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Longitudinal changes in juvenile and adolescent body mass indices before, during, and after the COVID-19 lockdown in New Zealand

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Abstract

Objective: This study uses longitudinal data from school children in Dunedin, New Zealand, to evaluate impacts of COVID-19 lockdown measures on changes in body mass (BMI, kg/m^2). Impacts are assessed using two non-mutually exclusive hypotheses. The "structured days" hypothesis holds that children tend to alter sleep patterns, reduce activity and increase snacking when not in structured environments. The bidirectional hypothesis proposes that over-weight or obese children are predisposed to further gains in unstructured settings.

Methods: Juveniles and adolescents ($n = 95$, 60% female) were recruited from Dunedin schools. Repeated measures analyses assessed variation in intra-individual change in BMI during four periods: P1 (before summer break), P2 (during summer break), P3 (during the COVID-19 lockdown), and P4 (after the lockdown ended). The model also examined if these changes were influenced by participants' sex or body size early in the first period assessed using log-transformed BMI, log-transformed weight, height, or lower leg length.

Results: Repeated measures analyses of per month gains in BMI (kg/m^2) during the four periods revealed consistent period ($p \leq .001$), period by sex ($p \leq .010$), and period by body size ($p \leq .001$) interactions across all four body size proxies. Both sexes experienced the greatest gains during the lockdown (P3), but differed in response to their summer break (P2).

Conclusion: Results are mostly consistent with the "structured days" hypothesis, but challenge the bidirectional hypothesis as defined. Further research better characterizing risks of gains in adiposity are needed.

1 | INTRODUCTION

This study uses longitudinal data to evaluate the relationship between a comparatively severe COVID-19 lockdown and change in body mass indices (BMI, kg/m^2) for 95 juvenile and adolescent school children in Dunedin, New Zealand. The COVID-19 lockdown in New Zealand was rapidly implemented in phases beginning on March

21st with the most stringent Level 4 phase coming into force on March 26th (see Table 1). Lockdown was represented by Levels 3 and 4, which lasted 50 days.

Surveys of adults in New Zealand indicate that self-reported adherence to government implemented public health measures during lockdown was very high (Mazey and Richardson 2020; Gray et al. 2021). As a consequence, physical activity declined and consumption of saturated fats, and salty and sweet snacks increased (Gerritsen et al. 2021; Murphy et al. 2021).

We anticipated that these changes would be reflected as significant within-individual gains in BMI during the period of lockdown. This expectation is supported by evidence of BMI gains in U.S. children during COVID-19 home quarantine (Brazendale et al. 2021; Weaver et al. 2021). Anticipated gains would also be consistent with documented gains in body mass during relatively long summer vacation periods in the U.S. (Brazendale et al. 2017; Moreno et al. 2013; Tanskey et al. 2018, 2019; von Hippel et al. 2007; Weaver et al. 2019, 2020).

TABLE 1 Implementation of policies to restrict the spread of SARS-CoV-2 in New Zealand in 2020

Beginning date	Lockdown level[a]	General characteristics and requirements
March 26	4	Stay home and maintain "bubble"; no travel except for necessities or for safe recreational activities; no public gatherings; wear masks when out; only essential businesses open; tracer details collected
April 28	3	Stay home, but "bubbles" can modestly enlarge to include members of one other family; wear mask when out of house; gatherings of up to 10 people allowed outdoors; take-out businesses in operation; tracer details collected
May 14	2	Most businesses open but some restriction on numbers of people still apply, social distancing and masking; tracer details collected
June 9	1	Business and schools open; no restrictions on movement; masks still required in healthcare settings and on public transport; tracer details collected

[a] Lockdown is defined here as the 50 days between initiation of levels 4 and 2.

Although recent studies of changes in children's body mass have consistently reported greater risks of gains in weight or BMI during summer vacation periods, studies do not necessarily agree on causal mechanisms (Brazendale et al., 2017; Moreno et al., 2013, 2015, 2019, 2021; Metcalf et al. 2011; Moore et al., 2003; Sprengeler et al. 2021; Tanaka et al. 2018). One prominent explanation, the "structured days" hypothesis, holds that juvenile gains in weight or BMI are more likely to accrue during periods of less-structured time (Brazendale et al. 2017; Weaver et al. 2020). The authors explicitly likened summer vacation to an extended weekend period when children's activities are less structured, with more time spent in sedentary activities that may include snacking between meals (Brazendale et al. 2017). Differences in sleep patterns during these periods have also been proposed as influencing weight gain (Nixon et al. 2008; Brazendale et al. 2017; Weaver et al. 2019; Moreno et al. 2021). Other authors argue that causal relationships among behavioral changes that include increased sedentary activities on weight gain may be bidirectional. This bidirectional hypothesis posits that children who are already overweight or obese are more likely in less structured settings to alter behaviors that then lead to increases in adiposity. In support of this latter hypothesis, these authors present evidence that children who are already overweight, defined using weight or BMI-status cut-offs, tend to be less active and more vulnerable to further gains in adiposity (Metcalf et al. 2011; Skrede et al. 2021; Tanaka et al., 2018). There are also suggestions that differences in seasonality contributing to variation in height growth may also, at least in some settings, contribute to summer gains in zBMI (Moreno et al. 2022).

Here, we evaluate these competing, but non-mutually exclusive hypotheses, using our longitudinal data subdivided into four periods: during school before the summer break (P1), during the six-week summer break (P2), during the COVID-19 lockdown (P3), and after the lockdown was over (P4) for the 95 participants (details of scheduling are in the next section). First, in accord with the "structured days" hypothesis, we anticipate the greatest within-period BMI gains for juvenile and adolescent students during the period that includes the relatively severe COVID-19 lockdown measures implemented in New Zealand in March 2020 (P3 > P1, P2 or P4). If we assume participants during summer breaks experienced less structure than during school periods and this contributed to more variation in sleep and waking times, snacking, and increased sedentary activities then we anticipate greater mean BMI gains in P2 than P1 or P4. Second, we explore the implications of the bidirectional hypothesis. If relatively high values of BMI at the beginning of P1 tend to increase individuals' risks of greater

BMI gains, we anticipate the strongest positive interactions between initial BMI and BMI gains during P3, with somewhat weaker but substantial effects in P2 if conditions similar to those described in other studies apply in New Zealand. We do not, however, anticipate similarly strong relationships between initial height or lower leg length and these within-period gains in BMI if the bidirectional hypothesis as presently defined applies.

2 | PARTICIPANTS AND METHODS

2.1 | The study population

Students were recruited in their last year of primary school and followed as they transferred to intermediate schools in the Dunedin area. The participants were part of the Biorhythm of Childhood Growth project (Mahoney et al. 2022). The project is an ongoing prospective cohort study that investigates childhood development in middle-income children from Southern New Zealand. While details about the socioeconomic circumstances of each participant and their families were not formally gathered, the decile ranks of participating schools provide composite information about the socioeconomic status of families contributing students to them. A decile rank represents a weighted composite of census information about students' family income, occupation, education, household crowding and income support. Decile one schools have the highest frequency of relatively less well-off families while decile 10 schools have the highest frequency of affluent families (New Zealand Ministry of Education, 2021). Decile ranks of participants' schools varied from 3 to 10 (median = 8; mean = 7.7 ± 1.6 SD). These values are similar to decile rank statistics for all schools in the Dunedin area (median = 8; mean = 7.2 ± 2.2 SD).

Of 121 students recruited before the COVID-19 lockdown began, seven transferred out before March 2020. Of the 114 who remained, 19 were excluded. Eight of these were excluded because they were missing more than one consecutive measurement in sessions immediately preceding or following the lockdown. The other 11 were eliminated because values were missing from session six, used to define the end of the summer break and the beginning of the lockdown period. Most participants were of New Zealand European ethnicity (76/95). Almost all other participants affiliated as either Māori or Pasifika.

Ethical approval for longitudinal data collection was obtained through the University of Otago Human Ethics Committee (approval number H19/030). Research consultation with Māori was obtained from the Ngāi Tahu Research Consultation Committee. Informed consent was obtained from all participants, and their parents or guardians.

2.2 | Measurements

One of us (SW) measured students 12 times on a regular schedule at each of the participating schools from late July 2019 through November 2020. To encourage participation, participants received a $30 NZ voucher useable in supermarkets or stationary stores at the last measurement session. Measurements were taken about once per month with the following exceptions. No January measurements were scheduled because of the 6-week summer holiday period. Measurements were taken again in late February to early March, but were then temporarily suspended because of COVID-19 lockdown measures already noted. The 7th measurement session resumed in late June. Table 2 shows the four periods considered with their mean durations (± SE). The modal beginning and ending measurement sessions for P1 were 1 (27/7/2019 to 7/8/2019) and 5 (11/12/2019 to 16/12/2019), for P2 they were sessions 5 and 6 (25/2/20 to 9/3/20), for P3 they were sessions 6 and 7 (22/6/2020 to 30/6/2020), and for P4 they were sessions 7 and 11 (28/10/2020 to 30/10/2020). In the instances where values were not available in these sessions, values from the closest available session were substituted. Six participants in P2 overlap with P1, with their summer period defined as sessions 4 (20/11/2019 to 21/11/2019) to 6. Eight participants in P3 overlap with P4, their lockdown period defined from sessions 6 to 8 (28/7/20 to 30/7/20).

Weight was recorded without shoes or heavy clothing on calibrated scales to the nearest 0.1 kg. Height was taken to the nearest millimeter using a Seca 213 Stadiometer. Lower leg length measurements were recorded three times per participant per visit with the children in a standardized seated position using a custom-made laser measuring device to the nearest millimeter. The mean of these three values per session was used in calculations of differences. Preliminary assessments of maturational timing were based upon kernel modeling of serial measurements of height or low length using pre-spurt minimum velocity as a means to judge the end of the juvenile period (Bogin 2020).

2.3 | Analyses

Individual change in BMI was computed on a per month basis for all participants by dividing their amount of change within a period by its duration in days multiplied

TABLE 2 Beginning measurement sessions for participants in each period, the associated n-values[a], and median and mean durations (± SD) for 95 participants

	2019				**2020**											
	Summer Lockdown															
Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Session	1	2	3	4	5		6				7	8	9	10	11	12
$n = 51$		38	6	6	95		95				87	8	2	2	75	16
	P1 Begins			**P2 Begins**			**P3 Begins**				**P4 Begins**					
P1	Median 110 days Mean 106.2 ± 29.6															
P2					Median 77 days Mean 79.6 ± 6.5											
P3							Median 119 days Mean 120.8 ± 10.6									
P4											Median 126 days Mean 124.7 ± 20.3					

[a]Highlighted n-values represent those associated with first measurement during a period. The modal beginning and ending measurement sessions were as follows: P1 (Session 1, 27/7/2019 to 7/8/2019 to Session 5, 11/12/2019 to 16/12/2019), P2 (Session 5 to Session 6, 25/2/20 to 9/3/20), P3 (Session 6 to Session 7, 22/6/2020 to 30/6/2020) and P4 (Session 7 to Session 11, 28/10/2020 to 30/10/2020). Differences from these were because of missing measurements in those sessions; values from the closest available sessions were substituted. Six participants in P2 overlay with P1, with their summer period defined as Sessions 4 (20/11/2019 to 21/11/2019) to 6. Eight participants in P3 overlap with P4, their lockdown period defined from Sessions 6 to 8 (28/7/20 to 30/7/20).

by 30.42 days per month. Model 1 is a generalized representation of repeated measures analyses used to evaluate whether within-individual monthly gains in BMI in P3 were significantly greater than gains during P1, P2 or P4, and whether sex/gender or one of four measures of initial body size (BMI, height, lower leg length, or weight) contributed. Within-individual per month changes in BMI during the four periods was chosen as the outcome variable because it serves as the best available indicator of within-individual changes in adiposity (Berkey and Colditz, 2007; Cole et al. 2005; von Hippel et al. 2015). Two of the initial body size proxies, BMI and weight, were natural log-transformed to better meet assumptions of normality.

Model 1: P1 Δ BMI, P2 Δ BMI, P3 Δ BMI, P4 Δ BMI = Constant + Sex + Initial Body Size Proxy.

We evaluated outcomes by first examining whether within-subject BMI gains during the lockdown (P3) were significantly greater than in P1, P2 or P4. Statistical significance was judged using the within-subjects single degree of freedom polynomial cubic contrasts for period, as well as post-hoc pair-wise comparisons. Following this, within-subjects interactions between period and sex or period and log-BMI (or the alternative proxies of log-weight, height, or lower leg length, all measured in the first session of P1) were assessed in a similar manner. Bivariate plots of per month gain in BMI by sex and each body size proxy were also used to illustrate similarities and differences in outcomes among proxies. Assessment of the effect-sizes of period, period by sex, and period by body size proxy interactions were judged using a simple measure of effect size, eta-squared. It is calculated as SS_{period} or $SS_{period\text{-}by\text{-}sex}$ or $SS_{period\text{-}by\text{-}proxy\ interaction}$ divided by SS_{total}. This measure is model-specific but easy to interpret in the present study because all models have the same structure.

Within period gains in BMI reflect greater changes in weight than height of a given individual. The bidirectional hypothesis proposes that children who are over-weight or obese at the outset of unstructured periods are more likely to exhibit greater within-period gains in BMI. We anticipated that if over-weight or obese children are more prone to further gains in adiposity in less structured settings, then the period by log-BMI body size proxy interactions should be most strongly positively associated with within-period gains in BMI per month in P3 and perhaps P2. Log-weight assessed at the outset of P1 is also anticipated to be strongly associated because it tends to be highly correlated with BMI. Following the same rationale, we do not anticipate participants' heights or lower leg lengths will be similarly positively associated with the period by body size interaction. There is, however, a possibility of confounding. If participants who are taller early on tend to gain less height than shorter individuals in later periods, they may tend to have larger BMI gains even if their amounts of weight gain are similar. This possibility was considered by evaluating BMI gains in later periods using the residuals of height at the beginning of P1 regressed on height gain during P2 or P3. No indications of confounding were found. Descriptive and inferential statistics were calculated using SYSTAT 10.

3 | RESULTS

Participants' descriptive statistics are reported first, followed by assessments of the hypotheses using the model described above. Table 3 reports descriptive statistics for age, height, lower leg length, weight, and BMI for the participants early in P1 separately by sex. As anticipated given the age range considered, females are larger, on average, in all physical dimensions considered. They are also consistently more variable, in part because a large majority had entered adolescence. While very few males had reached pre-spurt minimum velocity, almost all females had, judging from kernel modeling of serial measures of height or lower leg length.

A visual comparison of the extent of unadjusted mean (and median) BMI changes per month shown in Table 4 with adjusted mean BMI change per month from repeated measures analyses reported in Table 5 indicate the same central tendencies. Both reveal the same similarities and differences between female and male participants' responses across the four periods. Both sexes experienced the greatest mean BMI per month increases during P3 bracketing lockdown, though unadjusted (0.238) and adjusted mean female gains (0.222 to 0.227) were notably greater than comparable male values (0.113, 0.130 to 0.137). Extents of mean and median BMI per month change in P1 and P4 were similar within the

TABLE 3 Descriptive statistics for 95 participants at the beginning of the first period (P1)

Sex	Statistic	Age (year)	Height (cm)	Lower leg length (cm)	Weight (kg)	BMI (kg/m^2)
Female	Median	10.64	144.60	46.00	39.50	18.42
(*n* = 57)	Mean	10.52	144.81	45.76	40.29	19.01
	Std. error	0.07	0.99	0.33	1.27	0.42
	Std. Dev.	0.56	7.47	2.49	9.59	3.16
Male	Median	10.42	141.60	44.72	35.15	17.25
(*n* = 38)	Mean	10.45	142.19	44.88	36.44	17.93
	Std. error	0.10	0.85	0.32	1.07	0.38
	Std. Dev.	0.60	5.22	1.99	6.58	2.36

TABLE 4 Additional unadjusted descriptive statistics about within period change in BMI per month (kg/m^2) for 95 participants in the four periods

Sex	Statistic	P1	P2	P3	P4
Female	Students with Δ BMI >0 (N)	40	29	46	37
(*n* = 57)	Students with Δ BMI <0 (N)	17	28	11	20
	Mean Δ BMI per month	0.084	0.012	0.238	0.051
	Mean Δ BMI per month standard error	0.022	0.020	0.036	0.027
	Median Δ BMI per month	0.057	0.020	0.228	0.061
	Minimum Δ BMI per month	−0.250	−0.248	−0.378	−0.619
	Maximum Δ BMI per month	0.660	0.395	0.808	0.488
Male	Students with Δ BMI >0 (N)	17	31	29	22
(*n* = 38)	Students with Δ BMI <0 (N)	21	7	9	16
	Mean Δ BMI per month	0.006	0.103	0.113	0.030
	Mean Δ BMI per month standard error	0.025	0.020	0.033	0.024
	Median Δ BMI per month	−0.025	0.086	0.105	0.025
	Minimum Δ BMI per month	−0.258	−0.120	−0.372	−0.249
	Maximum Δ BMI per month	0.496	0.451	0.550	0.337

TABLE 5 Adjusted mean changes in BMI per month (kg/m^2) of 95 participants (57 females and 38 males) from repeated measures analyses among similar periods during school before summer break (P1), during summer break (P2), during the COVID-19 lockdown (P3) and after the lockdown (P4) in New Zealand. The model includes sex and log-transformed BMI, log-transformed weight, height or lower leg length of participants at the beginning of P1[a]

		Adjusted for log-BMI				Adjusted for log-weight			
Sex	Statistic	P1	P2	P3	P4	P1	P2	P3	P4
Female	Mean	0.079	0.015	0.227	0.054	0.077	0.017	0.222	0.054
	Std. error	0.021	0.018	0.031	0.025	0.021	0.018	0.031	0.025
Male	Mean	0.013	0.097	0.130	0.026	0.017	0.095	0.137	0.026
	Std. error	0.026	0.023	0.038	0.030	0.026	0.023	0.038	0.030

		Adjusted for height				Adjusted for lower leg length			
Sex	Statistic	P1	P2	P3	P4	P1	P2	P3	P4
Female	Mean	0.078	0.016	0.224	0.052	0.077	0.016	0.225	0.052
	Std. error	0.021	0.018	0.031	0.025	0.020	0.018	0.031	0.025
Male	Mean	0.015	0.096	0.133	0.029	0.017	0.096	0.131	0.029
	Std. error	0.026	0.023	0.038	0.03	0.025	0.023	0.038	0.030

[a] For all 95 participants the dependent variable means ± standard errors are P1: 0.053 ± 0.017; P2: 0.048 ± 0.015; P3: 0.188 ± 0.026; P4: 0.043 ± 0.019.

TABLE 6 Results of repeated measures analysis of BMI per month (kg/m^2) of 95 participants (57 females and 38 males) across four periods: During school before summer break (P1), during summer break (P2), during the COVID-19 lockdown (P3), and after (P4) in New Zealand. The model includes sex and log-transformed BMI, log-transformed weight, height or lower leg length of participants at the beginning of P1

Within subjects					
Single degree of freedom polynomial contrasts					
Source	SS	df	MS	F	P
Period	0.500	1	0.500	10.991	0.001
Period by sex	0.366	1	0.366	8.028	0.006
Period by Log-BMI	0.558	1	0.558	12.256	0.001
Error	4.189	92	0.046		
Period	0.727	1	0.727	16.972	< 0.0005
Period by sex	0.298	1	0.298	6.963	0.010
Period by log-weight	0.806	1	0.806	18.821	< 0.0005
Error	3.941	92	0.043		
Period	0.623	1	0.623	14.106	< 0.0005
Period by sex	0.336	1	0.336	7.599	0.007
Period by height	0.683	1	0.683	15.454	< 0.0005
Error	4.064	92	0.044		
Period	0.607	1	0.607	13.696	< 0.0005
Period by sex	0.344	1	0.344	7.762	0.006
Period by lower leg length	0.671	1	0.671	15.153	< 0.0005
Error	4.076	92	0.044		

sexes, and broadly similar between, though lower for males. Sex-associated differences in the outcome variable were apparent, however, in P2. Within this period, unadjusted BMI per month gains are significantly lower in females than males (0.012 vs. 0.103; $p = .006$). The same is true for adjusted gains reported from the repeated measures analyses (females: 0.015 to 0.017 vs. males: 0.095 to 0.097; $p \leq .008$).

As reported in Table 6, when males and females are taken together in the repeated measures analyses, variation by period in adjusted mean BMI change per month (kg/m^2) is statistically significant in all comparisons

($p \leq .001$). As already shown in Table 5, the pattern of values of the outcome variable (P3 > P1, P2 or P4) is consistent with initial expectations related to the "structured days" hypothesis. The overall adjusted means for this variable in P2 are not, though, significantly different than in P1 or P4 (0.048 vs. 0.053 or 0.043). The similarities among these three periods are not sustained when period by sex interactions are considered. All period by sex interactions are statistically significant (Table 6; $p \leq .01$) because patterns vary consistently by sex/gender (Table 5). Among females, mean BMI gains per month are greater in P1 (0.077 to 0.079) than P2 (0.015 to 0.017), but in males it is the inverse with P2 values (0.095 to 0.096) greater than those in P1 (0.013 to 0.017). As already suggested in values reported above, while differences in mean BMI change per month differed substantially for females in P2 vs. P3 ($p \leq .001$), differences in male values for these two periods were not statistically significantly different ($p \geq .447$). Overall, results reported so far are consistent with the "structured days" hypothesis, with the exception of the small mean female BMI per month gains during P2 that are less than their gains during P1.

Results reported in Table 5, Table 6, and Table 7 for the period by body size proxy interactions are not consistent with the bidirectional hypothesis. We anticipated that if over-weight or obese children are more prone to further gains in adiposity in less structured settings, then models that include earlier log-BMI should exhibit a stronger period by body size interaction than models using height or lower leg length. We do not find this. Differences in outcomes related to the proxy for early body size chosen are relatively small with log-weight being the most effective proxy, but height and lower leg length serving almost as well and Log-BMI being least effective.

Considerations of variation in slope of BMI change per month in each of the periods relative to each of the body size proxies used, shown in Figure 1, do not provide support for the bidirectional hypothesis either. During P3 when participants were exposed to lockdown conditions, both females and males showed positive slopes, with female slopes being greater, all consistent with extent of gains in mean BMI change per month. But these relationships are similar for all four body size proxies, including height and lower leg length. During P2, mean male BMI gains per month are only modestly reduced as compared to P3, but their associations with the body size proxies tend to be either near absent (using log-BMI or log-weight) or weakly negative.

4 | DISCUSSION

We found the largest mean within-individual per month gains in BMI during P3 for female and male participants in all comparisons. This was anticipated because the COVID-19 lockdown in New Zealand that occurred during P3 represented a clearly demarcated period with high levels of public adherence to comparatively strict public health restrictions, including home quarantine requirements (Mazey and Richardson 2020; Gray et al. 2021). Older adolescents and adults report reductions in physical activity and increases in snacking outside of regular meals (Gerritsen et al. 2021; Murphy et al. 2021). These New Zealand studies did not include participation by younger groups, though studies in Canada (Moore et al. 2020) and Italy (Pietrobelli et al. 2022) document substantial adverse impacts on physical activity and diet among children and adolescents during the pandemic. Additionally, while we are not aware of surveys documenting changes in sleep patterns during the New Zealand lockdown period, such changes may have contributed given what has been documented earlier in New Zealand (Nixon et al. 2008) and elsewhere (Moore et al. 2020; Moreno et al. 2021; Pietrobelli et al. 2020, 2022; Weaver et al. 2019). Pietrobelli et al. (2022) note, however, that changes in sleep patterns that took place early in the quarantine period were not found later on.

The extent of BMI gains per month for participants in the current study are somewhat greater than BMI gains reported for juveniles and adolescents of various ages in the few other studies on impacts associated with COVID-19 lockdowns where anthropometry have been directly assessed (Table 8). Brazendale et al. (2021) report BMI gains for 29 children of 0.60 ± 1.20 SD kg/m^2 over a five-month period surrounding a month-long stay-at-home order in a rural U.S. town (0.12 kg/m^2 per month). These children were an average 9.3 years of age. A similar mean gain of 0.51 ± 1.34 SD kg/m^2 (0.13 kg/m^2 per month) is

TABLE 7 The effects size as represented by eta-squared statistics using results from cubic polynomial contrasts for each of the predictors in the repeated measures model for 95 participants

	Proxy for body size used			
Predictor	**Log-BMI**	**Log-weight**	**Height**	**Lower leg length**
Period	0.089	0.126	0.109	0.107
Period by sex	0.065	0.052	0.059	0.060
Period by body size	0.099	0.140	0.120	0.118

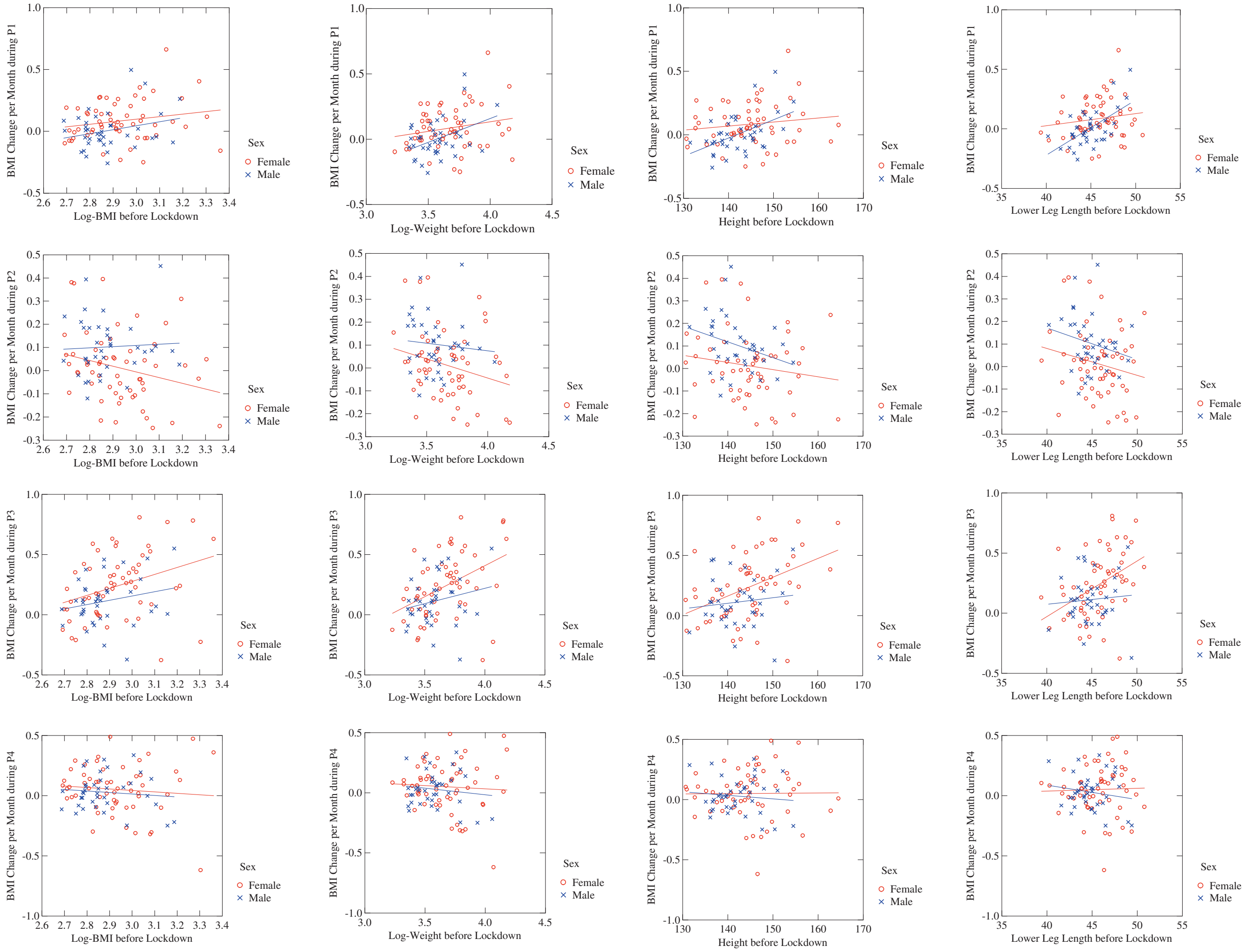

FIGURE 1 Changes in within-period BMI for 95 participants by sex during P1, P2, P3, and P4 (top to bottom) relative to log-BMI, log-weight (left), height or lower leg length (right) measured at the beginning of P1. Note that the range of y-axes are consistent within period, but differ among them.

reported for somewhat older Italian adolescents (mean age: 14.7 ± 2.1 SD years). These 31 males and 20 females, over-weight out-patients with normal fasting blood-glucose levels from a weight clinic, were measured in the 2 months preceding COVID-19 lockdown on March 8th and in the weeks after it ended on May 18th, 2020 (Maltoni et al. 2021).

As already noted in Table 5, female participant mean BMI per month gains (0.222 to 0.227) were notably greater than those for males (0.130 to 0.137) in P3, but not in P2 where female mean values (0.015 to 0.017) were less than those of male participants (0.095 to 0.097). P2 included the relatively short six-week summer school break in New Zealand. The values during P2 reported for male participants are similar to values reported (or estimated from reported data) for children during U.S. summer vacations in a number of published studies (see Table 8). Per month values for female participants fall below the maximum range of means reported or estimated from these studies (0.05 to 0.19), with one exception that focused specifically on children who were either underweight or normal weight (defined as ≤85 centile for BMI) (Lane et al. 2021). Curiously, in the preceding period when participants in the current study were in school (P1), female adjusted mean changes in BMI (0.077 to 0.079) were greater than male mean changes (0.013 to 0.017). These female values are modestly greater, and the male values modestly lower, than the school-time values reported or estimated from published research (0.02 to 0.07) noted in Table 8.

Another useful way of considering these values is provided by von Hippel et al. (2015). They provide information about the extent of BMI change among relatively well-off children of European ancestry from Ohio who participated in the Fels Longitudinal Growth Study. These authors take advantage of the long-term nature of

TABLE 8 Per monthly mean Δ BMI (kg/m^2) reported or estimated[a] from various studies. Values are for both sexes combined

Study	Setting	Mean Δ BMI per month
Current study	COVID-19 restrictions	0.18
Maltoni et al. (2021)[a]	COVID-19 restrictions	0.13
Brazendale et al. (2021)	COVID-19 restrictions	0.12
Lane et al. (2021)[b]	Summer - Model 1	−0.01
	Summer - Model 2	0.05
	Summer - Model 3	0.10
Moreno et al. (2021)[c]	Summer vacation	0.08
	School time	0.05
Tanskey et al. (2019)	Summer vacation	0.09
	School time	0.07
Weaver et al. (2020)[d]	Summer vacations	0.15 to 0.19
	School time	0.07
Von Hippel and Workman (2016)	Summer vacations	0.07 to 0.08
	School time	0.02 to 0.05

[a] The per month estimates for Lane et al. (2021, Table 2) were originally reported for Model 1 (underweight & normal weight, < 85% BMI percentile), Model 2 (overweight, > 85% and < 95 percentile), and Model 3 (obese, ≥ 95 BMI percentile). The adjusted mean difference in kg/m^2 (95% CI) for summer and the rest of the year was −0.04 (−0.09, 0.00) for Model 1, 0.27 (0.06, 0.46) for Model 2, and 0.50 (0.20, 0.80) for Model 3. Per month estimates were calculated by dividing reported values by the average interval between the reported measurements (April 28 (SD = 18.4 days) and September 30th (SD = 15.1 days)).

[b] The per month estimate for Maltoni et al. (2021) assumes the duration calculated from the mid-points of the periods before and after lockdown within which measurements took place.

[c] The per month estimates for Moreno et al. (2021; Table 4) were originally reported as mean ± SD of 0.39 ± 0.77 SD or 0.28 ± 0.66 SD. Each mean value was divided by the mean duration of summer vacation (143 ± 18 days) or school year periods (183 ± 28 days) and then multiplied by 30.42 days per month.

[d] Refers to summer vacations and school times for students in schools with traditional schedules for their area.

the Fels Study to provide a basis to assess recent longitudinally determined distributions of BMI change. Separate age and sex-specific estimates are provided for two Fels birth cohorts, participants born from 1946 to 1970 and from 1971 to 1995. Von Hippel et al. (2015; pg. 470) explicitly argue that these two cohorts are useful because the first grew up before the beginning of the obesity epidemic in the U.S. in the mid-1980 s, and the second overlaps it. We used data reported in von Hippel et al. (2015, Fig. 3, pg. 473) from the later cohort of the Fels study to estimate centiles that approximately match the adjusted mean values for our participants reported in Table 5 for each of our four periods. We selected centiles using 6-month measurement intervals as this duration is closer to those in the current study with somewhat greater dispersion across centiles than for their estimates using a 12-month measurement interval. Mean changes in BMI in P1 are at approximately the 55th centile for female and about the 35th centile for male participants. The inverse is found in P2 where females are at about the Fels 35th centile and males are at about the 70th centile. In P3, bracketing the lockdown period, female means rose to just over the 90th centile while male values rose to near the 80th centile. In P4, females shifted back to approximately the 45th centile while the males shifted to the 40th centile. These contrasts are consistent with the argument that environments experienced by participants in New Zealand were particularly obesogenic during P3, and perhaps to a lesser extent in P2 but only for males.

Neither hypothesis considered fully accounts for our results, though except for data from female participants during P2, outcomes are consistent with the "structured days" hypothesis. But interpretations of statistically significant period, period by sex, and period by body size interactions (Table 6) are limited here as no inquiries about participants' experiences were made. Neither did we directly assess their body composition, physical activity, sleep or diet. We speculate that greater mean changes in BMI among female participants (Table 5) and their stronger positive relationship between proxies of earlier body size and later BMI gains during P3 (Figure 1) arose because of sex-associated differences in maturity influencing their responses to shared changes in activities, diet and sleep. This is consistent with our participants' age range, their larger average body sizes (Table 3) and evidence of generally earlier female spurts in BMI (von Hippel et al. 2015).

A useful, if not well explained, finding of the present study is that the bidirectional hypothesis is not clearly supported despite early log-BMI and log-weight being significantly positively associated with BMI gains during P3. This is because we also found similar significant period by height or lower leg length interactions and BMI gains during P3 that are not anticipated by the bidirectional hypothesis. Greater height or lower leg length early on are not expected to predispose individuals to greater risks of gains in adiposity in less structured settings. These outcomes could be accounted for if height or lower leg length measured at the outset of P1 were highly correlated with log-BMI or log-weight, but they are not. As expected, log-BMI at the outset is highly correlated with log-weight among participants (females, $r = 0.92$; males, $r = 0.92$). Correlations between log-BMI and height or lower leg length were noticeably lower (females, $r = 0.49$ or 0.52; males, $r = 0.43$ or 0.50). Correlations between height, or lower leg length, and log-weight were intermediate (females, $r = 0.79$ or 0.78; males, $r = 0.75$ or 0.75).

Taken as a whole, these results hint that other not yet clearly identified factors may be important in influencing short-term BMI gains in at least some settings. Evidence of these factors are less likely to be identified if only ordinal categories of BMI or weight are used to distinguish adiposity-status. Evidence reported here may not be interpreted as refutation of the bidirectional hypothesis (Metcalf et al. 2011; Perez-Bey et al. 2020; Skrede et al. 2021; Tanaka et al., 2018), but should encourage additional research. Importantly, results from studies may differ given differences in distributions of circumstance, age range, body dimensions, body composition, and backgrounds that influence the likelihood of various outcomes.

During the review process, we were made aware of research that argues that reduced gains in height during the summer may be another factor in accounting for greater summer-time gains in BMI (Moreno et al. 2022). As already noted, we checked and did not find evidence of confounding during P3 from reduced height growth by taller participants at the outset. We also checked Pearson correlations within P1, P2 and P3 between per month changes in BMI relative to per month changes in weight or height for females and males separately. While correlations with weight change were consistently high (females, 0.90 to 0.96; males, 0.90 to 0.95), those with height change were weak (females, −0.12 to 0.16; males, −0.25 to −0.17).

Most research on seasonality and height growth suggests that the greatest height gains occur when exposure to daylight is greatest because it mediates vitamin D3 bioavailability (Schell et al. 2012; Bogin 2020). Consistent with this, Moreno et al. (2022) suggest that the phenomenon they describe may be related to participants' tendency to remain in-doors more frequently during the summer because of the hot, humid environment in Houston, Texas, where their study was carried out. Although speculative, it is plausible that we did not find similar evidence among our participants because summer temperatures in Dunedin during December and January are mild. Average high temperatures are 16^0 to 17^0 with average lows of 11^0 to 12^0 Celsius. Greater variability in within period correlations among female participants in our study is also consistent with research indicating that during adolescence inter-individual variation in growth velocities are likely to vary substantially so that seasonal effects related to duration of light exposure may not be detected (Bogin, 1978).

We do not offer an hypothesis but suggest that a tentative set of empirically supported relationships may offer clues for future investigations. First, biorhythm variation identified in deciduous teeth (the number of daily cross-striations between striae of Retzius) from a sub-sample of these Dunedin school children is associated with their weight gain over the full period of the study, but not in a linear manner (Mahoney et al. 2022). A portion of the variation in this expressed biorhythm might reflect physiology that is more sensitive to changing conditions of energy availability. Second, Pontzer et al. (2018) presented substantial evidence that overall distributions of energy expenditure assessed using stable oxygen isotopes do not differ among populations that vary dramatically in typical patterns of physical activity or levels of adiposity. They argue that the relationship between energy expenditure and activity is not linear. They also point to evidence that under typical conditions, both fat free mass and overall body mass are positively associated with energy expenditures in individuals assessed using these same techniques. Additionally, research suggests both within and among group variation in the percentage of lean body mass that is represented by a given BMI value (Rush et al. 2003; Weber et al. 2013). It might be that during conditions when physical activity for most children and adolescents decreases, those with larger bodies (and higher lean body mass) tend to be more affected by these changes because physical activities decline to a greater extent than energy intakes in these individuals. Alternatively, or perhaps in concert, rapid patterns of growth at an earlier age linked to larger body sizes at later ages (Stocks et al. 2011) may predispose larger juveniles and adolescents to greater gains in BMI during lockdown conditions. Finally, evidence suggests that differences in sleep patterns, not just amounts of sleep, are related to risks of BMI gains among children in developed (Moreno et al. 2021; Nixon et al. 2008; Olds et al. 2011; Weaver et al. 2019) and less-developed settings (Fatima et al. 2020). It would be worth exploring whether or how sleep duration or timing among children, measured over longer periods as suggested by Weaver et al. (2019) and known to vary seasonally (Nixon et al. 2008), influence changes in factors like physical activity or sedentary behaviors and diet known to contribute to gains in adiposity. Discerning consistent relationships from among the many complex settings that observational research is situated within will remain challenging.

5 | CONCLUSION

While lockdown measures are important public health measures in reducing the spread of diseases like SARS-CoV-2, one unintended consequence was increased risks of excess weight gain. This and other research may offer suggestions on how pandemic measures may help mitigate this potential long-term health issue. During the "lockdown", New Zealand families were asked to socially distance and remain in their "bubble", but outdoor exercise was permitted within these parameters. Should future "lockdowns" be necessary, health campaigns should emphasize the importance of regular physical activity, including greater promotion of outdoor family activities. Such efforts are particularly important given evidence that maintaining appropriate levels of activity is associated with better cardiovascular health (Perez-Bey et al. 2020; Metcalf et al. 2011). Secondly, given evidence in support of the "structured days" hypothesis, useful public health measures should increase parents' awareness of the need for their children to maintain regular schedules. This includes regular meals, avoidance of excess snacking, and consistent bedtimes.

AUTHOR CONTRIBUTIONS

B. Floyd, **H. Battles**, **C. Loch**, **G. McFarlane**, **D. Guatelli-Steinberg**, and **P. Mahoney** conceived of the study; **S. White** gathered the longitudinal data; **B. Floyd** led data analysis and writing; all authors participated in revision and final approval of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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