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Longitudinal Associations of Abdominal Fat Indices and Blood Pressure from Childhood to Adolescence: Findings from the Ellisras Longitudinal Study †

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† This is a part of Master Thesis of Thandiwe N. Mkhatshwa in University of Limpopo, Polokwane, South Africa.

Highlights

What are the main findings?

- Sex differences in cardiometabolic risk were evident from childhood, with girls showing consistently higher levels of abdominal obesity and elevated blood pressure.
- Childhood measurements of abdominal obesity and blood pressure were significantly associated across repeated assessments, highlighting persistence of risk characteristics during growth.

What is the implication of the main finding?

- Cardiometabolic risk surveillance should form part of routine child and adolescent health programmes in rural communities.
- Early identification of vulnerable children may strengthen strategies to reduce the future burden of obesity, hypertension, and cardiovascular disease.

Abstract

Background: The Ellisras Longitudinal Study (ELS) provides a unique opportunity to examine abdominal obesity and blood pressure patterns among rural South African children and adolescents. This study investigated associations between abdominal obesity indicators and blood pressure measurements obtained during autumn and corresponding spring assessments. Methods: A longitudinal analysis was conducted using repeated anthropometric and blood pressure measurements collected during autumn (May) and spring (November) surveys between 1999 and 2003 in the ELS. A total of 1974 children and adolescents aged 4–13 years were included at baseline. Generalized Estimating Equation (GEE) models were used to examine associations between autumn and corresponding spring measurements while adjusting for age and sex. Results: Girls consistently showed a higher prevalence of abdominal obesity and elevated blood pressure than boys, particularly among participants aged ≥12 years. The prevalence of obesity defined by waist circumference (WC) ranged from 8% to 26% among boys and 15% to 30% among girls, while obesity defined by waist-to-hip ratio (WHR) ranged from 13% to 24% among boys and 38% to 81% among girls. Significant associations between autumn and corresponding spring measurements were observed for selected anthropometric and blood pressure variables. In adjusted analyses, significant associations were identified for WC, waist-to-height ratio (WHtR), WHR, diastolic blood pressure (DBP), and systolic blood pressure (SBP) in 1999, while fewer significant associations were observed in subsequent survey years. Conclusions:

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Academic Editor: Joseph Mahgerefteh

Received: 6 October 2026
Revised: 10 November 2026
Accepted: 12 November 2026
Published: 21 November 2026

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Abdominal obesity and blood pressure outcomes varied according to age, sex, and survey period, with girls demonstrating a consistently higher burden of several cardiometabolic risk indicators. Significant associations between repeated measurements were observed for selected anthropometric and blood pressure variables, suggesting continuity in cardiometabolic characteristics across childhood and adolescence. These findings highlight the importance of early identification and monitoring of children at increased cardiometabolic risk and may inform obesity and cardiovascular disease prevention strategies in resource-constrained settings.

Keywords: abdominal obesity; blood pressure; children; adolescents; cardiometabolic risk; longitudinal study; Ellisras Longitudinal Study; South Africa

1. Introduction

Childhood obesity and elevated blood pressure have emerged as important early manifestations of the global non-communicable disease (NCD) epidemic, with evidence showing that cardiometabolic risk factors originate early in life and frequently extend into later stages of the life course [1,2]. Excess abdominal adiposity and elevated blood pressure during childhood are associated with adverse metabolic and cardiovascular outcomes in later life, including hypertension, type 2 diabetes, cardiovascular disease, and premature mortality [3–6]. Consequently, abdominal obesity indicators such as waist circumference (WC), waist-to-height ratio (WHtR), and waist-to-hip ratio (WHR) are increasingly recognised as practical measures for identifying early cardiometabolic risk among children and adolescents [7–9]. Abdominal adiposity and blood pressure are closely interconnected through shared physiological mechanisms, including insulin resistance, sympathetic nervous system activation, vascular dysfunction, chronic low-grade inflammation, and altered metabolic regulation [10]. Longitudinal studies have further demonstrated that higher levels of adiposity and blood pressure during childhood are associated with less favourable cardiometabolic profiles later in life, highlighting the value of early identification, monitoring, and prevention strategies during critical developmental periods [3,6,11].

Evidence from both high-income countries (HICs) and low- and middle-income countries (LMICs) suggests that obesity- and blood pressure-related measures may vary across different periods of the year, potentially reflecting changes in dietary intake, physical activity, environmental temperature, and energy expenditure [12–16]. Studies conducted among children and adolescents have reported temporal variation in adiposity and blood pressure measurements, with higher levels often observed during colder months [12–14]. However, evidence from sub-Saharan Africa (SSA) remains limited, as most studies have focused on the prevalence and determinants of obesity and elevated blood pressure at single points in time rather than evaluating patterns across repeated assessments [17,18]. As a result, there is limited understanding of how abdominal adiposity and blood pressure measurements relate to one another across repeated assessments in African child and adolescent populations.

Recent findings from the Ellisras Longitudinal Study (ELS) reported differences in blood pressure and visceral adiposity indicators across autumn and spring assessments among rural South African children and adolescents [19]. However, that study focused primarily on describing differences observed across survey periods and did not investigate whether measurements obtained during one assessment were associated with corresponding measurements obtained during subsequent assessments over time. Consequently, there is limited evidence on the extent to which abdominal adiposity and blood pressure measurements recorded during childhood and adolescence remain associated across re-

peated assessments in rural African populations. This knowledge gap is important because understanding patterns observed across successive assessments may contribute to the identification and monitoring of children at increased cardiometabolic risk during critical stages of growth and development.

The ELS, one of the longest-running child and adolescent cohorts in rural Africa, provides a valuable opportunity to investigate cardiometabolic patterns across repeated assessments during childhood and adolescence [20–22]. Rural South African populations continue to experience nutritional and epidemiological transitions characterised by the coexistence of undernutrition, overweight, obesity, and other cardiometabolic risk factors [23–25]. Understanding whether abdominal obesity and blood pressure measurements obtained during one assessment are associated with corresponding measurements recorded during subsequent assessments may provide insight into cardiometabolic patterns during critical periods of growth and development. The primary research question was whether abdominal obesity indicators (WC, WHtR, and WHR) and blood pressure measurements obtained during autumn were associated with corresponding measurements obtained during spring assessments among rural South African children and adolescents participating in the ELS. Therefore, this study used longitudinal data from the ELS collected between 1999 and 2003 to examine associations between abdominal obesity indicators (WC, WHtR, and WHR) and blood pressure measurements obtained during autumn and corresponding measurements obtained during spring surveys among rural South African children and adolescents. Improved understanding of these relationships may inform early identification, monitoring, and prevention of cardiometabolic risk among children in resource-constrained settings.

2. Materials and Methods

2.1. Study Design and Conceptual Framework

This study employed a longitudinal cohort design using repeated anthropometric and blood pressure measurements collected from children and adolescents participating in the Ellisras Longitudinal Study (ELS). The analysis examined associations between abdominal obesity indicators and blood pressure measurements obtained during autumn surveys and corresponding measurements obtained during subsequent spring surveys between 1999 and 2003. The study was informed by a life-course epidemiology framework, which recognises that cardiometabolic risk factors established during childhood may persist into adolescence and adulthood and contribute to future cardiovascular disease risks [2,4]. Within this framework, abdominal obesity and elevated blood pressure are considered early indicators of cardiometabolic risk that may remain associated over time. Accordingly, this study investigated whether measurements of waist circumference (WC), waist-to-height ratio (WHtR), waist-to-hip ratio (WHR), systolic blood pressure (SBP), and diastolic blood pressure (DBP) obtained during autumn were associated with corresponding measurements obtained during subsequent spring assessments. The study was reported according to the STROBE guidelines for observational studies [26].

Figure 1 presents the conceptual framework underpinning the study. The framework illustrates the analytical approach used to examine associations between autumn and corresponding spring measurements of abdominal obesity indicators and blood pressure among participants in the ELS. Abdominal obesity indicators, including WC, WHtR, and WHR, together with SBP and DBP, were measured during autumn and corresponding spring survey waves. Associations between repeated measurements were subsequently assessed using GEE models adjusted for age and sex.

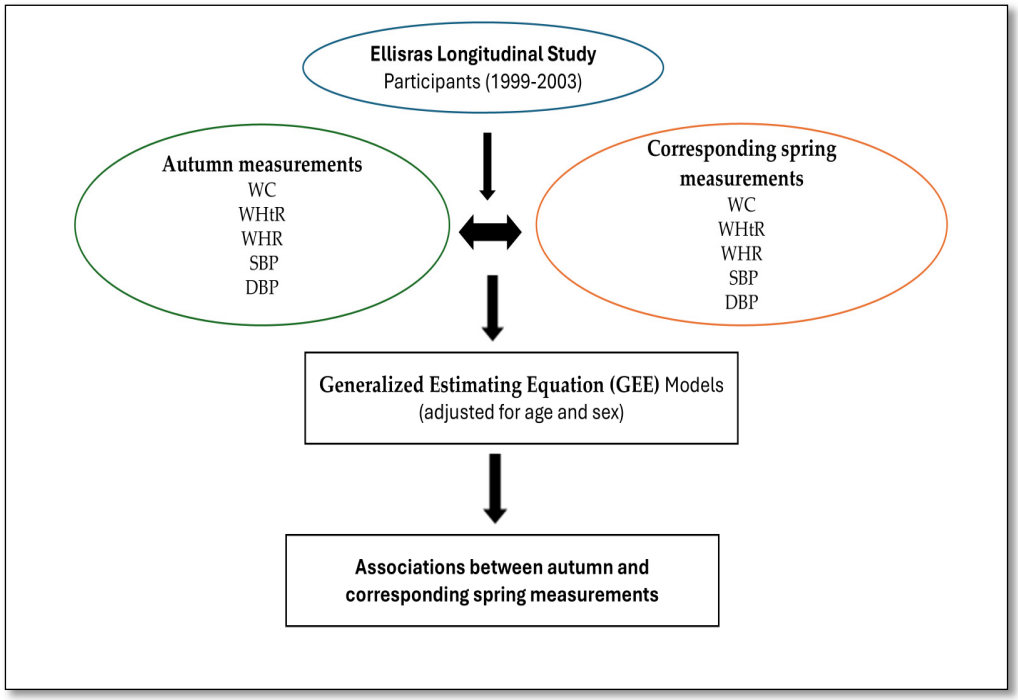


Figure 1. Conceptual framework illustrating associations between autumn and corresponding spring measurements of abdominal obesity indicators and blood pressure among participants in the Ellisras Longitudinal Study (1999–2003). Abbreviations: WC, waist circumference; WHtR, waist-to-height ratio; WHR, waist-to-hip ratio; SBP, systolic blood pressure; DBP, diastolic blood pressure; GEE, Generalized Estimating Equation.

2.2. Study Setting and Population

This study utilised data from the Ellisras Longitudinal Study (ELS), a prospective cohort established in 1996 to investigate growth, nutritional status, physical activity, cardiovascular health, and emerging non-communicable disease (NCD) risk factors among children and adolescents residing in rural South Africa [20–22,27]. The study was conducted in the Lephalale Local Municipality (formerly Ellisras) in Limpopo Province, South Africa. The area is predominantly rural and characterised by dispersed settlements, subsistence farming, livestock rearing, and limited socioeconomic opportunities. Many households experience poverty, food insecurity, and restricted access to health and social services, making the area relevant for investigating nutrition-related and cardiovascular health outcomes among children and adolescents [20,22]. The present analysis utilised data collected during the autumn (May) and spring (November) survey waves conducted between 1999 and 2003. A total of 1974 participants (1033 boys and 941 girls) aged 4–13 years were assessed during autumn 1999 and followed prospectively through successive survey waves. By spring 2003, 1701 participants (873 boys and 828 girls) aged 9–18 years remained under follow-up, representing an attrition rate of 13.8%. Repeated anthropometric and blood pressure measurements collected from the same participants during the autumn and spring survey waves were used in the present analyses to examine longitudinal associations between abdominal obesity indicators and blood pressure across childhood and adolescence.

2.3. Sample Size, Sampling, and Participant Eligibility

The ELS initially recruited approximately 2200 children aged 3–10 years from rural schools and villages in the Ellisras area using a cluster random sampling strategy designed to obtain a representative sample of children residing in the study communities [22,27]. Participants were subsequently followed through repeated survey waves to investigate

growth, nutritional status, cardiovascular health, and emerging NCD risk factors during childhood and adolescence. The present study utilised data collected during the autumn (May) and spring (November) survey waves conducted between 1999 and 2003. Participants were eligible for inclusion if they had available anthropometric and/or blood pressure measurements recorded during at least one of the selected survey waves. The baseline analytical sample comprised 1974 participants (1033 boys and 941 girls) assessed during autumn 1999. By spring 2003, 1701 participants (873 boys and 828 girls) remained under follow-up, representing an attrition rate of 13.8%. Participants with missing data for a specific anthropometric or blood pressure variable were excluded only from analyses involving that variable. Consequently, sample sizes varied slightly across outcome-specific analyses. An available-case approach was adopted, allowing all available observations to contribute to the analyses while maximising the use of longitudinal data.

2.4. Data Collection Procedures

Data were collected during the autumn (May) and spring (November) survey waves conducted between 1999 and 2003 as part of the ELS. Anthropometric and blood pressure measurements were obtained at participating schools by trained field workers using standardised protocols. Regular training, supervision, and quality-control procedures were implemented throughout the study period to ensure measurement consistency across survey waves.

- Anthropometric measurements

Anthropometric measurements were obtained according to the standardised procedures. Height was measured to the nearest 0.1 cm using a calibrated stadiometer (Leicester Height Measure; Seca Ltd., Birmingham, UK), with participants standing barefoot in an upright position and positioned in the Frankfurt plane [28]. WC was measured midway between the lowest rib margin and the iliac crest following normal expiration, while hip circumference was measured at the point of maximum posterior protrusion of the buttocks [28], using a non-stretchable anthropometric tape measure (Lufkin Executive Thinline, Apex Tool Group, Sparks, MD, USA), recorded to the nearest 0.1 cm. Abdominal obesity was assessed using three anthropometric indicators: WC, WHtR, and WHR. WHtR was calculated as WC divided by height, and WHR was calculated as WC divided by hip circumference. Abdominal obesity was defined as WC $\geq$ 90th percentile for age and sex, WHtR $\geq$ 0.50 for both boys and girls, and WHR $\geq$ 0.90 for boys and $\geq$0.80 for girls, based on criteria commonly applied in epidemiological studies investigating cardiometabolic risk [29–31]. The WHR cut-offs were retained to facilitate comparison with previous ELS studies and related literature.

- Blood pressure

Blood pressure (BP) was measured according to standardized blood pressure assessment procedures and the recommendations of the National High Blood Pressure Education Program (NHBPEP) Working Group on High Blood Pressure in Children and Adolescent [32,33]. Participants were seated quietly for at least five minutes before measurement, and appropriately sized cuffs were selected according to arm circumference. Three BP measurements were obtained using a validated electronic monitoring device (Micronta, Tandy Corporation, Fort Worth, TX, USA), and the average of the three readings was used for analysis. Blood pressure classification was based on the NHBPEP pediatric reference standards applicable during the period in which the data were collected. Elevated systolic blood pressure (SBP) or diastolic blood pressure (DBP) was defined as BP $\geq$ 90th percentile but <95th percentile for age, sex, and height, while hypertension was defined as SBP and/or DBP $\geq$ 95th percentile for age, sex, and height [32]. These reference standards were selected

to ensure consistency with the period of data collection and comparability with previous ELS publications.

2.5. Quality Assurance

The reliability and validity of anthropometric and blood pressure measurements within the ELS have been reported previously [21,31]. Standardisation sessions were conducted before each survey wave to ensure consistency among field workers and adherence to established measurement protocols. All anthropometric and blood pressure measurements were obtained by trained personnel using calibrated equipment and standardised operating procedures.

Inter- and intra-observer technical errors of measurement (TEM) were routinely assessed as part of the ELS quality-control programme. Technical error ranged from 0.0 to 3.4 cm (0–4%) for waist and hip circumferences and from 0.22 to 0.43 cm (0.12–0.32%) for height measurements, indicating acceptable reliability for field-based anthropometric assessments. In addition, a pilot validation assessment conducted prior to data collection demonstrated strong agreement ($r = 0.93$) between blood pressure measurements obtained using the automated Micronta monitoring device and those obtained using a standard mercury sphygmomanometer. Regular training and retraining of fieldworkers, calibration of equipment, and ongoing monitoring of measurement quality were undertaken throughout the study period to minimise measurement error and ensure consistency across survey waves.

2.6. Statistical Analysis

Data were entered into Microsoft Excel, screened for completeness and consistency, and subsequently analysed using IBM Statistical Package for the Social Sciences (SPSS) version 28 and Stata version 17 (StataCorp LLC, College Station, TX, USA). Continuous variables are presented as mean (standard deviation [SD]), while categorical variables are presented as frequencies and percentages. Participants were categorised into three age groups (4–7 years, 8–11 years, and ≥12 years) to reflect important developmental stages associated with growth, adiposity, and blood pressure changes during childhood and adolescence. Sex- and survey-wave differences in anthropometric and blood pressure measurements were assessed using independent-samples *t*-tests. These analyses were performed for descriptive comparisons only, whereas longitudinal associations between repeated measurements obtained from the same participants were examined using GEE models that account for within-participant correlation over time. The prevalence of abdominal obesity, elevated blood pressure, and hypertension was calculated using frequency analyses and expressed as percentages. Abdominal obesity was defined using three indicators: WC ≥ 90th percentile for age and sex, WHtR ≥ 0.50, and WHR ≥ 0.90 for boys and ≥0.80 for girls. Elevated blood pressure was defined as SBP and/or DBP ≥ 90th percentile but <95th percentile for age, sex, and height, whereas hypertension was defined as SBP and/or DBP ≥ 95th percentile for age, sex, and height.

To examine associations between measurements obtained during autumn and corresponding measurements obtained during subsequent spring assessments, GEE models were fitted. GEE was selected because it provides population-averaged estimates while accounting for the correlation arising from repeated measurements obtained from the same participants over time. Separate models were fitted for continuous anthropometric and blood pressure variables (WC, WHtR, WHR, SBP, and DBP) as well as for obesity and blood pressure outcome variables. For each model, the autumn measurement served as the independent variable and the corresponding spring measurement served as the dependent variable. All models were adjusted for age and sex because these factors are established

determinants of adiposity and blood pressure during growth and maturation. GEE models were estimated using a Gaussian distribution with an identity link function and an unstructured working correlation matrix to account for within-participant correlation across repeated measurements. Participants were identified using a unique study identification number, and autumn and spring observations were paired within participants across survey years using the observation date variable. The analyses were implemented in Stata using the xtgee procedure, specifying family (gaussian), link (identity), and corr (unstructured). Robust standard errors were used for statistical inference. Results are presented as regression coefficients (β), 95% confidence intervals (CI), and *p*-values. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Participant Characteristics

Table 1 presents the characteristics of participants included in the ELS between autumn 1999 and spring 2003. At baseline, 1974 children and adolescents (1033 boys and 941 girls) participated in the autumn 1999 survey. The number of participants gradually declined during follow-up, with 1701 participants (873 boys and 828 girls) remaining in spring 2003, representing an overall attrition rate of 13.8%. The age composition of the cohort changed progressively over time, reflecting the longitudinal follow-up of participants. Children aged 8–11 years constituted the largest age group at baseline (68.0%), whereas participants aged ≥2 years increased from 17.2% in autumn 1999 to 86.4% in spring 2003. Conversely, the proportion of children aged 4–7 years declined from 14.8% at baseline to no participants remaining in this age category by 2003. The sex distribution remained relatively stable across survey waves, with boys accounting for approximately 52% of participants throughout follow-up. The age range of participants increased from 4–13 years at baseline to 9–18 years by spring 2003, consistent with the maturation of the cohort over time.

Table 1. Descriptive characteristics of ELS participants by age group, sex, and survey wave (1999–2003).

Characteristic	Autumn 1999	Spring 1999	Autumn 2000	Spring 2000	Autumn 2001	Spring 2001	Autumn 2003	Spring 2003
Total participants, *n*	1974	1891	1924	1813	1877	1764	1820	1701
Boys, *n*	1033	983	1006	936	962	912	942	873
Girls, *n*	941	908	918	877	915	852	878	828
Age range (years)	4–13	5–13	5–14	6–15	6–15	7–16	8–17	9–18
Participants aged 4–7 years, *n* (%)	292 (14.8)	201 (10.6)	137 (7.1)	83 (4.6)	39 (2.1)	16 (0.9)	0 (0.0)	0 (0.0)
Participants aged 8–11 years, *n* (%)	1343 (68.0)	1187 (62.8)	1053 (54.7)	895 (49.4)	755 (40.2)	595 (33.7)	332 (18.2)	232 (13.6)
Participants aged ≥12 years, *n* (%)	339 (17.2)	503 (26.6)	734 (38.1)	835 (46.0)	1072 (57.1)	1153 (65.4)	1488 (81.8)	1469 (86.4)
Attrition from baseline (%)	0.0	4.2	2.5	8.2	4.9	10.6	7.8	13.8

3.2. Anthropometric and Blood Pressure Characteristics

Table 2 presents the anthropometric and blood pressure measurements as mean (standard deviation [SD]) according to age group, sex, and survey wave among ELS participants between autumn 1999 and spring 2003. Anthropometric and blood pressure measurements generally increased with age in both boys and girls across the study period. Participants aged ≥12 years consistently recorded higher mean WC, SBP, and DBP values than those

in the younger age groups. Mean WC was generally higher among girls than boys in the ≥12-year age group, whereas WHR tended to be higher among boys than girls. WHtR showed relatively little variation across survey waves, age groups, and sexes. Several statistically significant sex differences were observed for WC, WHR, DBP, and SBP during selected survey waves ($p \leq 0.05$; $p \leq 0.001$), indicating age- and sex-related variation in anthropometric and blood pressure characteristics across the study period.

3.3. Prevalence of Abdominal Obesity and Blood Pressure Outcomes

Table 3 presents the prevalence of abdominal obesity, elevated blood pressure, and hypertension as *n* (%) according to age group, sex, and survey wave among ELS participants between autumn 1999 and spring 2003. The prevalence of obesity defined by WC and WHR was generally higher among girls than boys, particularly among participants aged ≥12 years. In contrast, obesity defined by WHtR was relatively uncommon across survey waves and showed limited variation according to age group and sex. The prevalence of high DBP, high SBP, and hypertension was generally lower than that observed for abdominal obesity indicators, although higher prevalence estimates were frequently observed among girls during selected survey waves. Several statistically significant sex differences were identified across obesity and blood pressure outcomes ($p \leq 0.05$; $p \leq 0.001$), indicating variation according to age group, sex, and survey period within the study population.

3.4. Longitudinal Associations Between Autumn and Corresponding Spring Measurements

Table 4 presents the associations between autumn and corresponding spring anthropometric and blood pressure measurements as regression coefficients (β), *p*-values, and 95% confidence intervals (CIs) derived from GEE models before and after adjustment for age and sex. In the adjusted analyses, significant associations were observed for WC, WHtR, WHR, DBP, and SBP in 1999. WHtR was positively associated with the corresponding spring measurement (β = 0.618; 95% CI: 0.554–0.681; $p < 0.001$), while significant associations were also observed for WC (β = 0.008; 95% CI: 0.003–0.012; $p = 0.001$), DBP (β = 0.007; 95% CI: 0.000–0.012; $p = 0.028$), and SBP (β = 0.007; 95% CI: 0.002–0.012; $p = 0.009$). A statistically significant association was also observed for WHR in 1999 ($p = 0.001$). Fewer significant associations were observed from 2000 onwards. In 2000, only WC remained significantly associated with the corresponding spring measurement after adjustment for age and sex (β = 0.009; 95% CI: 0.004–0.014; $p = 0.001$), whereas no significant associations were observed for WHtR, DBP, or SBP. In 2001, only SBP demonstrated a significant association between autumn and corresponding spring measurements after adjustment (β = 0.006; 95% CI: 0.001–0.010; $p = 0.020$). By 2003, significant associations were observed for WC (β = 0.075; 95% CI: 0.056–0.094; $p < 0.001$) and SBP (β = 0.009; 95% CI: 0.003–0.016; $p = 0.003$), whereas DBP was not significantly associated with the corresponding spring measurement. Overall, significant associations between autumn and corresponding spring measurements were observed for selected anthropometric and blood pressure variables; however, the pattern of associations varied across survey years. WC demonstrated significant associations in 1999, 2000, and 2003, whereas SBP remained significantly associated in 1999, 2001, and 2003. WHtR, WHR, and DBP showed significant associations only in 1999 after adjustment for age and sex.

Table 2. Mean (SD) anthropometric and blood pressure measurements among ELS participants by age group, sex, and survey wave (1999–2003).

Variable	Age Group	Autumn 1999 Boys	Autumn 1999 Girls	Spring 1999 Boys	Spring 1999 Girls	Autumn 2000 Boys	Autumn 2000 Girls	Spring 2000 Boys	Spring 2000 Girls	Autumn 2001 Boys	Autumn 2001 Girls	Spring 2001 Boys	Spring 2001 Girls	Autumn 2003 Boys	Autumn 2003 Girls	Spring 2003 Boys	Spring 2003 Girls
WC (cm)	4–7 y	51.23 (3.23)	51.13 (3.28)	51.20 (2.89)	51.06 (3.71)	52.23 (3.06)	50.81 (2.67)	51.51 (2.56)	50.80 (3.33)	56.61 (4.31)	57.73 (4.88)	53.30 (3.78)	51.82 (4.14)	–	–	–	–
	8–11 y	55.42 (3.46)	55.61 (4.07)	55.09 (3.29)	54.91 (3.86)	55.69 (3.16) *	55.00 (3.89) *	55.38 (3.28) *	54.87 (3.85) *	57.36 (4.69)	58.53 (4.53)	55.26 (3.16) *	54.07 (3.78) *	55.47 (3.01) *	55.34 (3.73) *	54.06 (2.90) *	53.51 (3.72) *
	≥12 y	57.74 (4.33)	58.56 (4.38)	57.63 (3.53) **	58.77 (4.77) **	58.71 (3.42) **	58.77 (4.41) **	58.71 (3.54) **	59.05 (4.47) **	57.84 (4.75)	58.32 (4.45)	59.20 (4.09) **	59.05 (4.86) **	59.99 (3.93) **	55.34 (3.72) **	59.41 (4.49) **	60.02 (5.40) **
WHtR	4–7 y	0.44 (0.03)	0.44 (0.02)	0.43 (0.02)	0.43 (0.38)	0.43 (0.02)	0.43 (0.02)	0.42 (0.02)	0.42 (0.02)	0.46 (0.04)	0.48 (0.04)	0.41 (0.03)	0.44 (0.04)	–	–	–	–
	8–11 y	0.41 (0.02)	0.41 (0.02)	0.41 (0.02)	0.41 (0.02)	0.41 (0.02)	0.40 (0.02)	0.42 (0.02)	0.40 (0.02)	0.43 (0.04)	0.43 (0.04)	0.41 (0.02)	0.40 (0.02)	0.41 (0.02) *	0.40 (0.03) *	0.39 (0.02)	0.39 (0.02)
	≥12 y	0.40 (0.03)	0.41 (0.03)	0.40 (0.02)	0.40 (0.03)	0.40 (0.02)	0.40 (0.03)	0.40 (0.02)	0.40 (0.03)	0.39 (0.04)	0.39 (0.03)	0.39 (0.03)	0.39 (0.03)	0.39 (0.02)	0.39 (0.03)	0.38 (0.02) **	0.39 (0.02) **
WHR	4–7 y	0.93 (0.05)	0.91 (0.04)	0.92 (0.05)	0.89 (0.05)	0.93 (0.06)	0.90 (0.04)	0.92 (0.05)	0.89 (0.05)	0.86 (0.49)	0.85 (0.07)	0.87 (0.07)	0.92 (0.08)	–	–	–	–
	8–11 y	0.90 (0.04) *	0.87 (0.05) *	0.88 (0.05)	0.85 (0.05)	0.89 (0.05) *	0.85 (0.05) *	0.89 (0.04) *	0.85 (0.05) *	0.86 (0.05)	0.84 (0.05)	0.89 (0.05)	0.85 (0.05)	0.88 (0.05)	0.84 (0.05)	0.90 (0.05)	0.84 (0.06)
	≥12 y	0.87 (0.03) *	0.85 (0.04) *	0.86 (0.04) *	0.82 (0.05) *	0.87 (0.04) *	0.81 (0.05) *	0.86 (0.04) **	0.81 (0.06) **	0.86 (0.06)	0.85 (0.06)	0.86 (0.05)	0.81 (0.05)	0.85 (0.06) **	0.80 (0.07) **	0.86 (0.05) **	0.79 (0.05) **
DBP (mmHg)	4–7 y	57.50 (7.87)	60.02 (7.26)	61.12 (10.85)	62.95 (10.54)	65.15 (9.56)	66.09 (9.32)	62.66 (10.85)	62.94 (10.52)	63.10 (7.22)	67.47 (12.26)	65.91 (6.74) *	70.80 (20.49) *	–	–	–	–
	8–11 y	60.33 (7.90)	61.39 (7.62)	61.76 (9.29)	61.74 (9.24)	66.33 (8.67)	66.15 (8.80)	65.65 (9.15)	66.69 (8.77)	63.48 (7.84)	64.48 (7.75)	63.52 (7.74)	64.52 (7.74)	65.14 (8.37)	66.13 (7.02)	58.62 (10.48)	58.32 (8.10)
	≥12 y	61.36 (7.71)	63.22 (7.78)	62.44 (9.03)	63.64 (9.40)	65.93 (8.49)	67.44 (9.15)	67.21 (9.42)	68.06 (8.84)	63.32 (7.72)	63.98 (7.99)	62.52 (7.74)	63.71 (7.57)	67.51 (7.64)	69.11 (7.59)	60.66 (9.27)	63.27 (9.48)
SBP (mmHg)	4–7 y	91.73 (10.85)	94.40 (10.28)	96.52 (11.45) *	97.74 (13.50) *	96.49 (9.41)	97.53 (10.17)	93.40 (10.15)	94.53 (12.53)	97.44 (10.60)	102.00 (17.45)	100.14 (9.42) *	110.70 (27.22) *	–	–	–	–
	8–11 y	96.88 (10.35)	98.58 (10.52)	99.62 (11.48)	99.77 (11.42)	99.99 (10.98)	99.60 (10.92)	97.63 (10.73)	100.02 (10.73)	95.55 (9.79)	98.17 (11.15)	95.04 (9.22)	98.38 (11.14)	101.17 (11.44)	102.74 (10.96)	94.45 (13.52)	93.11 (11.31)
	≥12 y	99.05 (9.18) *	102.27 (11.34) *	102.27 (10.35)	104.32 (11.27)	101.59 (11.32)	103.42 (11.38)										

Abbreviations: WC, waist circumference; WHtR, waist-to-height ratio; WHR, waist-to-hip ratio; DBP, diastolic blood pressure; SBP, systolic blood pressure; SD, standard deviation; y, years. Values are presented as mean (SD). * $p \leq 0.05$; ** $p \leq 0.001$.

Table 3. Prevalence of obesity and blood pressure among ELS population aged 4–18 years.

Outcome	Age Group	Autumn 1999 Boys *n* (%)	Autumn 1999 Girls *n* (%)	Spring 1999 Boys *n* (%)	Spring 1999 Girls *n* (%)	Autumn 2000 Boys *n* (%)	Autumn 2000 Girls *n* (%)	Spring 2000 Boys *n* (%)	Spring 2000 Girls *n* (%)	Autumn 2001 Boys *n* (%)	Autumn 2001 Girls *n* (%)	Spring 2001 Boys *n* (%)	Spring 2001 Girls *n* (%)	Autumn 2003 Boys *n* (%)	Autumn 2003 Girls *n* (%)	Spring 2003 Boys *n* (%)	Spring 2003 Girls *n* (%)
Obesity by WC	4–7 y	1 (1)	0 (0)	0 (0) *	1 (1) *	0 (0)	0 (0)	0 (0)	0 (0)	2 (8) *	1 (7) *	0 (0)	0 (0)	–	–	–	–
	8–11 y	14 (2) **	28 (4) **	8 (1) *	13 (2) *	14 (3)	14 (3)	9 (2) *	15 (3) *	34 (9) **	62 (17) **	4 (1)	6 (2)	2 (1) *	4 (3) *	0 (0) *	2 (2) *
	≥12 y	17 (9)	25 (16)	22 (8) **	39 (17) **	36 (9) **	54 (16) **	42 (10) **	66 (17) **	72 (13) *	78 (15) *	89 (15) *	105 (19) *	197 (26) **	220 (30) **	142 (19) **	193 (27) **
Obesity by WHtR	4–7 y	5 (3)	2 (2)	1 (0)	2 (2)	1 (1)	0 (0)	0 (0)	0 (0)	5 (21)	6 (40)	0 (0) *	1 (20) *	–	–	–	–
	8–11 y	3 (0) *	6 (1) *	1 (0)	2 (0)	0 (0)	1 (0)	1 (0)	1 (0)	14 (4) **	27 (7) **	0 (0) *	1 (0) *	0 (0)	0 (0)	0 (0)	0 (0)
	≥12 y	1 (0) *	0 (0) *	0 (0) **	3 (1) **	0 (0)	0 (0)	1 (0)	2 (1)	7 (1) *	2 (0) *	3 (1)	2 (0)	0 (0)	0 (0)	3 (0)	4 (1)
Obesity by WHR	4–7 y	129 (79) **	128 (99) **	63 (59) **	95 (100) **	56 (70) **	57 (100) **	30 (64) **	36 (100) **	5 (21)	12 (80)	4 (36)	4 (80)	–	–	–	–
	8–11 y	283 (41) *	630 (96) *	176 (29) *	486 (84) *	226 (42) **	425 (82) **	172 (38) **	266 (83) **	89 (23)	297 (80)	110 (35) **	249 (89) **	78 (44) **	114 (74) **	62 (51) **	83 (76) **
	≥12 y	45 (24) *	123 (81) *	35 (13) **	160 (68) **	88 (23) **	209 (61) **	74 (17) **	216 (54) **	129 (22)	411 (80)	92 (16) **	310 (55) **	127 (17) **	361 (50) **	123 (16) **	275 (38) **
High DBP	4–7 y	3 (1.8)	1 (1)	12 (11)	14 (15)	7 (9)	5 (9)	5 (11)	5 (14)	0 (0) *	1 (7) *	0 (0) *	1 (20) *	–	–	–	–
	8–11 y	6 (1) *	11 (2) *	21 (3)	23 (4)	36 (7)	37 (7)	36 (8)	37 (8)	13 (3)	15 (4)	10 (3)	12 (4)	5 (3)	5 (3)	4 (3) **	0 (0) **
	≥12 y	2 (1)	2 (1)	9 (3)	11 (5)	17 (4) **	27 (8) **	31 (7)	28 (7)	6 (1)	9 (2)	2 (0) **	8 (1) **	20 (3)	21 (3)	15 (2) *	21 (3) *
High SBP	4–7 y	5 (3) *	7 (5) *	7 (7) **	14 (15) **	2 (3)	2 (4)	1 (2)	2 (6)	0 (0) *	3 (20) *	0 (0) *	2 (40) *	–	–	–	–
	8–11 y	13 (2) *	19 (3) *	18 (3) **	32 (6) **	17 (3)	20 (4)	14 (3)	15 (3)	3 (1) **	14 (4) **	1 (0) **	11 (4) **	5 (3)	7 (5)	1 (1)	2 (2)
	≥12 y	1 (1) *	3 (2) *	7 (3)	4 (2)	9 (2)	9 (3)	5 (1) **	16 (4) **	4 (1) *	7 (1) *	1 (0) *	3 (1) *	8 (1) **	19 (3) **	13 (2) *	20 (3) *
Hyperten-sion	4–7 y	0 (0) *	1 (1) *	5 (5) **	12 (13) **	0 (0) *	1 (2) *	1 (2)	2 (6)	0 (0) *	1 (7) *	0 (0) *	1 (20) *	–	–	–	–
	8–11 y	0 (0) **	3 (1) **	11 (2) *	16 (3) *	7 (1)	10 (2)	10 (2)	9 (2)	3 (1) *	6 (2) *	1 (0) **	5 (2) **	1 (1)	1 (1)	0 (0)	0 (0)
	≥12 y	0 (0)	0 (0)	5 (2)	3 (1)	4 (1)	4 (1)	4 (1)	3 (1)	2 (0) *	5 (1) *	0 (0) *	2 (0) *	3 (0) *	7 (1) *	3 (0)	4 (1)

Abbreviations: WC, waist circumference; WHtR, waist-to-height ratio; WHR, waist-to-hip ratio; DBP, diastolic blood pressure; SBP, systolic blood pressure; SD, standard deviation; *n*, frequency; y, year. Values are presented as mean (SD). * $p \leq 0.05$; ** $p \leq 0.001$.

Table 4. GEE analysis of associations between autumn and corresponding spring measurements of abdominal obesity and blood pressure indicators among the ELS population.

Year	Variables	Unadjusted			Adjusted for Age and Gender		
		β	*p*	95% CI	β	*p*	95% CI
1999	WC	0.006	0.000 *	0.003–0.016	0.008	0.001 *	0.003–0.012
	WHtR	0.619	0.000 *	0.556–0.683	0.618	0.000 *	0.554–0.681
	WHR	1.000	0.000 *	1.000–1.000	0.000	0.001 *	0.000–0.000
	DBP	0.001	0.267	−0.001–0.003	0.007	0.028 *	0.000–0.012
	SBP	0.003	0.055	0.000–0.007	0.007	0.009 *	0.002–0.012
2000	WC	0.010	0.000 *	0.005–0.014	0.009	0.001 *	0.004–0.014
	WHtR	−0.001	0.936	−0.267–0.246	−0.002	0.884	−0.028–0.024
	WHR	-	-	-	0.000	1.000	0.000–0.000
	DBP	0.000	0.975	−0.004–0.004	0.000	0.952	−0.004–0.004
	SBP	0.000	0.747	−0.002–0.002	0.000	0.666	−0.002–0.003
2001	WC	0.000	0.873	−0.004–0.005	0.002	0.535	−0.004–0.008
	WHtR	0.011	0.499	−0.021–0.042	0.011	0.499	−0.207–0.042
	WHR	-	-	-	0.000	0.000	0.000–0.000
	DBP	0.002	0.131	−0.001–0.005	0.003	0.136	−0.001–0.006
	SBP	0.005	0.027 *	0.000–0.009	0.006	0.020 *	0.001–0.010
2003	WC	0.006	0.006 *	0.002–0.011	0.075	0.000 *	0.056–0.094
	WHtR	-	-	-	-	-	-
	WHR	-	-	-	0.000	1.000	0.000–0.000
	DBP	0.002	0.292	−0.001–0.005	0.002	0.291	−0.001–0.005
	SBP	0.010	0.002 *	0.004–0.016	0.009	0.003 *	0.003–0.016

Abbreviations: WC, waist circumference; WHtR, waist-to-height ratio; WHR, waist-to-hip ratio; DBP, diastolic blood pressure; SBP, systolic blood pressure; CI, confidence interval; GEE, Generalized Estimating Equation. Values are presented as regression coefficients (β), *p*-values, and 95% confidence intervals (CIs). Adjusted models were controlled for age and sex. GEE models were fitted using a Gaussian distribution, identity link function, and unstructured working correlation matrix. Autumn and spring measurements were paired within participants across survey years. '–' indicates collinearity. * $p \leq 0.05$.

3.5. Associations Between Autumn and Corresponding Spring Obesity and Blood Pressure Outcomes

Table 5 presents the associations between obesity and blood pressure outcomes measured during autumn and corresponding spring assessments as regression coefficients (β), *p*-values, and 95% confidence intervals (CIs) derived from GEE models before and after adjustment for age and sex. In the adjusted analyses, statistically significant associations were observed for obesity defined by WC, obesity defined by WHtR, obesity defined by WHR, high DBP, and high SBP in 1999. Obesity defined by WHtR was positively associated with the corresponding spring outcome (β = 0.618; 95% CI: 0.554–0.681; $p < 0.001$), while significant associations were also observed for obesity defined by WC (β = 0.007; 95% CI: 0.002–0.011; $p = 0.002$), obesity defined by WHR (β = −0.003; 95% CI: −0.004 to −0.002; $p < 0.001$), high DBP (β = 0.006; 95% CI: 0.001–0.011; $p = 0.020$), and high SBP (β = 0.007; 95% CI: 0.000–0.014; $p \leq 0.05$). From 2000 onwards, fewer statistically significant associations were identified. In 2000, only obesity defined by WC remained significantly associated

with the corresponding spring outcome after adjustment for age and sex (β = 0.012; 95% CI: 0.006–0.020; $p < 0.001$). In 2001, significant associations were observed for high DBP (β = 0.008; 95% CI: 0.002–0.013; $p = 0.008$) and hypertension (β = 0.013; 95% CI: 0.003–0.023; $p = 0.008$), whereas no significant associations were observed for obesity indicators or high SBP. By 2003, high SBP remained significantly associated with the corresponding spring outcome after adjustment (β = 0.033; 95% CI: 0.014–0.054; $p = 0.001$), while no significant associations were observed for obesity defined by WC, obesity defined by WHR, high DBP, or hypertension. The distribution of significant associations differed across survey years. Obesity defined by WC was significantly associated with corresponding spring outcomes in 1999 and 2000, high DBP and hypertension in 2001, and high SBP in 1999 and 2003 after adjustment for age and sex.

Table 5. GEE analysis of associations between autumn and corresponding spring obesity and blood pressure outcomes among participants in the ELS (1999–2003).

Year	Variable	Unadjusted β	*p*-Value	95% CI	Adjusted β	*p*-Value	95% CI
1999	Obesity by WC	0.003	0.001 *	0.003–0.011	0.007	0.002 *	0.002–0.011
	Obesity by WHtR	0.619	0.000 *	0.556–0.683	0.618	0.000 *	0.554–0.681
	Obesity by WHR	0.005	0.049 *	0.000–0.017	−0.003	0.000 *	−0.004 to −0.002
	High DBP	0.006	0.019 *	−0.001–0.012	0.006	0.020 *	0.001–0.011
	High SBP	0.007	0.046 *	0.000–0.014	0.007	0.050 *	0.000–0.014
	Hypertension	0.003	0.290	−0.002–0.008	0.003	0.306	−0.002–0.008
2000	Obesity by WC	0.012	0.000 *	0.006–0.018	0.012	0.000 *	0.006–0.020
	Obesity by WHtR	−0.001	0.936	−0.027–0.025	−0.002	0.884	−0.028–0.024
	Obesity by WHR	0.003	0.098	0.000–0.006	0.001	0.435	−0.002–0.004
	High DBP	0.000	0.971	−0.005–0.005	0.000	0.981	−0.005–0.005
	High SBP	0.000	0.097	−0.004–0.005	0.000	0.988	−0.005–0.005
	Hypertension	−0.001	0.947	−0.028–0.026	−0.002	0.904	−0.029–0.026
2001	Obesity by WC	0.001	0.640	−0.006–0.009	0.003	0.525	−0.005–0.011
	Obesity by WHtR	0.011	0.499	−0.021–0.042	0.011	0.499	−0.207–0.042
	Obesity by WHR	0.000	0.947	0.000–0.000	0.000	0.852	−0.002–0.002
	High DBP	0.008	0.009 *	0.002–0.013	0.008	0.008 *	0.002–0.013
	High SBP	0.003	0.081	0.000–0.006	0.003	0.087	0.000–0.006
	Hypertension	0.013	0.006 *	0.004–0.023	0.013	0.008 *	0.003–0.023
2003	Obesity by WC	0.017	0.080	−0.002–0.035	0.003	0.550	−0.008–0.015
	Obesity by WHtR	–	–	–	–	–	–
	Obesity by WHR	0.000	0.570	−0.001–0.002	0.006	0.142	−0.002–0.013
	High DBP	0.000	0.898	−0.004–0.004	0.000	0.976	−0.004–0.004
	High SBP	0.036	0.001 *	0.016–0.057	0.033	0.001 *	0.014–0.054
	Hypertension	0.003	0.384	−0.004–0.013	0.003	0.329	−0.005–0.013

Abbreviations: WC, waist circumference; WHtR, waist-to-height ratio; WHR, waist-to-hip ratio; DBP, diastolic blood pressure; SBP, systolic blood pressure; CI, confidence interval; GEE, Generalized Estimating Equation. Values are presented as regression coefficients (β), *p*-values, and 95% confidence intervals (CIs). Adjusted models were controlled for age and sex. GEE models were fitted using a Gaussian distribution, identity link function, and unstructured working correlation matrix. Autumn and spring outcomes were paired within participants across survey years. – indicates collinearity. * $p \leq 0.05$.

4. Discussion

This study determined associations between abdominal obesity indicators and blood pressure measurements obtained during autumn and corresponding spring assessments

among rural South African children and adolescents participating in the Ellisras Longitudinal Study (ELS). To our knowledge, few longitudinal studies from SSA have investigated relationships between abdominal adiposity and blood pressure measurements collected across repeated assessments during childhood and adolescence. The present study extends previous ELS findings by examining associations between repeated anthropometric and blood pressure measurements across survey periods rather than solely describing differences observed between survey waves. The findings showed clear sex-related differences in abdominal obesity and blood pressure outcomes, with girls consistently exhibiting higher prevalence estimates than boys across several survey waves. In addition, significant associations were observed between autumn and corresponding spring measurements for selected abdominal obesity indicators and blood pressure outcomes, particularly during the earlier survey years. These findings are consistent with longitudinal evidence indicating that childhood adiposity and elevated blood pressure are associated with adverse cardiometabolic profiles later in life [3,11,34]. The pattern observed in the present study suggests that measurements obtained during one assessment were related to corresponding measurements obtained at later assessments despite variation across survey periods. However, the findings should be interpreted as evidence of longitudinal associations between repeated measurements rather than direct evidence of individual tracking, rank-order stability, or maintenance of cardiometabolic risk status over time.

The sex-related differences observed in this study may reflect biological, behavioural, and environmental factors that influence adiposity and blood pressure during childhood and adolescence [2,35]. In rural South African settings such as Ellisras, variations in food availability, dietary intake, physical activity patterns, and environmental conditions across different periods of the year may contribute to differences in anthropometric and blood pressure measurements [36,37]. Previous studies have shown that seasonal changes in lifestyle and environmental exposures may influence body composition and cardiovascular health during growth and development [14,16,38]. The higher prevalence of abdominal obesity observed among girls across several survey waves is consistent with findings from the ELS [31] and with reports from other African populations demonstrating a greater burden of adiposity among adolescent girls than boys [18,39]. Similar sex-related patterns have also been documented internationally, with girls typically exhibiting higher levels of total and central adiposity during and after pubertal development [35]. Although differences were observed between autumn and spring assessments, the present findings should be interpreted cautiously because the analyses examined associations between measurements obtained during different survey periods rather than the independent effects of season on cardiometabolic outcomes. Nevertheless, the observed associations indicate that abdominal obesity and blood pressure measurements obtained at one assessment were related to corresponding measurements obtained at later assessments during childhood and adolescence, a developmental period during which cardiometabolic risk factors continue to evolve [2,11,34]. These observations are particularly relevant in South Africa and other SSA countries undergoing nutritional and epidemiological transitions characterised by increasing levels of childhood obesity, elevated blood pressure, and other cardiometabolic risk factors [2,40].

An important finding of this study was the consistently higher prevalence of abdominal obesity and elevated blood pressure among girls than boys. Obesity defined by WC reached 30% among girls compared with 26% among boys, whereas obesity defined by WHR reached 81% among girls compared with 24% among boys during selected survey waves among participants aged ≥12 years. These findings are consistent with previous reports from the ELS and other South African studies demonstrating a higher burden of adiposity among girls during adolescence [18,31]. In addition, findings from the ELS among young adults

demonstrated significant relationships between waist circumference, waist-to-hip ratio, skinfold thicknesses, and blood pressure, indicating that associations between adiposity and cardiovascular risk factors remain evident beyond adolescence [31]. Similar sex-related differences have been reported in international studies, where girls generally exhibit higher levels of total and central adiposity than boys during and after pubertal development [35]. Girls also demonstrated higher prevalence estimates of elevated SBP, elevated DBP, and hypertension during several survey waves. Evidence from African and international studies has shown that increased adiposity is associated with higher blood pressure levels during childhood and adolescence, supporting the coexistence of these cardiometabolic risk factors observed in the present study [11,17,18]. Measures of central adiposity, including WC, WHR, and WHtR, are widely recognised indicators of cardiometabolic risk because of their association with adverse cardiovascular and metabolic outcomes later in life [7,41,42]. Collectively, these findings suggest that girls in rural South African settings may experience a greater burden of early cardiometabolic risk factors and could benefit from targeted monitoring and prevention strategies during childhood and adolescence [2,39].

Differences in abdominal obesity measures were observed across survey waves, with WC- and WHR-defined obesity generally demonstrating greater variation in prevalence than WHtR. Higher prevalence estimates for WC- and WHR-defined obesity were observed during several spring assessments, particularly among girls aged ≥12 years. Similar patterns have been reported in studies showing that dietary intake, physical activity, energy expenditure, and environmental conditions may contribute to temporal changes in body composition among children and adolescents [13,14,38]. In rural South African communities, fluctuations in household food security, dietary diversity, and food availability across the year have also been documented and may influence adiposity outcomes among children and adolescents [36,37]. The relatively consistent WHtR values observed across survey waves are consistent with evidence suggesting that WHtR is less affected by growth-related changes than absolute anthropometric measures and may serve as a useful indicator of central adiposity during childhood and adolescence [7,41,42]. Because the present analyses examined associations between measurements obtained at different assessments rather than the independent effect of season, the observed differences should be interpreted with caution. Nevertheless, the findings emphasise the importance of routinely monitoring abdominal obesity during childhood and adolescence, particularly in populations experiencing rapid nutritional and epidemiological transitions [2,35].

Blood pressure outcomes also varied across survey waves and between sexes, with girls generally demonstrating higher prevalence estimates of elevated SBP, elevated DBP, and hypertension than boys during several assessment periods. These findings parallel the higher prevalence of abdominal obesity observed among girls and are consistent with previous studies reporting positive associations between adiposity and blood pressure among children and adolescents [11,17,43]. The greater burden of abdominal obesity observed among girls may therefore contribute, at least in part, to the higher prevalence of elevated blood pressure recorded in this group [2,18]. Seasonal differences in blood pressure have been reported in both children and adults and have been linked to environmental temperature, vascular responses, physical activity patterns, and behavioural changes occurring throughout the year [12,44]. Among children, Ziegelasch et al. reported significant seasonal variation in blood pressure, with higher values observed during colder periods of the year, suggesting that environmental conditions may contribute to temporal variation in cardiovascular regulation during growth and development [45]. Similar observations have been described among paediatric populations, where higher blood pressure values are often reported during colder periods [16]. Evidence from African child and adolescent populations remains comparatively scarce [16,17]. Together, these findings add to the lim-

ited longitudinal evidence describing blood pressure patterns across repeated assessments in rural African populations experiencing rapid nutritional and epidemiological transitions and increasing cardiometabolic risk [2,40].

A key contribution of this study is the identification of significant associations between abdominal obesity indicators and blood pressure measurements obtained during autumn and corresponding measurements obtained during subsequent spring assessments among rural South African children and adolescents. Although anthropometric and blood pressure measures varied across survey waves, several indicators remained significantly associated across repeated assessments, particularly during the earlier survey years. Childhood adiposity and elevated blood pressure are well-established precursors of later cardiometabolic disorders, including hypertension, type 2 diabetes, and cardiovascular disease [2,5,6]. In SSA, where longitudinal evidence on childhood cardiometabolic health remains limited and much of the existing literature is based on cross-sectional data, findings from the ELS provide valuable insight into cardiometabolic patterns during critical stages of growth and development [17,39]. The observed associations between repeated measurements indicate that abdominal obesity and blood pressure characteristics recorded at one assessment were related to corresponding measurements obtained at later assessments. However, these findings should not be interpreted as evidence of individual tracking, rank-order stability, or maintenance of cardiometabolic risk status over time. From a public health perspective, the results support the importance of early identification, routine monitoring, and timely intervention during childhood and adolescence, particularly in populations undergoing nutritional and epidemiological transitions where obesity and hypertension are becoming increasingly prevalent [2,40].

Strengths and Limitations

This study has several strengths. First, it utilised data from the ELS, one of the few long-running cohort studies in Africa with repeated anthropometric and blood pressure measurements collected during childhood and adolescence. Second, the longitudinal design and repeated assessments across multiple survey waves provided an opportunity to examine associations between abdominal obesity indicators and blood pressure measurements during important stages of growth and development. Third, the large community-based sample and standardised measurement procedures enhanced the reliability of the data and the relevance of the findings for rural South African populations. The findings should, however, be interpreted considering several limitations. The analyses were based on historical cohort data collected between 1999 and 2003 and may not fully reflect contemporary patterns of childhood obesity and blood pressure in South Africa. In addition, although measurements were obtained during autumn and spring survey waves, season was not modelled as an independent exposure in the statistical analyses. Consequently, the findings should not be interpreted as evidence of causal seasonal effects on abdominal obesity or blood pressure. Furthermore, while significant associations between repeated measurements were identified, the analyses did not directly assess individual tracking, rank-order stability, or transitions between cardiometabolic risk categories over time. In addition, although blood pressure outcomes were further classified using the NHBPEP paediatric reference standards, which account for age, sex, and height, the primary analyses of systolic and diastolic blood pressure were based on absolute values. Consequently, some observed associations may partly reflect physiological changes associated with growth and maturation during childhood and adolescence. The use of age-, sex-, and height-standardised blood pressure z-scores may have provided additional insight and could potentially yield different findings. Future studies should consider the use of standardised paediatric blood pressure z-scores to further examine blood pressure patterns across development. Unmea-

sured factors, including dietary intake, physical activity, pubertal status, socioeconomic circumstances, and environmental exposures, may also have influenced the observed associations. Despite these limitations, the study contributes valuable longitudinal evidence on abdominal obesity and blood pressure patterns among children and adolescents living in a rural South African setting, where prospective data on cardiometabolic risk remain scarce.

5. Conclusions

This study provides longitudinal evidence from rural South Africa showing that abdominal obesity indicators and blood pressure measurements obtained during autumn were significantly associated with corresponding measurements obtained during subsequent spring assessments among children and adolescents participating in the ELS. Differences in abdominal obesity and blood pressure outcomes were observed across survey periods and between sexes, with girls generally exhibiting higher prevalence estimates of abdominal obesity and elevated blood pressure than boys. These findings indicate that cardiometabolic characteristics emerge early in life and may remain observable across repeated assessments during childhood and adolescence in a rural African population. Given the increasing burden of obesity, hypertension, and other NCDs in South Africa and other LMICs, early identification and routine monitoring of children at increased cardiometabolic risk remain important public health priorities. Attention should be directed towards girls, who consistently demonstrated a higher burden of abdominal obesity and elevated blood pressure across several survey waves. Interventions that promote healthy dietary practices, regular physical activity, and early cardiometabolic screening may contribute to reducing future cardiovascular disease risk and improving long-term population health outcomes. The findings contribute to national and global priorities for NCD prevention and control across the life course, including South Africa's National Development Plan (NDP) 2030 and Sustainable Development Goal (SDG) 3, which emphasise healthy lives, well-being, and the reduction in premature mortality from NCDs. Beyond surveillance, the ELS provides a valuable platform for future research examining the determinants, progression, and prevention of cardiometabolic risk from childhood into adulthood. Future investigations should explore the influence of dietary behaviours, physical activity, pubertal development, socioeconomic conditions, and environmental exposures on obesity and blood pressure trajectories, while evaluating school- and community-based interventions aimed at reducing cardiometabolic risk among vulnerable populations. Such work would support the translation of longitudinal evidence into policy and practice and strengthen efforts to prevent NCDs across the life course in rural South Africa and similar settings.

Author Contributions: Conceptualization, K.D.M. and T.N.M.; methodology, K.D.M. and T.N.M.; software, K.D.M. and T.N.M.; validation, K.D.M.; formal analysis, K.D.M. and T.N.M.; investigation, T.N.M.; resources, K.D.M.; data curation, K.D.M. and T.N.M.; Validation, K.D.M.; Visualization, P.M. and M.M.; writing—original draft preparation, T.N.M., M.M. and P.M.; writing—review and editing, K.D.M., T.N.M., M.M. and P.M.; supervision, K.D.M., M.M. and P.M.; project administration, K.D.M.; funding acquisition, K.D.M. and T.N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Foundation (NRF) of South Africa, grant numbers SRUG200303507851 and MND210713622357.

Institutional Review Board Statement: The study was conducted in accordance with the principles of the Declaration of Helsinki [46]. The Ellisras Longitudinal Study (ELS) received ethical approval from the Turfloop Research Ethics Committee (TREC), University of Limpopo, South Africa, and has undergone continued ethical review and renewal for follow-up and analysis of ELS data, including approval TREC/323/2017: IR-Renewed. Permission to conduct the original ELS was obtained from the relevant educational authorities, participating schools, communities, parents or legal guardians, and participants, as appropriate. The present study involved a secondary analysis of ELS data collected between 1999 and 2003. Secondary analysis of the data was approved under TREC/360/2022: PG.

Informed Consent Statement: Written informed consent was obtained from parents or legal guardians, and assent was obtained from participating children and adolescents at the time of data collection in accordance with the ethical requirements applicable during the conduct of the Ellisras Longitudinal Study (ELS). The present study used de-identified data obtained through secondary analysis.

Data Availability Statement: The data analysed in this study are not publicly available because they form part of the ongoing Ellisras Longitudinal Study (ELS) cohort and are subject to ethical, institutional, and participant confidentiality requirements. De-identified data may be made available by the corresponding author upon reasonable request and with permission from the Ellisras Longitudinal Study principal investigators and relevant institutional authorities, subject to applicable ethical and data governance approvals.

Acknowledgments: The authors express their sincere gratitude to the children, adolescents, parents, guardians, schools, and communities who have participated in the ELS over the years. The authors also acknowledge the Department of Physiology and Environmental Health, University of Limpopo, for their continued support of the ELS. Special appreciation is extended to the fieldworkers, research assistants, and healthcare personnel who contributed to data collection and management throughout the study period. The long-term commitment of the Ellisras communities has made it possible to generate valuable life-course evidence on growth, cardiometabolic health, and NCD risk among rural South African populations.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BP	Blood Pressure
DBP	Diastolic Blood Pressure
ELS	Ellisras Longitudinal Study
GEE	Generalised Estimating Equation
HICs	High-Income Countries
LMICs	Low- and Middle-Income Countries
NCD	Non-Communicable Disease
NDP	National Development Plan
NHBPEP	National High Blood Pressure Education Program Working Group
SBP	Systolic Blood Pressure
SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
TEM	Technical Errors of Measurement
WC	Waist Circumference
WHtR	Waist-to-Height Ratio
WHR	Waist-to-Hip Ratio

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