+1	-1	-1
ilr2	-1	0	+1	-1
ilr3	-1	0	0	+1

(C) SBP for Moderate-Vigorous PA

	sed	*lpa*	*mvpa*	*sleep*
ilr1	-1	-1	+1	-1
ilr2	-1	-1	0	+1
ilr3	+1	-1	0	0

(D) SBP for Sleep

	sed	*lpa*	*mvpa*	*sleep*
ilr1	-1	-1	-1	+1
ilr2	-1	-1	+1	0
ilr3	-1	+1	0	0

For each of the movement behaviours, only the first ilr (*ilr1)* is interpreted, which expresses the ratio of the behaviour of interest, relative to the others. In the SBP for sedentary behaviour, *ilr1* represents the time spent in sedentary behaviour relative to all other behaviours; for light PA, *ilr1* represents the time spent in light PA relative to all other behaviours, and so on. A series of compositional multiple regression models were fitted to each set of ilrs. The *ilr1* variables for each movement behaviour were included as independent variables, while recovery time (in days) was specified as the dependent variable. Four models were fit in total, each time using a different SBP, such that each behaviour of interest was represented as *ilr1*. From these models, the coefficient for *ilr1* was extracted. Following this, adjusted models were repeated with the inclusion of age and symptom burden as covariates.

Lastly, a compositional isotemporal substitution was conducted to examine theoretical changes in recovery time by reallocating time spent in different movement behaviours. Predicted changes in recovery time by increasing time spent in one behaviour (at the expense of the other three behaviours) were estimated from 0 to ±60 minutes in 15-minute intervals. The reallocations of time were proportional to the time spent in each behaviour.

Results

Analysis One: Group Comparison Concussions versus Controls

A MANOVA was conducted to determine if group membership (concussion or control) was associated with the proportion of time spent in the four movement behaviours (sedentary behaviour, light PA, moderate-vigorous PA, sleep). The MANOVA was not statistically significant, $F(1,3) = 1.94$, $p = 0.13$. Results indicated that only 7.0% of the variance in the time-use-composition of participants' behaviour could be explained by the group that they were in ($\eta_p^2 = 0.07$). Comparative group data was generated alongside the MANOVA and can be found in Table 2 (a summary of average movement behaviours by group), Figure 2 (an illustration of the percentage difference between groups) and Figure S1 in the Supplementary Materials (a log ratio comparison).

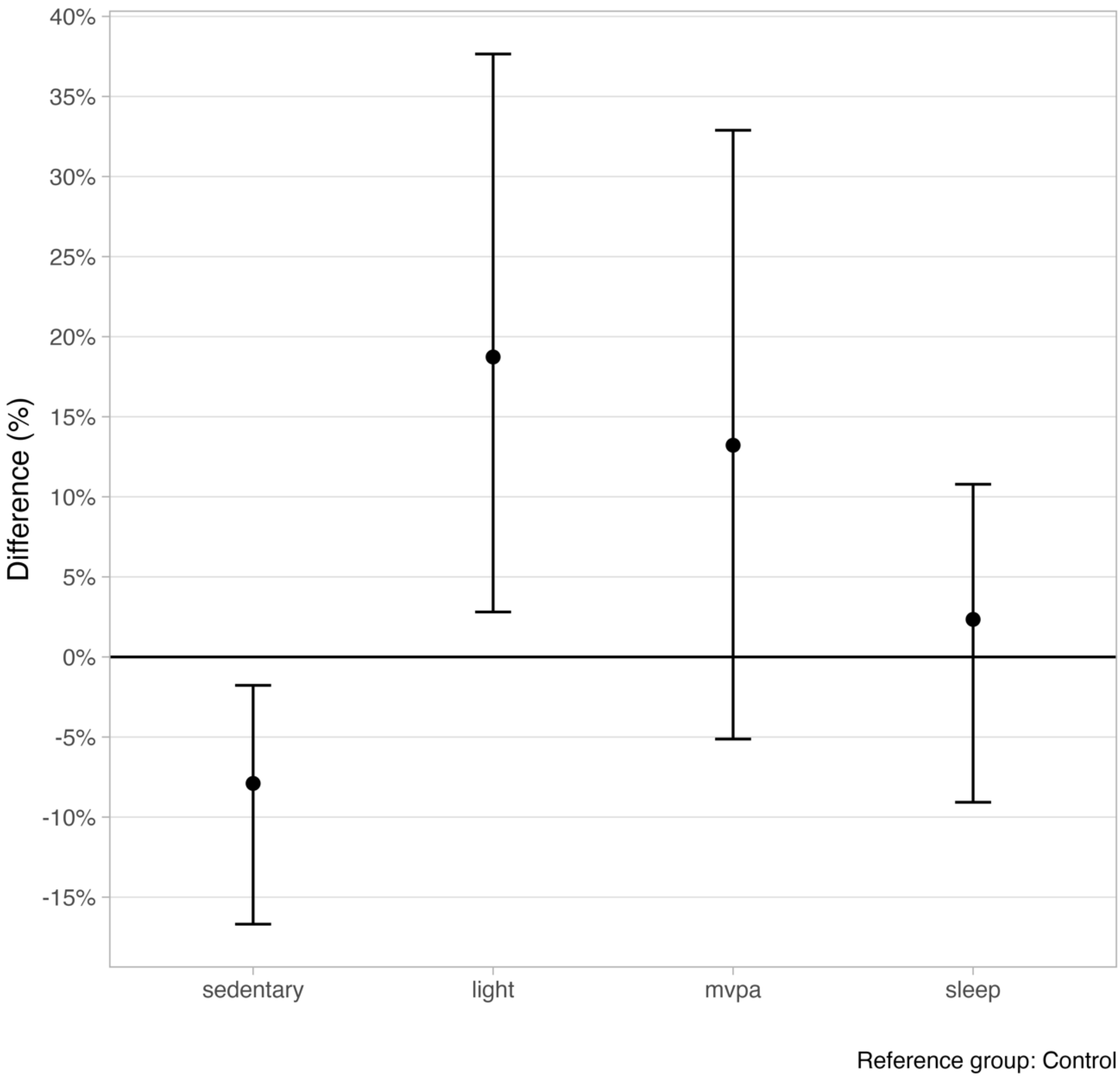
Table 2

Average Movement Behaviours for Concussion and Control Groups

		Proportions				Minutes			
	N	Sed	LPA	MVPA	Sleep	Sed	LPA	MVPA	Sleep
Concussion	35	48%	13%	8%	30%	697	194	113	436
Control	45	52%	11%	7%	30%	754	161	99	426

Figure 2

Percentage Differences in Movement Behaviours for Concussions versus Controls



Note. This figure illustrates between-group differences in movement behaviours as percentage differences, with the control group as the reference group and bootstrapped 95% confidence intervals (i.e. positive percentages indicate the concussion group spent more time engaged in that movement behaviour compared to the control group).

Analysis Two: Time-Use-Composition Association with Recovery

A compositional linear regression model was used to analyse the association between time-use-composition and recovery time within the concussion group, with participant age and initial symptom burden (total BIST scores) included as covariates. Time spent sleeping was significantly associated with recovery time ($p = 0.03$), with a positive association between sleep and recovery ($\beta = 50.54$). However, once the model was adjusted for age and initial symptom burden, the association between sleep and recovery was no longer significant ($p = 0.06$). Time spent in sedentary, light PA and moderate-vigorous PA were all negatively correlated with recovery, but these associations were not statistically significant (see Table 3 for a summary of results and Table S1 in Supplementary Materials for a complete breakdown of the models adjusted with age only and with both age and BIST score).

Table 3

Relationship Between Movement Behaviour Compositions (expressed as isometric log-ratio coordinates) and Recovery Time

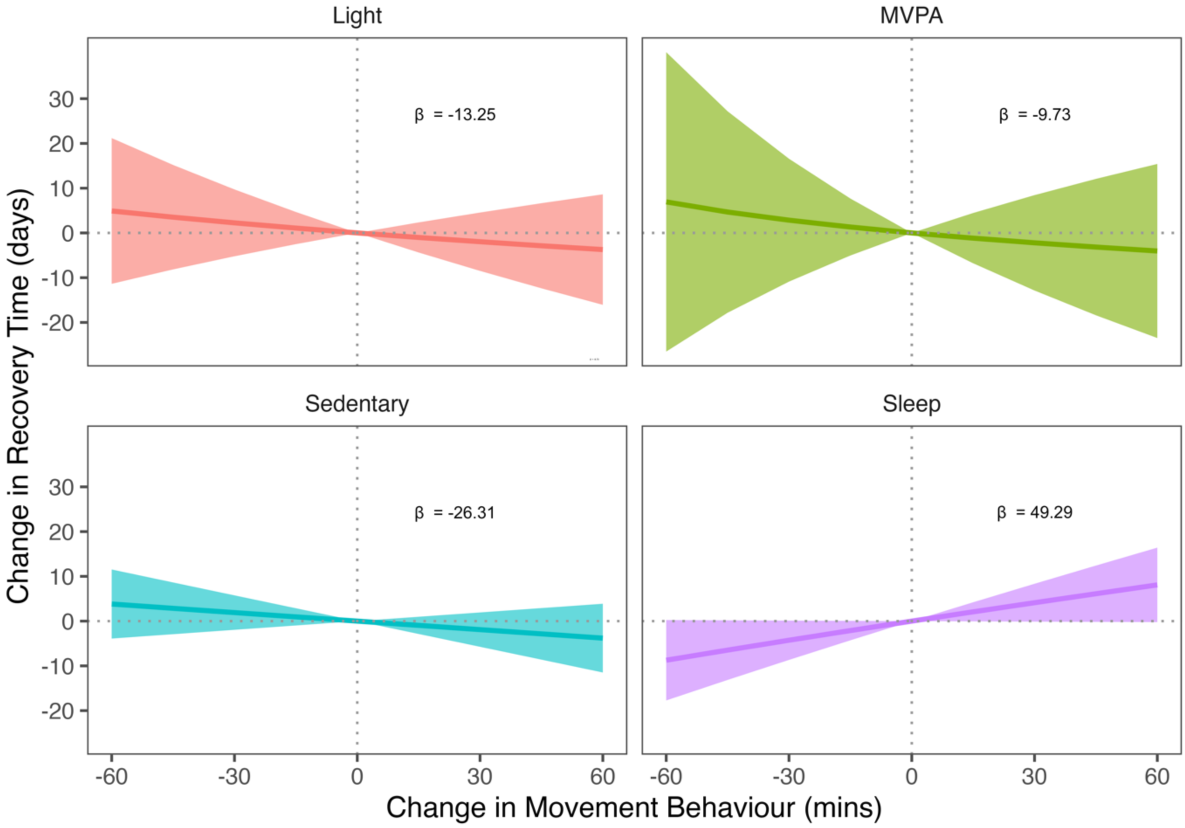
	Unadjusted Model			**Adjusted Model** (age and BIST score)		
Isometric log-ratio predictor	β	P-value	R^2	β	P-value	R^2
sed/lpa*mvpa*sleep	-26.95	0.24	0.16	-26.31	0.32	0.01
lpa/sed*mvpa*sleep	-15.02	0.42	0.16	-13.25	0.54	0.01
mvpa/sed*lpa*sleep	-8.58	0.64	0.16	-9.73	0.67	0.01
sleep/SB*lpa*mvpa	50.54	0.03*	0.16	49.29	0.06	0.01

Note. * indicates statistical significance at $p < .05$

A compositional isotemporal substitution model was also conducted, of predicted changes in recovery time when time from one movement behaviour is reallocated to/from the remaining movement behaviours (see Figure 3). For example, reallocating more time to moderate-vigorous PA, proportionately from sedentary behaviour, light PA and sleep, was associated with reduced recovery time, however, this association was not statistically significant. Specifically, the model suggests that a theoretical increase in light or moderate-vigorous PA of 60 minutes per day, for example, proportionate to the other movement behaviours, would result in a reduction in recovery time by approximately 4 days. Conversely, a theoretical 60-minute increase in sleep per day, proportionate to the other movement behaviours, would result in a 8-day increase in recovery time. See Table S2 in Supplementary Materials for a complete table of the reallocation results.

Figure 3

Reallocation of Movement Behaviour Time on Recovery Time



Note. The above figure illustrates the adjusted compositional isotemporal substitution model for the four movement behaviours; light PA (top left), moderate-vigorous PA (top right), sedentary behaviour (bottom left) and sleep (bottom right). This shows the predicted theoretical changes in recovery time (in days) when time from one movement behaviour (in minutes) is reallocated proportionately to/from the remaining movement behaviours.

Discussion

Despite a growing shift toward more active, individualised approaches to concussion management, uncertainty remains regarding the optimal type and timing of PA following injury. This study sought to address that gap by investigating how PA influences clinical recovery, focusing on four key movement behaviours: light PA, moderate-to-vigorous PA, sedentary behaviour, and sleep. To the author's knowledge, this is the first study to examine time-use behaviours in individuals recovering from concussion using CoDA. This innovative approach provided novel insights into how reallocating time between different behaviours may support improved recovery outcomes.

Our compositional linear regression analysis revealed no significant associations between moderate-to-vigorous PA, light PA, or sedentary behaviour and recovery time. However, sleep showed a significant positive correlation with recovery time, suggesting that spending more time sleeping - relative to other movement behaviours - may be linked to longer recovery durations. When the model was adjusted for age, the association between sleep and recovery remained significant (see Table S1 in the Supplementary Materials), however when initial symptom burden (as indicated by total BIST score) was added to the model, this association was no longer significant. This suggests that the initial link between sleep and delayed recovery may reflect a higher acute symptom burden, with individuals requiring more sleep due to the severity of their injury. In other words, those who slept more may have also experienced more severe symptoms and, consequently, slower recovery. However, as this is a correlational finding, it remains unclear whether increased sleep contributes to prolonged recovery, or if individuals with more severe symptoms and thus slower recovery, simply tend to sleep more. Future experimental studies are needed to investigate this relationship directly.

We also conducted an exploratory compositional isotemporal substitution analysis to examine whether theoretical changes in time-use composition were associated with recovery outcomes. Results from this model suggested that reallocating more time to sleep, proportionally away from the other movement behaviours, was linked to a longer recovery duration. Although these findings were not statistically significant, the model provides valuable insights into potential behavioural reallocations that could hold clinical relevance. For instance, increasing time spent in light or moderate-to-vigorous PA, relative to other behaviours, may be associated with faster recovery. Importantly, these types of time-use recommendations should be considered on a case-by-case basis with regards to the individual's personal activity and sleep needs. Further research with a larger sample is needed to validate these preliminary findings and support their application in clinical practice.

In our group comparison, there were no statistically significant differences between the concussion group and healthy controls in the proportion of time spent in each of the four movement behaviours. Group status accounted for only 7% of the variance in movement behaviours, indicating that we cannot conclude whether individuals with sports-related concussions engaged in more or less PA of varying intensities, or sleep, during recovery. These findings may suggest that acutely concussed individuals in this sample were able to participate in physical activity at levels comparable to their healthy counterparts, without adverse effects on recovery. Further validation is needed, however, these results add to the body of literature emphasising PA as a safe component of recovery interventions.

Deepening our understanding of the complex relationship between PA, sleep, and concussion recovery is essential, as significant uncertainty remains in this area. For decades, the standard approach involved strict physical and cognitive rest until full symptom resolution (Howell et al., 2019; Leddy et al., 2019; Markovic et al., 2021; Micay et al., 2018; Willer et al., 2019). However, growing evidence now indicates that prolonged strict rest may hinder recovery. Instead, current guidelines recommend a brief period of relative rest (24–48 hours), followed by a gradual, stepwise return to activity for optimal recovery outcomes (Buckley et al., 2022; Coslick et al., 2020; Dobney et al., 2017; Grool et al., 2016; Lawrence et al., 2018; Leddy et al., 2016; Leddy et al., 2019; Patricios et al., 2023; Schneider et al., 2017; Seehusen et al., 2021; Silverberg & Iverson, 2013; Thomas et al., 2015; Wilson et al., 2020). Multiple factors have been identified as influencing the risk of prolonged recovery. For example, McGeown et al. (2020) reported that individuals who are female, present with a higher initial symptom burden, or exhibit cervicogenic and/or vestibulo-ocular dominant symptoms are more likely to experience extended recovery periods (>14 days). As our understanding of these risk factors continues to evolve, it becomes increasingly important to identify strategies that actively support optimal recovery - highlighting the need to refine and individualise rehabilitation approaches through a better understanding of PA's role in recovery.

One potential mechanism underlying the beneficial effects of PA on concussion recovery is its ability to modulate inflammation (Swain et al., 2023; Metsios et al., 2020). PA may help attenuate the post-concussion inflammatory response by reducing chronic microgliosis, altering cytokine profiles, and lowering systemic low-grade inflammation (Ma et al., 2013; Markovic et al., 2021; Nimmo et al., 2013; Paolucci et al., 2018; Piao et al., 2013). It exerts these effects through the release of inflammatory mediators from leukocytes, adipose tissue, and skeletal muscle. During acute bouts of PA, skeletal muscle releases anti-inflammatory cytokines such as interleukin-6, with concentrations increasing in proportion to PA intensity, duration, fitness level, and muscle mass (Szostak & Laurant, 2011). Interleukin-6 initiates a cascade of anti-inflammatory processes by suppressing pro-inflammatory cytokines such as interleukin-1β and tumor necrosis factor-alpha, while promoting the release of the anti-inflammatory cytokine interleukin-10 (Nimmo et al., 2013). Additionally, PA has been associated with reductions in C-reactive protein, a widely recognised marker of systemic inflammation (Abramson & Vaccarino, 2002; Fedewa et al., 2003; Ford, 2002). For instance, Nilsson et al. (2018) demonstrated that replacing 30 minutes of sedentary or light activity with moderate-to-vigorous PA significantly lowered C-reactive protein levels. Furthermore, using a rodent model of TBI, Kim et al. (2022) demonstrated that early initiation of exercise training reduced microglial activation and infiltration, as well as the expression of pro-inflammatory cytokines such as IL-1, IL-13, and IL-1β, which had initially increased following the injury. Collectively, these findings underscore the important role of PA in regulating inflammation, which may be a key contributor to its positive effects on concussion recovery.

PA also stimulates the production of proteins associated with neural plasticity, such as brain-derived neurotrophic factor (BDNF) (Cordingley et al., 2024; Kreber & Griesbach, 2016; Mastrorilli & Vecchioli, 2024; Szuhany et al., 2015). BDNF, a key member of the neurotrophin family, is highly concentrated in brain regions critical for cognitive and motor function, including the hippocampus, hypothalamus, and cerebellum (Kreber & Griesbach, 2016; Szuhany et al., 2015). It plays a vital role in neuronal growth, differentiation, and survival by supporting neurogenesis, dendritic development, and long-term potentiation (Dinoff et al., 2016; Szuhany et al., 2015). Research has shown that BDNF levels acutely increase in peripheral blood following PA, with the extent of change dependent on the type, intensity, and duration of activity (Bazarian et al., 2023). Even a single session of exercise can elevate BDNF, with regular exercise amplifying this effect over time (Szuhany et al., 2015). Aerobic exercise, in particular, has been associated with increased resting BDNF concentrations (Dech et al., 2019). Since BDNF expression is often suppressed following concussion, PA may aid brain recovery by promoting BDNF production and enhancing neuroplasticity (Cordingley et al., 2024; Dech et al., 2019). Through its involvement in ionic regulation, metabolic support, and structural repair processes, BDNF may play a critical role in neural repair and functional recovery after brain injury (Cordingley et al., 2024; Dech et al., 2019; Kreber & Griesbach, 2016).

Expanding our understanding of PA engagement following concussion and identifying the optimal time-use composition of movement behaviours may have important clinical implications. If individual variations in time-use composition influence recovery, then reallocating time from one movement behaviour to another could enhance outcomes. For example, if increasing time spent in moderate-to-vigorous PA, relative to light PA, sedentary behaviour, and sleep, is found to accelerate recovery, clinicians could incorporate this evidence into rehabilitation guidelines. Conversely, if excessive sleep relative to other movement behaviours is shown to impede recovery, recommendations could be adjusted to help patients structure their daily routines more effectively. Given the high prevalence of SRC and the significant burden it places on individuals and society, identifying strategies to improve recovery outcomes is of considerable value. A more nuanced understanding of how reallocations of movement behaviours influence recovery trajectories could provide clinicians with additional, evidence-based tools to support patient rehabilitation and promote more effective recovery.

A key strength of this study is the extended wear time of the tracking devices (M = 11.5 days). This provided a robust dataset for calculating daily averages, thereby enhancing the internal validity of the findings. Another major strength is the use of an objective device -

the Axivity AX3 wrist-worn sensor - to record movement behaviours. This allowed for precise quantification of PA and sleep, improving data reliability while minimising recall bias and subjective reporting errors. Additionally, this method imposed a lower burden on participants compared to frequent self-reported activity logs. Although objective recording devices have been used in prior research (e.g., Neely et al., 2022; Petit et al., 2022; Seehusen et al., 2021), much of the existing literature on daily PA and concussion recovery relies on subjective measures (e.g., Boisgontier et al., 2020; Buckley et al., 2022; Coslick et al., 2020; Grool et al., 2016; Howell et al., 2016; Krainin et al., 2021; Remigio-Baker et al., 2020; Wilson et al., 2020). This study contributes to bridging that gap by employing an objective approach that reduces measurement error and enables robust statistical analysis.

The use of CoDA is another significant strength of the study. This approach considers movement behaviours holistically, recognising them as interdependent components of a 24-hour cycle rather than isolated variables. Since increasing PA inherently reduces time spent in other behaviours (e.g., sleep), understanding the most beneficial time reallocations is critical for optimising recovery. For example, clinicians could engage patients in discussions about “time budgets” that illustrate the trade-offs between behaviours on a day-to-day basis. This might involve strategies for reallocating time from sleep to light or moderate-vigorous PA at appropriate times, considering the patient's symptom exacerbation levels. If such collaborative planning between clinician and patient were implemented during the acute phase post-concussion, it could foster individualised time-use plans that potentially shorten recovery and facilitate a more efficient return to play.

Interpreting these findings requires consideration of potential limitations, particularly the limited sample size and reduced statistical power. Additionally, the limited variability in PA among participants may have hindered the detection of statistically significant results. Since concussion participants were primarily recruited from the same clinic, they likely received similar rehabilitation recommendations (e.g., structured exercise protocols such as daily stationary cycling). Consequently, the proportion of time spent in different movement behaviours may have been relatively uniform, which could have diminished the ability to identify meaningful associations with recovery. Future research should aim to recruit a more diverse sample from multiple sources, over a longer period of their recovery, to increase variability in movement behaviours and enhance the generalisability of findings.

Additionally, the external validity may be limited due to the homogenous, male-only sample. If both sexes were to be included, separating them into distinct groups and comparing them would be most sensible, as there may be sex differences in presentation following concussion (e.g., due to differences in hormones at the time of injury). Conducting such between-group comparisons would require a larger sample size, which could have impacted the feasibility of the study. Future research should aim to expand the sample size and include an accurate representation of both sexes and explore group differences, such as the influence of estrogen and progesterone during the acute phase of injury and how these hormonal factors may interact with the relationship between PA and recovery. Furthermore, although efforts were made to recruit participants as soon as possible post-injury, PA monitoring began within a 14-day window, limiting the ability to assess movement behaviours during the very acute phase. To enhance understanding of the optimal timing for PA initiation, future studies should aim to commence monitoring earlier in the recovery process, thus improving insights into the clinical applicability of PA interventions.

While the current study may have been underpowered to detect significant associations, future research should continue to explore time-use composition in individuals recovering from concussion. With more robust and objective evidence, concussion rehabilitation guidelines could be refined to incorporate specific PA recommendations. Given that sub-symptom PA is both feasible and cost-effective, a structured, stepwise return to activity could prove to be an effective treatment strategy, ultimately supporting safer and more efficient recovery pathways.

Conclusion

This is the first study to prospectively examine movement behaviours using wearable accelerometers and time-use compositions in the acute phase following sports-related concussion. Our findings indicate that, on average, physical activity did not differ between the concussed and control groups, supporting the tolerability of physical activity in the early weeks after a concussion. Additionally, increased relative time spent sleeping was associated with longer recovery times. In an exploratory analysis, we observed that a theoretical increase of 60 minutes per day in light or moderate-to-vigorous physical activity, proportionate to the other movement behaviours, would result in a reduction in recovery time by approximately four days. Although limited by statistical power, these findings contribute to the growing understanding of the complex interactions between physical activity and concussion recovery. With further validation, compositional data analysis could inform the development of personalised time-use plans in clinical settings, potentially accelerating recovery and supporting a safer return-to-play. Larger studies with more diverse concussion cohorts are essential to validate these findings and facilitate clinical translation.

Conflicts of Interest:
None to declare.

Funding:
This project was funded by a grant from the Health Research Council of New Zealand (HRC), grant #21/622.

Data Availability:
The data that support the findings of this study are available on request from the corresponding author

References

Abramson, J. L., & Vaccarino, V. (2002). Relationship between physical activity and inflammation among apparently healthy middle-aged and older US adults. *Archives of internal medicine*, *162*(11), 1286-1292. https://doi.org/10.1001/archinte.162.11.1286

Alam, A., Thelin, E.P., Tajsic, T., Khan, D.Z., Khellaf, A., Patani, R., Helmy, A., 2020. Cellular infiltration in traumatic brain injury. J. Neuroinflammation 17, 328.https://doi.org/10.1186/s12974-020-02005-x.

Bazarian, J. J., Abar, B., Merchant-Borna, K., Pham, D. L., Rozen, E., Mannix, R., ... & Gill, J. M. (2023). Effects of physical exertion on early changes in blood-based brain biomarkers: implications for the acute point of care diagnosis of concussion. *Journal of neurotrauma, 40*(7-8), 693-705.

Boisgontier, M. P., Cheval, B., & Schmidt, J. (2020). Daily life physical activity and concussion symptoms in adolescents. *Canadian journal of occupational therapy, 87*(5), 364-371. https://doi.org/10.1177/000841742095322

Buckley, T. A., Munkasy, B. A., Evans, K. M., & Clouse, B. (2021). Acute Physical and Mental Activity Influence on Concussion Recovery. *Medicine and science in sports and exercise.* https://doi.org/10.1249/MSS.000000000000278

Cordingley, D. M., Gomez, A., Ellis, M., & Zeiler, F. A. (2024). Identifying the cerebral physiologic response to aerobic exercise following concussion: A scoping review. *The Journal of Head Trauma Rehabilitation, 39*(5), E407-E418. https://doi.org/ 10.1097/HTR.0000000000000930

Coslick, A. M., Chin, K. E., Kalb, L. G., Slomine, B. S., & Suskauer, S. J. (2020). Participation in physical activity at time of presentation to a specialty concussion clinic is associated with shorter time to recovery. *PM&R, 12*(12), 1195-1204. https://doi.org/10.1002/pmrj.12443

Dech, R. T., Bishop, S. A., & Neary, J. P. (2019). Why exercise may be beneficial in concussion rehabilitation: a cellular perspective. Journal of science and medicine in sport, 22(10), 1090-1096. https://doi.org/10.1016/j.jsams.2019.06.007

Dinoff, A., Herrmann, N., Swardfager, W., Liu, C. S., Sherman, C., Chan, S., & Lanctot, K. L. (2016). The effect of exercise training on resting concentrations of peripheral brain-derived neurotrophic factor (BDNF): a meta-analysis. *PloS one, 11*(9), e0163037. https://doi.org/10.1371/journal.pone.0163037

Dobney, D. M., Grilli, L., Kocilowicz, H., Beaulieu, C., Straub, M., Friedman, D., & Gagnon, I. (2017). Evaluation of an active rehabilitation program for concussion management in children and adolescents. *Brain Injury: [BI]*, *31*(13-14), 1753–1759. https://doi.org/10.1080/02699052.2017.1346294

Dumuid, D., Pedišić, Ž., Palarea-Albaladejo, J., Martín-Fernández, J. A., Hron, K., & Olds, T. (2020). Compositional data analysis in time-use epidemiology: what, why, how. International journal of environmental research and public health, 17(7), 2220. https://doi.org/10.3390/ijerph17072220

Dumuid, D., Stanford, T. E., Martin-Fernández, J. A., Pedišić, Ž., Maher, C. A., Lewis, L. K., ... & Olds, T. (2018). Compositional data analysis for physical activity, sedentary time and sleep research. *Statistical methods in medical research*, *27*(12), 3726-3738. https://doi.org/10.1177/0962280217710835

Dumuid, D., Wake, M., Burgner, D., Tremblay, M. S., Okely, A. D., Edwards, B., ... & Olds, T. (2021). Balancing time use for children’s fitness and adiposity: evidence to inform 24-hour guidelines for sleep, sedentary time and physical activity. *PloS one, 16*(1), e0245501. https://doi.org/10.1371/journal.pone.0245501

Ezeugwu, V. E., & Manns, P. J. (2024). Compositional associations between movement-related behaviours and functional outcomes post-stroke. *Disability and Rehabilitation, 46*(24), 5901–5907. https://doi.org/10.1080/09638288.2024.2317995

Fedewa, M. V., Hathaway, E. D., & Ward-Ritacco, C. L. (2017). Effect of exercise training on C reactive protein: a systematic review and meta-analysis of randomised and non-randomised controlled trials. *British journal of sports medicine*, *51*(8), 670-676. https://doi.org/10.1136/bjsports-2016-095999

Grgic, J., Dumuid, D., Bengoechea, E. G., Shrestha, N., Bauman, A., Olds, T., & Pedisic, Z. (2018). Health outcomes associated with reallocations of time between sleep, sedentary behaviour, and physical activity: a systematic scoping review of isotemporal substitution studies. *International Journal of Behavioral Nutrition and Physical Activity, 15*, 1-68. https://doi.org/10.1186/s12966-018-0691-3

Grool, A. M., Aglipay, M., Momoli, F., Meehan, W. P., Freedman, S. B., Yeates, K. O., & Pediatric Emergency Research Canada (PERC) Concussion Team. (2016). Association between early participation in physical activity following acute concussion and persistent postconcussive symptoms in children and adolescents. *Jama, 316*(23), 2504-2514. https://doi.org/10.1001/jama.2016.17396

Hedayatrad, L., Stewart, T., Paine, S. J., Marks, E., Walker, C., & Duncan, S. (2022). Sociodemographic differences in 24-hour time-use behaviours in New Zealand children. International Journal of Behavioral Nutrition and Physical Activity, 19(1), 131. https://doi.org/10.1186/s12966-022-01358-1

Hooker, S. P., Diaz, K. M., Blair, S. N., Colabianchi, N., Hutto, B., McDonnell, M. N., Vena, J. E., & Howard, V. J. (2022). Association of accelerometer-measured sedentary time and physical activity with risk of stroke among US adults. *JAMA Network Open, 5*(6), e2215385-e2215385. doi:10.1001/jamanetworkopen.2022.15385

Howell, D. R., Taylor, J. A., Tan, C. O., Orr, R., & Meehan, W. P., 3rd. (2019). The role of aerobic exercise in reducing persistent sport-related concussion symptoms. *Medicine and Science in Sports and Exercise*, *51*(4), 647–652. https://doi.org/10.1249/MSS.0000000000001829

Kara, S., Crosswell, H., Forch, K., Cavadino, A., McGeown, J., Fulcher, M. (2020). LessThan Half of Patients Recover Within 2 Weeks of Injury After a Sports-Related MildTraumatic Brain Injury: A 2-Year Prospective Study. Clinical Journal of Sport Medicine, *30*, 96–101. https://doi.org/10.1097/JSM.0000000000000811.

Krainin, B. M., Seehusen, C. N., Smulligan, K. L., Wingerson, M. J., Wilson, J. C., & Howell, D. R. (2021). Symptom and clinical recovery outcomes for pediatric concussion following early physical activity. *Journal of Neurosurgery: Pediatrics, 28*(6), 623-630. https://doi.org/10.3171/2021.6.PEDS21264

Kreber, L. A., & Griesbach, G. S. (2016). The interplay between neuropathology and activity based rehabilitation after traumatic brain injury. Brain research, 1640, 152-163. https://doi.org/10.1016/j.brainres.2016.01.016

Lawrence, D. W., Richards, D., Comper, P., & Hutchison, M. G. (2018). Earlier time to aerobic exercise is associated with faster recovery following acute sport concussion. *PloS One*, *13*(4), e0196062. https://doi.org/10.1371/journal.pone.0196062

Leddy, J. J. (2025). Sport-Related Concussion. New England Journal of Medicine, 392(5), 483-493. https://doi.org/10.1056/NEJMcp2400691

Leddy, J. J., Haider, M. N., Ellis, M. J., Mannix, R., Darling, S. R., Freitas, M. S., Suffoletto, H. N., Leiter, J., Cordingley, D. M., & Willer, B. (2019). Early Subthreshold Aerobic Exercise for Sport-Related Concussion: A Randomized Clinical Trial. *JAMA Pediatrics*, *173*(4), 319–325. https://doi.org/10.1001/jamapediatrics.2018.4397

Leddy, J., Hinds, A., Sirica, D., & Willer, B. (2016). The Role of Controlled Exercise in Concussion Management. *PM & R: The Journal of Injury, Function, and Rehabilitation*, *8*(3 Suppl), S91–S100. https://doi.org/10.1016/j.pmrj.2015.10.017

Leddy, J. J., Master, C. L., Mannix, R., Wiebe, D. J., Grady, M. F., Meehan, W. P., ... & Willer, B. S. (2021). Early targeted heart rate aerobic exercise versus placebo stretching for sport-related concussion in adolescents: a randomised controlled trial. *The Lancet Child & Adolescent Health, 5*(11), 792-799.

Liangruenrom, N., Dumuid, D., & Pedisic, Z. (2023). Physical activity, sedentary behaviour, and sleep in the Thai population: A compositional data analysis including 135,824 participants from two national time-use surveys. *Plos one*, *18*(1), e0280957. https://doi.org/10.1371/journal.pone.0280957

Lishchynsky, J. T., Rutschmann, T. D., Toomey, C. M., Palacios-Derflingher, L., Yeates, K. O., Emery, C. A., & Schneider, K. J. (2019). The association between moderate and vigorous physical activity and time to medical clearance to return to play following sport-related concussion in youth ice hockey players. *Frontiers in Neurology, 10*, 588. https://doi.org/10.3389/fneur.2019.00588

Ma, Y., He, M., & Qiang, L. (2013). Exercise Therapy Downregulates the Overexpression of TLR4, TLR2, MyD88 and NF-κB after Cerebral Ischemia in Rats. *International Journal of Molecular Sciences*, *14*(2), 3718–3733. https://doi.org/10.3390/ijms14023718

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in Sports: Postconcussive Activity Levels, Symptoms, and Neurocognitive Performance. *Journal of Athletic Training*, *43*(3), 265–274. https://doi.org/10.4085/1062-6050-43.3.265

Markovic, S.J., Fitzgerald, M., Peiffer, J.J., Scott, B.R., Rainey-Smith, S.R., Sohrabi, H.R., Brown, B.M., 2021. The impact of exercise, sleep, and diet on neurocognitiverecovery from mild traumatic brain injury in older adults: A narrative review. *Ageing Research Reviews, 68*, 101322. https://doi.org/10.1016/j.arr.2021.101322.

Mastrorilli, V., & Vecchioli, S. F. (2024). Physical exercise and traumatic brain injury: is it question of time?. Neural regeneration research, 19(3), 475-476. https://doi.org/ 10.4103/1673-5374.380888

McGeown, J. P., Kara, S., Fulcher, M., Crosswell, H., Borotkanics, R., Hume, P. A., Quarrie, K. L., & Theadom, A. (2020). Predicting sport-related mTBI symptom resolution trajectory using initial clinical assessment findings: a retrospective cohort study. *Sports medicine*, *50*, 1191-1202. https://doi.org/10.1007/s40279-019-01240-4

McInnes, K., Friesen, C.L., MacKenzie, D.E., Westwood, D.A., & Boe, S.G. Mild Traumatic Brain Injury (mTBI) and chronic cognitive impairment: A scoping review. *PloS One*. 2017;12(4):e0174847. https://doi.org/10.1371/journal.pone.0174847

Mellow, M. L., Dumuid, D., Olds, T., Stanford, T., Dorrian, J., Wade, A. T., ... & Smith, A. E. (2024). Cross-sectional associations between 24-hour time-use composition, grey matter volume and cognitive function in healthy older adults. *International Journal of Behavioral Nutrition and Physical Activity, 21*(1), 11. https://doi.org/10.1186/s12966-023-01557-4

Metsios, G. S., Moe, R. H., & Kitas, G. D. (2020). Exercise and inflammation. Best practice & research Clinical rheumatology, 34(2), 101504. https://doi.org/10.1016/j.berh.2020.101504

Micay, R., Richards, D., & Hutchison, M. G. (2018). Feasibility of a postacute structured aerobic exercise intervention following sport concussion in symptomatic adolescents: a randomised controlled study. *BMJ Open Sport & Exercise Medicine*, *4*(1), e000404. https://doi.org/10.1136/ bmjsem-2018-000404

Neely, L., Smulligan, K. L., Wingerson, M. J., Seehusen, C., Simon, S., Wilson, J. C., & Howell, D. R. (2022). Evaluating the Association of Sleep & Physical activity with Prolonged Concussion Symptoms. *The FASEB Journal, 36*. https://doi.org/10.1096/fasebj.2022.36.S1.R3687

Nimmo, M. A., Leggate, M., Viana, J. L., & King, J. A. (2013). The effect of physical activity on mediators of inflammation. *Diabetes, Obesity and Metabolism*, *15*(s3), 51-60. https://doi.org/10.1371/journal.pone.0263173

Oris, C., Kahouadji, S., Durif, J., Bouvier, D., Sapin, V., 2023. S100B, Actor and Biomarker of Mild Traumatic Brain Injury. *International Journal of Molecular Sciences, 24* (7), 6602. https://doi.org/10.3390/ijms24076602

Orme, M. W., Clague-Baker, N. J., Richardson, M., Drewry, S., Robinson, T. G., & Singh, S. J. (2020). Does cardiac rehabilitation for people with stroke in the sub-acute phase of recovery lead to physical behaviour change? Results from compositional analysis of accelerometry-derived data. *Physiotherapy, 107*, 234-242. https://doi.org/10.1016/j.physio.2019.10.003

Paolucci, E. M., Loukov, D., Bowdish, D. M. E., & Heisz, J. J. (2018). Exercise reduces depression and inflammation but intensity matters. *Biological Psychology*, *133*, 79–84. https://doi.org/10.1016/j.biopsycho.2018.01.015

Pedišić, Ž., Dumuid, D., & S Olds, T. (2017). Integrating sleep, sedentary behaviour, and physical activity research in the emerging field of time-use epidemiology: definitions, concepts, statistical methods, theoretical framework, and future directions. *Kinesiology*, *49*(2.), 252-269. https://hrcak.srce.hr/186506

Patricios, J. S., Schneider, K. J., Dvorak, J., Ahmed, O. H., Blauwet, C., Cantu, R. C., ... & Meeuwisse, W. (2023). Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport–Amsterdam, October 2022. *British journal of sports medicine*, *57*(11), 695-711. https://doi.org/10.1136/bjsports-2023-106898

Petit, K. M., Kuenze, C. M., Pfeiffer, K. A., Fitton, N., Saffarian, M., & Covassin, T. (2022). Relationship between physical activity participation and recovery outcomes in college-aged adults with a concussion. *Journal of athletic training, 57*(5), 452-457. https://doi.org/10.4085/1062-6050-0158.21

Piao, C.-S., Stoica, B. A., Wu, J., Sabirzhanov, B., Zhao, Z., Cabatbat, R., Loane, D. J., & Faden, A. I. (2013). Late exercise reduces neuroinflammation and cognitive dysfunction after traumatic brain injury. *Neurobiology of Disease*, *54*, 252–263. https://doi.org/10.1016/j.nbd.2012.12.017

Remigio-Baker, R. A., Bailie, J. M., Gregory, E., Cole, W. R., McCulloch, K. L., Cecchini, A., ... & Ettenhofer, M. L. (2020). Activity level during acute concussion may predict symptom recovery within an active duty military population. *The Journal of Head Trauma Rehabilitation, 35*(2), 92-103. https://doi.org/10.1097/HTR.0000000000000498

Remigio-Baker, R. A., Bailie, J. M., Gregory, E., Cole, W. R., McCulloch, K. L., Cecchini, A., ... & Ettenhofer, M. L. (2019). Activity level and type during post-acute stages of concussion may play an important role in improving symptoms among an active duty military population. *Frontiers in Neurology, 10*, 602. https://doi.org/10.3389/fneur.2019.00602

Schneider, K. J., Leddy, J. J., Guskiewicz, K. M., Seifert, T., McCrea, M., Silverberg, N. D., Feddermann-Demont, N., Iverson, G. L., Hayden, A., & Makdissi, M. (2017). Rest and treatment/rehabilitation following sport-related concussion: a systematic review.

British Journal of Sports Medicine, *51*(12), 930–934. https://doi.org/10.1136/bjsports-2016-097475

Seehusen, C. N., Wilson, J. C., Walker, G. A., Reinking, S. E., & Howell, D. R. (2021). More physical activity after concussion is associated with faster return to play among adolescents. *International journal of environmental research and public health, 18*(14), 7373. https://doi.org/10.3390/ijerph18147373

Silverberg, N. D., & Iverson, G. L. (2013). Is Rest After Concussion "The Best Medicine?": Recommendations for Activity Resumption Following Concussion in Athletes, Civilians, and Military Service Members. *The Journal of Head Trauma Rehabilitation*, *28*(4), 250. https://doi.org/10.1097/HTR.0b013e31825ad658

Swain, C. T., Drummond, A. E., Milne, R. L., English, D. R., Brown, K. A., Lou, M. W., ... & Lynch, B. M. (2023). Linking physical activity to breast cancer risk via inflammation, Part 1: The effect of physical activity on inflammation. *Cancer Epidemiology, Biomarkers & Prevention*, OF1-OF9. https://doi.org/10.1158/1055-9965.EPI-22-0928

Szostak, J., & Laurant, P. (2011). The forgotten face of regular physical exercise: a 'natural'anti-atherogenic activity. *Clinical science*, *121*(3), 91-106. https://doi.org/10.1042/CS20100520

Szuhany, K. L., Bugatti, M., & Otto, M. W. (2015). A meta-analytic review of the effects of exercise on brain-derived neurotrophic factor. *Journal of psychiatric research, 60*, 56-64. https://doi.org/10.1016/j.jpsychires.2014.10.003

Thomas, D. G., Apps, J. N., Hoffmann, R. G., McCrea, M., & Hammeke, T. (2015). Benefits of strict rest after acute concussion: a randomized controlled trial. *Pediatrics*, *135*(2), 213–223. https://doi.org/10.1542/peds.2014-0966

Van de Mortel, T. F. (2008). Faking it: social desirability response bias in self-report research. *Australian Journal of Advanced Nursing, The*, *25*(4), 40-48.

Van Hees, V. T., Sabia, S., Jones, S. E., Wood, A. R., Anderson, K. N., Kivimäki, M., ... & Weedon, M. N. (2018). Estimating sleep parameters using an accelerometer without sleep diary. Scientific reports, 8(1), 12975. https://doi.org/10.1038/s41598-018-31266-z

Willer, B. S., Haider, M. N., Bezherano, I., Wilber, C. G., Mannix, R., Kozlowski, K., & Leddy, J. J. (2019). Comparison of Rest to Aerobic Exercise and Placebo-like Treatment of Acute Sport-Related Concussion in Male and Female Adolescents. *Archives of Physical Medicine and Rehabilitation*, *100*(12), 2267–2275. https://doi.org/10.1016/j.apmr.2019.07.00

Wilson, J. C., Kirkwood, M. W., Potter, M. N., Wilson, P. E., Provance, A. J., & Howell, D. R. (2020). Early physical activity and clinical outcomes following pediatric sport-related concussion. *Journal of clinical and translational research, 5*(4), 161.

Van den Boogaart, K. G., & Tolosana-Delgado, R. (2008). "Compositions": a unified R package to analyze compositional data. *Computers & Geosciences, 34*(4), 320-338. https://doi.org/10.1016/j.cageo.2006.11.017

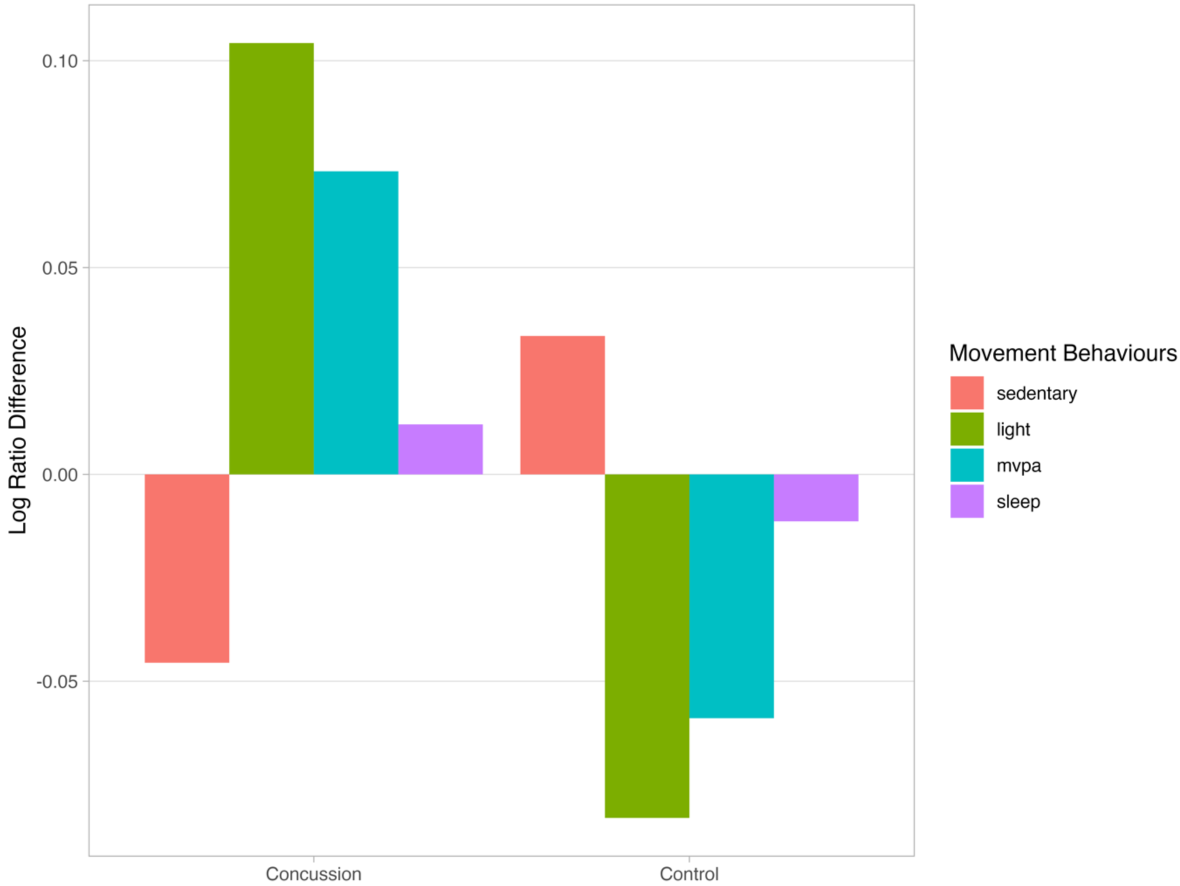
Verboon, L. N., Patel, H. C., & Greenhalgh, A. D. (2021). The immune system's role in the consequences of mild traumatic brain injury (concussion). *Frontiers in Immunology, 12*, 620698. https://doi.org/10.3389/fimmu.2021.620698

Yang, J., Yeates, K. O., Shi, J., Sullivan, L., Xun, P., Taylor, H. G., ... & ReAct Clinical Study Group. (2021). Association of self-paced physical and cognitive activities across the first week postconcussion with symptom resolution in youth. *The Journal of Head Trauma Rehabilitation, 36*(2), E71-E78. https://doi.org/10.1097/HTR.0000000000000642

Supplementary Materials

Figure S1

Log Ratio Differences in Movement Behaviours for Concussions versus Controls



Note. The above figure illustrates the between-group differences in movement behaviours (sedentary behaviour, light PA, moderate-vigorous PA, and sleep) by comparing the log ratio mean of each group to the overall log ratio mean. Each bar represents the difference to the overall mean of both groups, for each respective movement behaviour (e.g., the concussion group engaged in less sedentary behaviour but more light PA, moderate-vigorous PA and sleep, compared to the overall mean).

Table S1

Models of the Relationship Between Movement Behaviour Compositions and Recovery Showing Different Levels of Adjustment

	Unadjusted Model			**Adjusted Model** (Age)			**Adjusted Model** (Age and BIST score)		
Isometric log-ratio predictor	β	P-value	R^2	β	P-value	R^2	β	P-value	R^2
Sed	-26.95	0.24	0.16	-28.06	0.24	0.05	-26.31	0.32	0.01
LPA	-15.02	0.42	0.16	-16.20	0.42	0.05	-13.25	0.54	0.01
MVPA	-8.58	0.64	0.16	-6.88	0.75	0.05	-9.73	0.67	0.01
Sleep	50.54	0.03*	0.16	51.15	0.03*	0.05	49.29	0.06	0.01

Note. Sed refers to the proportion of time spent in sedentary behaviour relative to the other movement behaviours, *LPA* refers to the proportion of time spent in light PA relative to the other movement behaviours, *MVPA* refers to the proportion of time spent in moderate-vigorous PA relative to the other movement behaviours, and *Sleep* refers to the proportion of time spent in sleep relative to the other movement behaviours. * indicates statistical significance at $p < .05$

Table S2

Compositional Isotemporal Substitution Model of Predicted Theoretical Changes in Movement Behaviours and their Impact on Recovery from Concussion

Movement Behaviour	**Reallocated Time (mins)**	**Predicted Change in Recovery (days)**	**Lower 95% C.I.**	**Upper 95% C.I.**
Sedentary	-60	3.82	-3.90	11.54
Light PA	-60	4.91	-11.37	21.19
MVPA	-60	6.94	-26.51	40.39
Sleep	-60	-8.74	-17.72	0.25
Sedentary	-45	2.86	-2.92	8.64
Light PA	-45	3.52	-8.15	15.19
MVPA	-45	4.67	-17.84	27.18
Sleep	-45	-6.48	-13.14	0.19
Sedentary	-30	1.90	-1.94	5.75
Light PA	-30	2.25	-5.21	9.71
MVPA	-30	2.85	-10.88	16.57
Sleep	-30	-4.27	-8.67	0.12
Sedentary	-15	0.95	-0.97	2.87
Light PA	-15	1.08	-2.51	4.68
MVPA	-15	1.32	-5.04	7.68
Sleep	-15	-2.11	-4.29	0.06
Sedentary	15	-0.95	-2.87	0.97
Light PA	15	-1.01	-4.37	2.35
MVPA	15	-1.17	-6.78	4.45
Sleep	15	2.07	-0.06	4.21
Sedentary	30	-1.90	-5.74	1.94
Light PA	30	-1.97	-8.48	4.55
MVPA	30	-2.21	-12.87	8.44
Sleep	30	4.11	-0.12	8.34
Sedentary	45	-2.85	-8.61	2.91
Light PA	45	-2.87	-12.37	6.64
MVPA	45	-3.16	-18.40	12.08
Sleep	45	6.12	-0.18	12.41
Sedentary	60	-3.80	-11.48	3.88
Light PA	60	-3.72	-16.06	8.62
MVPA	60	-4.03	-23.48	15.41
Sleep	60	8.09	-0.23	16.42

Note. For all reallocations, a negative value indicates a reduction in the corresponding movement behaviour, relative to all other movement behaviours, while a positive value indicates an increase. All reallocations with a * indicate a significant association with an alpha of 0.05.

R Scripts

Code for Extracting Data from Raw .cwa Files

```
library(GGIR)

datadir= "/Users/mayanbedggood/Documents/Axivity_AX3/Raw_Data/"

outputdir= "/Users/mayanbedggood/Documents/Axivity_AX3/Output/"

g.shell.GGIR(
   desiredtz = "UTC",

  mode = 1:5,
  maxdur = 15,
  do.report = c(2:5),
  visualreport = TRUE,

  do.parallel=TRUE,
  maxNcores = 8,
  doanglez = TRUE,
  overwrite = TRUE,

  datadir=datadir,
  outputdir=outputdir
)
```

Code for Analysis 1

```
#devtools::install_github('TheTS/CodaContrast')
library(zCompositions)
library(tidyverse)
library(compositions)
library(RVAideMemoire)
library(psych)
library(CodaContrast)
library(jmv)
library(lubridate)
library(broom)
library(heplots)
library(readxl)
library(patchwork)

setwd
("/Users/mayanbedggood/Documents/Axivity_AX3/")
df <- read_xlsx("concussion_Data.xlsx")

#Compositional Descriptives
#Overall
df_all <- df %>%
  select(Sedentary,Light, MVPA, Sleep) %>%
  filter(complete.cases(.))

comp <- acomp(df_all)

round(mean(comp),2)

round(clo(mean(comp), total=1440))
```

Code for Analysis 1 (continued)

```r
# By Group
dfControl <- df %>%
  dplyr::select(sedentary, light, mvpa, sleep, group) %>%
  filter(group == 'Control') %>%
  dplyr::select(-group) %>%
  filter(complete.cases(.))

dfConcussion <- df %>%
  dplyr::select(sedentary, light, mvpa, sleep, group) %>%
  filter(group == 'Concussion') %>%
  dplyr::select(-group) %>%
  filter(complete.cases(.))

comp_Control <- acomp(dfControl)
mean(aplus(dfControl))
round(mean(comp_Control), 2)
round (clo(mean(comp_Control), total = 1440))

comp_Concussion <- acomp(dfConcussion)
mean(aplus(dfConcussion))
round(mean(comp_Concussion), 2)
round (clo(mean(comp_Concussion), total = 1440))

#Compositional MANOVA

df_all <- df %>%
  select(sedentary, light, mvpa, sleep, group) %>%
  filter(complete.cases(.))

comp <- acomp(df_all[,1:4])

mean(comp)
round (clo(mean(comp), total = 1440))

round(variation(comp), 2)

m1 <- manova(ilr(comp) ~ df_all$group)
summary(m1)

etasq(m1)

# Geomeric mean plot
plot1 <- plot_geo_means(composition = comp, group = df_all$group, type = 'component')

plot1 <- plot1 +
  theme_light() +
  labs(y= "Log Ratio Difference", fill="Movement Behaviours") +
  theme(panel.grid.minor = element_blank(), panel.grid.major.x = element_blank())

ggsave(filename="Plot1.png", plot=plot1, width=8,height=6,dpi=900)

# Contrasts
lr <- log_ratio_difference(composition = comp,
                           group = df_all$group, reference_group = 'Control')
print(lr)

plot2 <- plot_log_ratio_difference(lr,percentage = TRUE)

plot2 <- plot2 + scale_y_continuous(labels = scales::percent, breaks = c(seq(from=-0.25, to=0.44, by=0.05))) +
  theme_light() +
  theme(panel.grid.minor = element_blank(), panel.grid.major.x = element_blank())

ggsave(filename="Plot2.png", plot=plot2, width=6,height=6,dpi=900)

#plot1 + plot2 + plot_annotation(tag_levels = "A")
```

Code for Analysis 2

```
library(compositions)
library(lubridate)
library(tidyverse)
library(car)
library(performance)
library(deltacomp)
library(plyr)
library(readxl)
library(janitor)
library(ggthemes)
library (psych)

setwd ("/Users/mayanbedggood/Documents/Axivity_AX3/")
df <- read_xlsx("concussion_Data.xlsx") %>%
  clean_names()

df_all <- df %>%
  filter(group == 'Concussion') %>%
  dplyr::select(sedentary, light, mvpa, sleep,
         recovery_time,
         participant_age, bist)


mean(df_all$participant_age)
sd(df_all$participant_age)

df_all %>%
  dplyr::select(sedentary, light, mvpa, sleep) %>%
  describe()
comp <- acomp(cbind(df_all$sedentary, df_all$light, df_all$mvpa, df_all$sleep))
round(mean(comp),2)
round(clo(mean(comp), total=1440))
round(var(comp),3)

#Compositional multiple regression
#Building the sequential binary partition matrices

               # sed, lpa, mvpa, sleep

sbp_sed <- matrix(c(1, -1, -1, -1,
                    0,  1, -1, -1,
                    0, 0, 1, -1),
                  ncol=4, byrow=TRUE) # ilr1 = sed/lpa+mvpa+sleep
sbp_lpa <- matrix(c(-1, 1, -1, -1,
                    -1, 0,  1, -1,
                    -1, 0, 0, 1),
                  ncol=4, byrow=TRUE) # ilr1 = lpa/sed+mvpa+sleep
sbp_mvpa <- matrix(c(-1, -1, 1, -1,
                     -1, -1, 0,  1,
                     1, -1, 0, 0),
                   ncol=4, byrow=TRUE) # ilr1 = mvpa/sed+lpa+sleep
sbp_sleep <- matrix(c(-1, -1, -1, 1,
                      -1, -1, 1, 0,
                      -1, 1, 0, 0),
                    ncol=4, byrow=TRUE) #ilr1 = sleep/sed+lpa+mvpa
colnames(sbp_sed) <- c('Sedentary', 'LPA', 'MVPA', 'Sleep')
rownames(sbp_sed) <- c('ilr1', 'ilr2', 'ilr3')
sbp_sed

#Creating isometric log ratios
sbp <- gsi.buildilrBase(t(sbp_sed))
ilr.comp_sed <- ilr(comp, V = sbp)

sbp <- gsi.buildilrBase(t(sbp_lpa))
ilr.comp_lpa <- ilr(comp, V = sbp)

sbp <- gsi.buildilrBase(t(sbp_mvpa))
ilr.comp_mvpa <- ilr(comp, V = sbp)

sbp <- gsi.buildilrBase(t(sbp_sleep))
ilr.comp_sleep <- ilr(comp, V = sbp)
```

Code for Analysis 2 (continued)

```
#Fit model (m0 = unadjusted, m1 = adjusted)
m0_sed <- lm(df_all$recovery_time ~ ilr.comp_sed)
m1_sed <- lm(df_all$recovery_time ~ ilr.comp_sed + df_all$participant_age + df_all$bist)

m0_lpa <- lm(df_all$recovery_time ~ ilr.comp_lpa)
m1_lpa <- lm(df_all$recovery_time ~ ilr.comp_lpa + df_all$participant_age + df_all$bist)

m0_mvpa <- lm(df_all$recovery_time ~ ilr.comp_mvpa)
m1_mvpa <- lm(df_all$recovery_time ~ ilr.comp_mvpa + df_all$participant_age + df_all$bist)

m0_sleep <- lm(df_all$recovery_time ~ ilr.comp_sleep)
m1_sleep <- lm(df_all$recovery_time ~ ilr.comp_sleep + df_all$participant_age + df_all$bist)

#Model Summaries
summary(m0_sed)
summary(m1_sed)

summary(m0_lpa)
summary(m1_lpa)

summary(m0_mvpa)
summary(m1_mvpa)

summary(m0_sleep)
summary(m1_sleep)


##run test to compare Concussion group to control group

#Check assumptions for linear regression model
check_model(m1_sed)
check_model(m1_lpa)
check_model(m1_mvpa)
check_model(m1_sleep)

#Compositional isotemporal substitution
#Increment (mins)
RA = 15
#Substitution
df_pred <- predict_delta_comps(data = df_all,
                               y = "recovery_time",
                               comps = c("sedentary", "light", "mvpa", "sleep"),
                               covars = c('participant_age', 'bist'),
                               comparisons = "prop-realloc",
                               deltas = seq(-60, 60,by=RA)/(24*60),
                               alpha = 0.05)
df_pred %>%
  as_tibble() %>%
  mutate(realloc = rep(seq(-60, 60,by=RA), each = 4)) %>%
  dplyr::select(1:3, 9, 4:8) %>%
  write_csv('reallocations_intensity_zrecovery.csv')

df_pred <- df_pred %>%
  as.data.frame() %>%
  mutate(`comp+`=ifelse(`comp+`=="mvpa","MVPA",str_to_sentence(`comp+`)))

ggplot(df_pred, aes(x=(delta*1440), y=delta_pred)) +
  geom_line(aes(color = `comp+`), size=1) +
  geom_ribbon(aes(ymin=ci_lo, ymax=ci_up, fill = `comp+`), alpha = 0.6) +
  geom_vline(xintercept = 0, size = 0.5, color="grey60", linetype="dotted") +
  geom_hline(yintercept = 0, size = 0.5, color="grey60", linetype="dotted") +
  facet_wrap(`comp+`~.) +
    scale_y_continuous(breaks = c(seq(from=-30, to=30, by=10))) +
  theme_few() +
  theme(legend.position = "none") +
  labs(x="Change in Movement Behaviour (mins)", y= "Change in Recovery Time (days)")

ggsave(filename="Plot3.png", width=7,height=5,dpi=900)
```