EFFECTS OF MUSCLE STRENGTH AND ENDURANCE ON BLOOD PRESSURE AND RELATED CARDIO-METABOLIC RISK FACTORS FROM CHILDHOOD TO ADOLESCENCE

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ABSTRACT

Objective: This study aimed to examine the evolution of relationships between measures of muscle strength and endurance with individual cardio-metabolic risk factors from childhood to late adolescence in a prospective population based cohort.

Methods: Participants from the Western Australian Pregnancy Cohort (Raine) Study at ages 10, 14 and 17 were analysed, using longitudinal linear mixed model analyses.

Results: Handgrip strength after adjusting for the confounding effects of BMI was positively associated with systolic BP, but not diastolic BP. The association between handgrip strength and systolic BP was stronger in males than females at all time points (coefficient (females): 0.18, $p<0.001$; sex*handgrip strength coefficient: 0.09, $p=0.002$). The association was strongest at 10 years and significantly attenuated over time (year*handgrip coefficient from 10 to 14 years: -0.11, $p=0.003$; year*handgrip coefficient from 10 to 17 years: -0.19, p=<0.001). After the inclusion of BMI as a confounder, handgrip strength was significantly negatively associated with HOMA-IR and hs-CRP over time in both sexes. Back muscle endurance was positively associated with systolic BP, but not diastolic BP, after adjustment for the confounding effects of BMI (coefficient: 0.01, $p=0.002$). There were small, albeit significant inverse associations between back muscle endurance and log HOMA-IR and log hs-CRP.

Conclusion: The positive association between handgrip strength and back muscle endurance with systolic BP throughout childhood and adolescence contrasts with beneficial effects on other related traditional cardio-metabolic risk factors. Mechanisms underlying these paradoxical effects on systolic BP warrant further investigation.

CONDENSED ABSTRACT

Objective: To examine the evolution of relationships of muscle strength and endurance with individual cardio-metabolic risk factors from childhood to late adolescence in a prospective population based cohort.

Results: Handgrip strength and back muscle endurance were positively associated with systolic BP at 10, 14 and 17 years of age in both sexes. The association of handgrip strength with systolic BP was stronger at all ages in males. There were no associations between handgrip strength and back muscle endurance with diastolic BP at any age. Handgrip strength and back muscle endurance were significantly negatively associated with HOMA-IR and hs-CRP over time.

Conclusion: The positive association between muscle strength with systolic BP throughout childhood and adolescence contrasts with beneficial effects on other traditional cardio-metabolic risk factors.

Keywords: muscle strength; endurance; blood pressure; cardio-metabolic risk factors; epidemiology; obesity; observational studies

INTRODUCTION

Moderate to high levels of cardiorespiratory fitness have been associated with lower mortality rates (1) and lower levels of hypertension, dyslipidemia and insulin resistance (2, 3). Muscle strength and endurance are key contributors to measures of physical fitness. Muscle strength is defined as the ability to generate a maximal force during a single contraction, whereas muscle endurance is the ability to maintain a repeated exertion of force over an extended period of time (4). The handgrip test acts as a proxy for general muscle strength and is associated with total body strength measures in adults (5) and children (6).

In middle-aged adults, low muscle strength has been associated with high morbidity and mortality rates (7). At least part of this effect is suggested to be mediated by beneficial influences on standard cardio-metabolic risk factors. For example, increased muscular mass due to resistance training has been shown to be protective against the onset of insulin resistance (8). Furthermore, large epidemiological studies have shown high levels of handgrip strength are associated with lower levels of undiagnosed hypertension (9) and to be a moderately strong predictor of incident cardiovascular disease in adults (10). However, there are limited data in children and adolescents.

Adolescence is a critical period of substantial physiological, psychological and lifestyle changes which can impact on future adult behaviours and health outcomes (11). Muscle strength and endurance increase as children age, due to growth in muscle mass and muscle fibre size (12). In addition, blood pressure (BP) has been shown to linearly increase throughout adolescence (13). With a view to understanding the ontogeny of effects of muscle strength and endurance on adolescent risk factors for cardio-metabolic disease, we have examined two modes of muscle function, specifically handgrip strength and back muscle endurance. We then analysed their relationships with a range of individual cardio-metabolic risk factors in participants from the population based Western Australian Pregnancy Cohort (Raine) Study. We hypothesised that higher levels of handgrip strength and back muscle endurance would be associated with lower levels of cardio-metabolic risk factors.

METHODS

Participants

The Raine Study is a prospective population study that recruited 2900 pregnant women between 16 to 20 weeks' gestation from King Edward Memorial Hospital and closely located practices, in Perth, Western Australia, Australia. The mothers gave birth to 2868 live infants. The offspring have been followed at approximately three-year intervals with a comprehensive range of anthropometry, BP, lifestyle, psychosocial and biochemical measures recorded. Details on methods of the Raine Study have previously been reported (14). Ethics approvals for the 10, 14 and 17 year assessments were obtained from the Human Research Ethics Committees at the University of Western Australia, Curtin University and Princess Margaret Hospital. Written informed consent was obtained from the participant's parent and the participant at 17 years age. Handgrip strength measures, BMI and BP recordings were recorded at 10, 14 and 17 years. Back muscle endurance, cardiorespiratory fitness, puberty and biochemistry measures were recorded at 14 and 17 years.

Muscle strength

Muscle strength was assessed using a handgrip dynamometer (Dynamometer, Therapeutic Instruments Clifton N.J.) following the protocol developed by McCarron (15). Participants were asked to extend and hold the hand dynamometer at shoulder length and pull hard on the device to record grip force (kg). Measurements were assessed with the right hand and the left hand with the process being repeated. The best score of the two trials for each hand was recorded. These were combined to create a total handgrip strength score (kg).

Muscle Endurance

The sustained back muscle endurance test was employed to evaluate dynamic back muscle endurance by testing the postural trunk muscles using a procedure described by Biering-Sorensen (16). Participants were instructed to lie in the prone position with their lower body strapped to a bed and the upper body extended beyond the bed. Subjects were required to maintain the horizontal position isometrically for as long as possible. The endurance time was recorded (seconds).

Cardiorespiratory fitness

Cardiorespiratory fitness was estimated from heart rate recordings during sub-maximal cycle ergometry using the Physical Work Capacity Protocol (PWC_{170}) (Monark cycle ergonometer). Heart rate at three different workloads (watts) was used to extrapolate the load required to reach a heart rate of 170 bpm. PWC_{170} is the maximal steady state power attained for a heart rate of 170 beats per minute on a cycle ergometer (17).

Anthropometry

Height was measured using a mounted stadiometer (to the nearest 0.1 cm) and weight was measured (to the nearest 100g) with participants dressed in light clothes. Body mass index (BMI) was calculated as weight (kg) divided by the square of height (m^2).

Puberty

Puberty was assessed using the Tanner Stages of physical development. This scale asks participants to rate their development based on a number of physical sexual characteristics, such as development of breasts, genitalia and pubic hair. The five stages range from 1 (prepubertal) to 5 (fully developed) (18). At 14 years of age, misreporting occurred when approximately 330 individuals were shown the wrong developmental stage chart. To account for this, these individuals were omitted from the analyses when using puberty as a confounder.

Biochemistry

Venous blood samples were taken after an overnight fast and analysed in the PathWest Laboratory at Royal Perth Hospital for serum glucose, insulin, total cholesterol, HDL-C, triglycerides and C-reactive protein (hs-CRP) (19). LDL-C was calculated using the Friedewald formula (20). The homeostasis model of assessment for insulin resistance (HOMA-IR) was calculated using the formula: fasting insulin (μU/ml) x fasting glucose (mmol/L) / 22.5 (21).

Blood pressure

Systolic and diastolic BP were measured by trained personnel using an oscillometric sphygmomanometer (DINAMAP vital signs monitor 8100, DINAMAP XL vital signs monitor or DINAMAP ProCare 100; GE Healthcare) after resting for 5 minutes and using the appropriate cuff size on the right arm. Three cuff sizes were available. At 10 years, two BP readings were obtained every 2 minutes in the seated position and the average calculated. At 14 years, six BP readings were obtained every 2 minutes within a 10-minute period in the seated position, whereas at 17 years, the same protocol was employed in the supine position.

The average BP was calculated using the last five readings at 14 and 17 years. BP was recorded on a separate day to handgrip strength and back muscle endurance assessments.

Statistical analysis

Descriptive data were summarised by year and sex using means, geometric means and their 95% confidence intervals. There is no consensus in the literature regarding the need to adjust handgrip strength for body size or how this might be achieved. To explore this issue, handgrip strength was calculated at each year by regressing handgrip strength on height or weight respectively, we then added the residuals from these analyses to the mean handgrip strength, to obtain a height adjusted and weight adjusted handgrip strength. Potential non-linearity was accommodated by using fractional polynomials. Hierarchal linear mixed models of a selection of cardio-metabolic outcomes (systolic BP, diastolic BP, log HOMA-IR, log triglycerides, HDL-C, hs-CRP) were then used to compare the performance of raw handgrip strength, height adjusted handgrip strength and weight adjusted handgrip strength. A simple model was adopted for this purpose, containing time, sex and subsequently an adjustment for adiposity, using BMI. Models were assessed using Akaike Information Criterion (AIC) where the lowest value indicates the better model.

Longitudinal patterns of raw handgrip strength and back muscle endurance over time as well as individuals cardio-metabolic risk factors were investigated using hierarchical linear mixed models, to account for nesting of time within an individual and siblings within a family. In these models, maximum likelihood estimation was utilised to retain those with outcome data from at least one-time point in the analysis, resulting in unbiased estimates when missing data is missing at random. Random effects Tobit regression (for censored data) was utilised for hs-CRP due to the lower boundary of the test (but does not make any adjustment for siblings)

(22). HOMA-IR, triglycerides and hs-CRP were not normally distributed and hence were log transformed. Initial associations between cardio-metabolic risk factors and handgrip strength and back muscle endurance were investigated after adjusting for sex and year. A further adjustment for adiposity was investigated in a subsequent model using BMI. Interactions between handgrip strength or back muscle endurance with time or sex were tested to determine whether the relationship varied over time or sex. In addition, a time and sex interaction was included to determine whether an outcome varied over time and sex. Interactions were excluded from the model if $p \geq 0.05$. Cardiorespiratory fitness was included as a confounder in both handgrip strength and back muscle endurance models with either systolic BP or diastolic BP as the outcome. Data were analysed using STATA (StataCorp, 2011. *Stata Statistical Software: release 13.* College Station. TX: StataCorp, LP). All reported p values are 2-tailed and significance was set at $\alpha = 0.05$.

RESULTS

Participant characteristics

At 10, 14 and 17 years, 1632, 1560 and 1234 participants, respectively had complete data for handgrip strength and systolic BP (Figure 1). Handgrip strength and biochemistry at 14 and 17 years was available for 1346 and 1048 participants, respectively. At 14 and 17 years, 1554 and 1158 participants, respectively, had complete data for back muscle endurance and systolic BP, whereas 1341 and 983 participants, respectively, had complete data for back muscle endurance and biochemistry.

Interpretation of handgrip strength: Comparison of unadjusted and adjusted measures

For the determination of the 'better' handgrip strength measure, identical models of raw handgrip strength, height adjusted handgrip strength and weight adjusted handgrip strength were compared (Supplementary Table 1a, 1b and 1c, Table, Supplemental Digital Content 1). Raw handgrip strength in unadjusted and BMI confounder adjusted models exhibited the lowest AIC compared to height and weight adjusted handgrip strength. Therefore, raw handgrip strength was deemed a better fit for the outcome of systolic BP and hence was employed as the preferred handgrip strength measure in the final analyses. The same pattern was observed for other cardio-metabolic risk factors investigated (only systolic BP data shown as supplementary material, Table, Supplemental Digital Content 1).

Longitudinal linear mixed models of handgrip strength, back muscle endurance, blood pressure and biochemical risk factors

Handgrip strength increased between 10 to 17 years in both sexes ($p<0.001$), but to a greater extent in males ($p<0.001$) (Table 1). Back muscle endurance was higher in females than in males at 14 years ($p=0.021$) but by 17 years there was no difference between the sexes ($p=0.200$) (Table 1). Back muscle endurance increased between 14 and 17 years in females ($p <0.001$) and also in males but to a greater extent ($p=0.001$) (Table 1). Handgrip strength and back muscle endurance were weakly correlated ($r= 0.07$, $p= 0.008$ at 14 years; $r= 0.08$, $p= 0.004$ at 17 years). Systolic BP increased between 10, 14 and 17 years in both sexes but to a greater extent in males ($p<0.001$) (Table 1). Diastolic BP increased between years 10 and 14 in both sexes but to a greater extent in females ($p<0.001$). There was no significant change in diastolic BP between 14 and 17 years for either sex. Log HOMA-IR decreased between 14 and 17 years in both sexes to a similar extent ($p<0.001$) (Table 1). Cholesterol decreased in males ($p<0.001$) with no change in females over time ($p=0.281$). Log triglycerides increased in males ($p<0.001$) with no change in females over time ($p=0.547$). LDL-C increased in females ($p=0.004$) with no change in males over time ($p=0.818$). HDL-C decreased in both sexes but to a greater extent in males ($p<0.001$). Log hs-CRP increased from 14 to 17 years in females ($p<0.001$), but decreased in males ($p<0.001$).

Longitudinal linear mixed models examining associations between handgrip strength and cardio-metabolic risk factors over time

Handgrip strength was positively associated with systolic BP at all time points in both sexes. The association was strongest at 10 years and attenuated over time (Table 2, Supplementary Table 2, Table, Supplemental Digital Content 1 and Supplementary Figure 1, Figure, Supplemental Digital Content 2).

After adjustment for the confounding effects of BMI, similar associations were detected (Table 2, Supplementary Table 2, Table, Supplemental Digital Content 1 and Figure 2). The association between handgrip strength and systolic BP was stronger in males than females at all time points (sex*handgrip strength coefficient: 0.09, p=0.002). In both sexes, handgrip strength was positively associated with systolic BP at 10 years of age and attenuated over time, (year*handgrip for 10 to 14 years coefficient: -0.11, p=0.003; year*handgrip for 10 to 17 years coefficient: -0.19, p=<0.001) resulting in a non-significant association at 17 years of age in females. The change in systolic BP resulting from a 1 SD change (noted in brackets) in females was 1.07 mm Hg (5.94 kg) and 0.72 mm Hg (9.02 kg) for years 10 and 14 respectively. The corresponding changes in males were 1.78 mm Hg (6.37 kg), 2.50 mm Hg (14.70 kg) and 1.43 mm Hg (15.86 kg) for years 10, 14 and 17 respectively.

To investigate whether these associations may be attributable to cardiorespiratory fitness (only available at 14 and 17 years); PWC_{170} was included as a further confounder with BMI (Supplementary Table 2, Table, Supplemental Digital Content 1). The same pattern was observed after the additional adjustment for PWC_{170} between 14 and 17 years when BMI was the sole confounder in adjusted models.

There were no associations between handgrip strength and diastolic BP at any time point in the unadjusted, BMI-adjusted (Table 2) and the PWC_{170} and BMI-adjusted models (data not shown).

Handgrip strength was positively associated with HOMA-IR in both sexes at all time points (coefficient (log HOMA-IR): 0.003, p=0.013) (Table 3 and Supplementary Table 3, Table, Supplemental Digital Content 1). After the inclusion of BMI as a confounder in the model, handgrip strength was negatively associated with HOMA-IR in both sexes at all time points, (coefficient (log HOMA-IR): -0.003, p<0.001). A 1 SD change in handgrip strength at 14 years (13.40 kg) and 17 years (20.58 kg) equated to a decrease in HOMA-IR of 3.9% and 6 %, respectively.

Handgrip strength was positively associated with triglycerides at all time point in both sexes in the unadjusted model (coefficient (log triglycerides): 0.002, p=0.006) (Table 3). After the inclusion of BMI as a confounder, the aforementioned association was no longer significant (coefficient (log triglycerides): -0.0007, p=0.302). Handgrip strength was negatively associated with HDL-C and this association attenuated from 14 to 17 years in both sexes, (coefficient at 14 years: -0.004, p<0.001; year*handgrip coefficient: 0.003, p<0.001) (Table 4 and Supplementary Table 4, Table, Supplemental Digital Content 1). After, the inclusion of BMI as a confounder, handgrip strength remained negatively associated with HDL-C at 14 years (coefficient: -0.003, p<0.001) but the association was no longer significant at 17 years (year*handgrip coefficient: 0.003, p<0.001). A 1 SD change in handgrip strength at 14 years (13.40 kg) equated to a 0.04 mmol decrease in HDL-C.

There was a positive association between handgrip strength and hs-CRP (coefficient (log hs-CRP): 0.005, p=0.013) (Table 3 and Supplementary Table 5, Table, Supplemental Digital

Content 1). After the inclusion of BMI as a confounder, there was a small negative, albeit significant, association between handgrip strength and hs-CRP (coefficient (log hs-CRP): -0.006, p=0.007). These associations did not vary with sex or time. A 1 SD change in handgrip strength at 14 years (13.40 kg) and 17 years (20.58 kg) equated to a decrease in hs-CRP of 7.7% and 11.3%, respectively.

Longitudinal linear mixed models examining associations between back muscle endurance and cardio-metabolic risk factors over time

There were no interactions for back muscle endurance and time or back muscle endurance and sex for any of the cardio-metabolic risk factors investigated. The associations reported therefore apply to both time points in both sexes.

Back muscle endurance was not associated with systolic BP in unadjusted analysis (coefficient: -0.001, p=0.723) (Table 5, Supplementary Table 6, Table, Supplemental Digital Content 1, Supplementary Figure 2, Figure, Supplemental Digital Content 2). After the inclusion of BMI as a confounder in the model, back muscle endurance was positively associated with systolic BP (coefficient: 0.01, p=0.002) (Table 5, Supplementary Table 6, Table, Supplemental Digital Content 1 and Figure 3). A 1 SD (14 years: 62.83 seconds; 17 years: 56.67 seconds) increase in back muscle endurance equated to a 0.06 mm Hg increase in systolic BP. After the inclusion of cardiorespiratory fitness as a further confounder, these associations were not altered (Supplementary Table 6, Table, Supplemental Digital Content 1). Back muscle endurance was not associated with diastolic BP in unadjusted, BMI adjusted (Table 5) and the PWC_{170} and BMI-adjusted models (data not shown).

Back muscle endurance was inversely associated with HOMA-IR (coefficient (log HOMA-IR): -0.002, p<0.001) (Table 5 and Supplementary Table 7, Table, Supplemental Digital Content 1). With BMI as a confounder in the model, back muscle endurance remained negatively associated with HOMA-IR (coefficient (log HOMA-IR): -0.001, p<0.001). A 1 SD (14 years: 62.83 seconds; 17 years: 56.67 seconds) increase in back muscle endurance equated to a 6% and 5.5% decrease in HOMA-IR at 14 and 17 years, respectively.

Back muscle endurance was inversely associated with triglycerides (coefficient (log triglycerides): -0.0009, p<0.001) and remained significant after the inclusion of BMI as a confounder (coefficient (log triglycerides): -0.0004, p=0.007) (Table 5 and Supplementary Table 8, Table, Supplemental Digital Content 1). A 1 SD (14 years: 62.83 seconds; 17 years: 56.67 seconds) increase in back muscle endurance equated to a 2.5% and 2.2% decrease in triglycerides at 14 and 17 years, respectively. Back muscle endurance was positively associated with HDL-C (coefficient: 0.0005, p<0.001), but this was no longer significant after the inclusion of BMI as a confounder (coefficient: 0.0001, p=0.209) (Table 5). Back muscle endurance was negatively associated with hs-CRP (coefficient (log hs-CRP): -0.003, p<0.001) and the relationship remained significant after inclusion of BMI in the model (coefficient (log hs-CRP): -0.001, p=0.018) (Table 5 and Supplementary Table 9, Table, Supplemental Digital Content 1). A 1 SD (14 years: 62.83 seconds; 17 years: 56.67 seconds) increase in back muscle endurance equated to a 6% and 5.5% decrease in hs-CRP at 14 and 17 years, respectively.

DISCUSSION

To our knowledge, this the first study examining the relationship between measures of muscle performance i.e. muscle strength and endurance, with blood pressure and other cardio-metabolic risk factors from childhood to late adolescence. The study has shown unexpectedly, handgrip strength was positively associated with systolic BP and attenuated over time. The association between handgrip strength and systolic BP was stronger in males than females, with a non-significant association at 17 years of age in females. More predictably, handgrip strength and back muscle endurance were inversely associated with HOMA-IR and hs-CRP after the inclusion of BMI as a confounder. Additionally, back muscle endurance was inversely associated with plasma triglycerides.

Previous paediatric studies investigating the effects of muscle strength on cardiovascular risk factors have examined cardio-metabolic risk factors as components of a clustered metabolic risk score. These studies have shown an inverse relationship between muscle strength and clustered metabolic risk (23-25). Artero et al. (23) used a muscular fitness score computed using the standardized values of handgrip strength and standing long jump (separately for males and females) and showed a negative association with a clustered metabolic risk score which included systolic BP, HOMA-IR, total cholesterol/HDL-cholesterol and triglycerides in 12 to 17 year old participants of the HELENA study. In addition, the ACFIES study observed that poorer handgrip strength were associated with a worse cardio-metabolic risk in Columbian schoolchildren, aged 8-14 years (26). However, the aforementioned studies did not examine BP and related cardio-metabolic risk factors individually. More recently, Zaqout et al. (27) examined the longitudinal associations between individual components of physical fitness (cardiorespiratory fitness, handgrip strength and lower limb strength and speed/agility) and the combined sum of these individual physical fitness components (using *z*-scores) with metabolic risk markers, in 6-11 year old European participants in the IDEFICS study. No longitudinal associations were observed between handgrip strength or the sum of physical fitness with clustered metabolic risk (sum of age and sex specific *z*-scores of waist circumference, systolic BP, diastolic BP, triglycerides, HDL-C and HOMA-IR) or with systolic BP, HOMA-IR and blood lipids. Lower limb strength (measured by standing long jump) showed longitudinal and inverse associations with clustered metabolic risk, blood lipids and HOMA-IR but there were no associations with systolic BP. No studies to date have examined BP or related cardio-metabolic risk factors individually or longitudinally from childhood through to adolescence where significant maturational changes occur. Additionally, no studies have examined the association between isometric endurance of the trunk extensor muscles and the individual risk factors.

Adult population studies present conflicting results with muscle fitness and BP. Sayer et al. (28) have shown a lower handgrip strength was associated with higher systolic BP in a population based sample of 2677 men and women aged 59 – 73 years from the Hertfordshire study. In that study, a 1 SD decrease in handgrip strength associated with high BP (OR 1.13 p= 0.004). Vaara et al (29) found that muscle endurance was inversely associated with both systolic and diastolic BP in young men (25±years). The younger age of our participants and our use of dynamic assessment of muscle endurance may explain the observational differences seen in our study. In contrast, Viitasalo et al. (30) found positive correlations between muscle strength of the trunk extensor muscles with systolic BP in young healthy men (mean age 19.7 years). Takaema et al. (31) reported higher levels of handgrip strength associated with higher resting BP in a large population based sample of Japanese men and women (aged 66 years).

In contrast to our study of muscle strength and muscle endurance per se, a study of self-reported aerobic exercise in young adults (<30 years), showed an association with lower diastolic BP and higher pulse pressure (32). Aerobic physical activity was self-reported via questionnaire (International Physical Activity Questionnaire, 2002) and individuals who reported regular resistance training were excluded. There were no differences in central or brachial systolic BP between exercising and non-active individuals. This study contrasts with our results, as we found a positive association between handgrip strength and back muscle endurance with systolic BP, even after adjustment for cardiorespiratory fitness. Additionally, we observed no associations between muscle strength or muscle endurance with diastolic BP in our young population. Discrepancies between the two studies are likely due to the different measurement methods, types of physical fitness assessed, and different ages of the populations.

Population data are in contrast to resistance training studies which have consistently shown improvements in handgrip strength are associated with reductions in systolic BP (33-35). Owen et al. (36) suggested handgrip exercise might increase forearm blood flow and/or improve local flow-mediated dilation. Enhanced brachial FMD response as well as endothelium dependent vasodilatation were observed after isometric handgrip training in older men, elderly hypertensives and chronic heart failure subjects (37). Similarly, forearm blood flow was increased with regular handgrip exercise training in young men and in middle aged men (38). However, it is important to note various factors, such as exercise intensity, different populations and exercise modality can have differing influences on BP.

The lack of effect of muscle strength and muscle endurance on diastolic BP in our study is of interest given that systolic BP and more predominantly diastolic BP in young adults are predictive of subsequent cardiovascular events and mortality (39). Our findings of a positive relationship between handgrip strength and back muscle endurance with systolic BP across periods of the survey may be related to the fact that both muscle strength and BP increase in magnitude during adolescence. Nevertheless, we saw similar associations cross-sectionally at each time point in subjects that were predominantly pre-pubertal at 10 years to post-puberty at 17 years. Thus it is possible that changes in androgen levels related to puberty influenced muscle mass and strength (40, 41) and thereby the positive association with systolic BP (42). Increases in testosterone could increase muscle mass and may have an additive effect on BP, although the associations in our study were seen in females as well as males making this explanation unlikely. This critical period of growth in the Raine cohort is associated with other hormonal changes such as growth hormone, which might also contribute to parallel changes in muscle strength (12) and left ventricular mass and contractility (43, 44) and hence BP. The association between handgrip strength and back muscle endurance with systolic BP in our study could be explained by an increase in arterial stiffness and/or vascular hypertrophy with a higher degree of muscle fitness in childhood and adolescents.

In accordance with our findings with HOMA-IR and triglycerides, adult studies have consistently shown inverse associations between different measures of muscle strength and measures of insulin resistance and lipids (45, 46). Vaara et al. (29) showed that muscular endurance (sit-ups, push-ups and repeated squats) was inversely associated with blood triglycerides and glucose in young men. Increased muscle mass is the most likely explanation for the effects on glucose homeostasis and lipids which appear to persist through childhood and adolescence into adult life. Skeletal muscle is one of the primary tissue sites for glucose and lipid metabolism and is considered a determinant of resting metabolic rate. Thus changes in muscle mass may influence multiple cardio-metabolic risk factors (47).

The results of our study are likely to be generalizable as Raine study participants were derived from a cohort broadly representative of the general population and were not a selected group of athletes. Strengths of our study include serial measures of detailed phenotypes in a large cohort of population-based children and adolescents, allowing the study of the evolution of associations between different aspects of muscle function and a panel of cardio-metabolic risk factors. Limitations include the use of BMI in the analyses which does not distinguish between fat and lean mass. In addition, not all measures were repeated at every time point. BP recordings varied across the three time points in terms of posture and number of measurements obtained. This could have influenced the associations observed. Relationships with home BP or 24-hour ambulatory monitoring would be of further interest.

In conclusion, we have demonstrated that paradoxically handgrip strength and back muscle endurance were positively associated with higher systolic BP in children and adolescents despite inverse associations with HOMA-IR, lipids and hs-CRP. These BP findings warrant replication in other populations and further evaluation to the possible underlying mechanisms. In view of the fact grip strength increases from childhood through to 20-30 years of age (48, 49), it will be of particular interest to ascertain whether the association between handgrip strength and back muscle endurance, with systolic BP, are maintained or reversed in later adulthood. Equally important will be to determine the optimal period to gain a substantial benefit from resistance strength training for the early prevention of Type 2 diabetes, dyslipidemia and hypertension.

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Table 1. Characteristics of the participants by age and sex

	Males			Females		
	10 years n=849	14 years n=815	17 years n=628	10 years n=783	14 years n=774	17 years n=616
Height (cm)	143.69 (143.25, 144.14)	166.27 (165.65, 166.88)	178.3 (177.74, 178.88)	143.64 (143.20, 144.09)	162.02 (161.58, 162.46)	165.90 (165.39, 166.41)
Weight (kg)	38.57 (38.00, 39.14)	58.62 (57.66, 59.59)	72.29 (71.13, 73.41)	38.71 (38.13, 39.31)	56.67 (55.82, 57.52)	63.66 (62.61, 64.71)
Body mass index (kg/m2)	20.97 (19.86, 21.18)	21.06 (20.78, 21.35)	22.69 (22.36, 23.02)		21.53 (21.24, 21.83)	23.12 (22.76, 23.48)
Waist circumference (cm)		76.31 (75.52, 77.09)	80.53 (79.67, 81.04)		74.60 (73.88, 75.31)	77.55 (76.63, 78.47)
Handgrip strength (kg)	32.02 (31.60, 32.45)	57.00 (55.98, 58.02)	81.18 (79.93, 82.43)	29.01 (28.59, 29.43)	46.29 (45.64, 46.93)	49.74 (48.95, 50.53)
Back muscle endurance (sec)		78.07 (73.86, 82.28)	102.82 (98.55, 107.10)		85.82 (81.26, 90.39)	98.99 (94.03, 103.95)
Cardiorespiratory fitness PWC_{170} (watts)		124.35 (122.14, 126.56)	154.39 (151.08, 157.69)		97.20 (95.79, 98.63)	99.62 (97.60, 101.34)
Systolic BP (mm Hg)	106.9 (106.2, 107.5)	113.84 (113.1 114.6)	117.82 (117.07, 118.57)	106.22 (105.54, 106.89)	108.80 (108.15, 109.46)	108.66 (107.94, 109.38)
Diastolic BP (mm Hg)	56.7 (56.2, 57.1)	58.6 (58.0, 59.0)	58.2 (57.7, 58.7)	56.8 (56.3, 57.2)	59.3 (58.8, 59.7)	59.5 (58.9, 60.0)
Glucose (mmol)		4.72 (4.64, 4.92)	4.65 (4.82, 4.92)		4.88 (4.68, 4.76)	4.87 (4.61, 4.70)
Insulin (mU/L)		12.29 (11.29, 13.30)	8.96 (8.36, 9.57)		12.71 (12.06, 13.36)	9.91 (8.93, 10.89)
HOMA-IR*		0.65 (0.61, 0.70)	0.50 (0.46, 0.55)		0.72 (0.68, 0.77)	0.52 (0.47, 0.56)
Triglycerides (mmol)*		0.22 (0.20, 0.26)	0.27 (0.24, 0.30		0.19 (0.17, 0.22)	0.21 (0.18, 0.24)

Total cholesterol (mmol)	4.06 (4.01, 4.11)	3.96 (3.90, 4.01)		4.28 (4.23, 4.34)	3.96 (4.24, 4.36)
HDL cholesterol (mmol)	1.35 (1.33, 1.37)	1.20 (1.18, 1.22)		1.43 (1.41, 1.45)	1.38 (1.36, 1.41)
LDL cholesterol (mmol)	2.25 (2.21, 2.30)	2.25 (2.20, 2.31)		2.38 (2.36, 2.43)	2.44 (2.38, 2.49)
hs-CRP (mg/L)*	0.61 (0.52, 0.71)	0.65 (0.55, 0.76)		0.54 (0.42, 0.68)	0.74 (0.64, 0.84)

Descriptive characteristics are presented as means, geometric means and 95% CI. HDL, high-density lipoprotein; LDL, low-density lipoprotein; hs-CRP, high sensitivity C-reactive protein; HOMA-IR, homeostatic model assessment - insulin resistance; BP, blood pressure. BP was measured in the seated position at ages 10 and 14 years, and in the supine position at 17 years.
*Variables were log transformed.

Table 2. Handgrip strength associations with blood pressure generated from a longitudinal linear mixed model

	Unadjusted model		BMI adjusted model	
	Systolic BP			
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Females				
10 years	0.29 (0.21, 0.37)	<0.001	0.18 (0.11, 0.26)	<0.001
14 years	0.15 (0.09, 0.20)	<0.001	0.08 (0.02, 0.13)	0.007
17 years	0.07 (0.01, 0.12)	0.016	-0.001 (-0.06, 0.05)	0.960
Males				
10 years	0.35 (0.28, 0.42)	<0.001	0.28 (0.20, 0.35)	<0.001
14 years	0.21 (0.17, 0.25)	<0.001	0.17 (0.13, 0.20)	<0.001
17 years	0.13 (0.09, 0.17)	<0.001	0.09 (0.05, 0.13)	<0.001
	Diastolic BP			
All years	-0.006 (-0.02, 0.01)	0.558	-0.13 (-0.03, 0.01)	0.196

N= 4425 observations from 1916 participants

Coefficients reported were generated from longitudinal linear mixed models (shown in Supplementary tables).

Table 3. Handgrip strength associations with HOMA-IR, triglycerides and hs-CRP generated from a longitudinal linear mixed model or random effects tobit model

	Unadjusted	BMI adjusted
Log HOMA-IR		
Coefficient	0.003	-0.003
(95% CI)	(0.0006, 0.005)	(-0.005, -0.002)
P value	0.013	0.001
Log Triglycerides		
Coefficient	0.002	-0.0007
(95% CI)	(0.0006, 0.003)	(-0.002, 0.0006)
P value	0.006	0.302
Log hs-CRP*		
Coefficient	0.005	-0.006
(95% CI)	(0.001, 0.01)	(-0.01, -0.002)
P value	0.013	0.007

N= 4425 observations from 1916 participants
*N= 1967 observations from 1363 participants as participants with values >10 were excluded

Coefficients reported were generated from longitudinal linear mixed models or random effects tobit model (shown in Supplementary tables).

Table 4. Handgrip strength associations with HDL-C generated from a longitudinal linear mixed model

	Unadjusted model		BMI adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
14 years	-0.004 (-0.006, -0.003)	<0.001	-0.003 (-0.004, -0.002)	<0.001
17 years	-0.002 (-0.003, -0.0007)	0.002	-0.0002 (-0.001, 0.001)	0.796

N= 2396 observations from 1506 participants

Coefficients reported were generated from longitudinal linear mixed models (shown in Supplementary tables).

Table 5. **Longitudinal linear models of back endurance with cardio-metabolic outcomes generated from a longitudinal linear mixed model or random effects tobit model**

	Unadjusted	BMI adjusted
Systolic BP^		
Coefficient	-0.001	0.01
(95% CI)	(-0.007, 0.005)	(0.004, 0.02)
P value	0.723	0.002
Diastolic BP^		
Coefficient	0.002	0.002
(95% CI)	(-0.002, 0.006)	(-0.002, 0.007)
P value	0.384	0.285
Log HOMA-IR		
Coefficient	-0.002	-0.001
(95% CI)	(-0.002, -0.001)	(-0.001, -0.0006)
P value	<0.001	<0.001
Log Triglycerides		
Coefficient	-0.0009	-0.0004
(95% CI)	(-0.001, -0.0006)	(-0.0007, -0.0001)
P value	<0.001	0.007
HDL-C		
Coefficient	0.0005	0.0001
(95% CI)	(0.0003, 0.0007)	(-0.00007, 0.0003)
P value	<0.001	0.209
Log hs-CRP*		
Coefficient	-0.003	-0.001
(95% CI)	(-0.004, -0.002)	(-0.002, -0.0002)
P value	<0.001	0.018

N= 2325 observations from 1491 participants
^N= 2712 observations from 1687 participants
*N= 1895 observations from 1337 participants as participants with values >10 were excluded

Coefficients reported were generated from longitudinal linear mixed models or random effects tobit model (shown in Supplementary tables).

Figure 1. Flow diagram of Raine Study participants attending the 10, 14 and 17 year follow-up with complete handgrip strength and back muscle endurance data

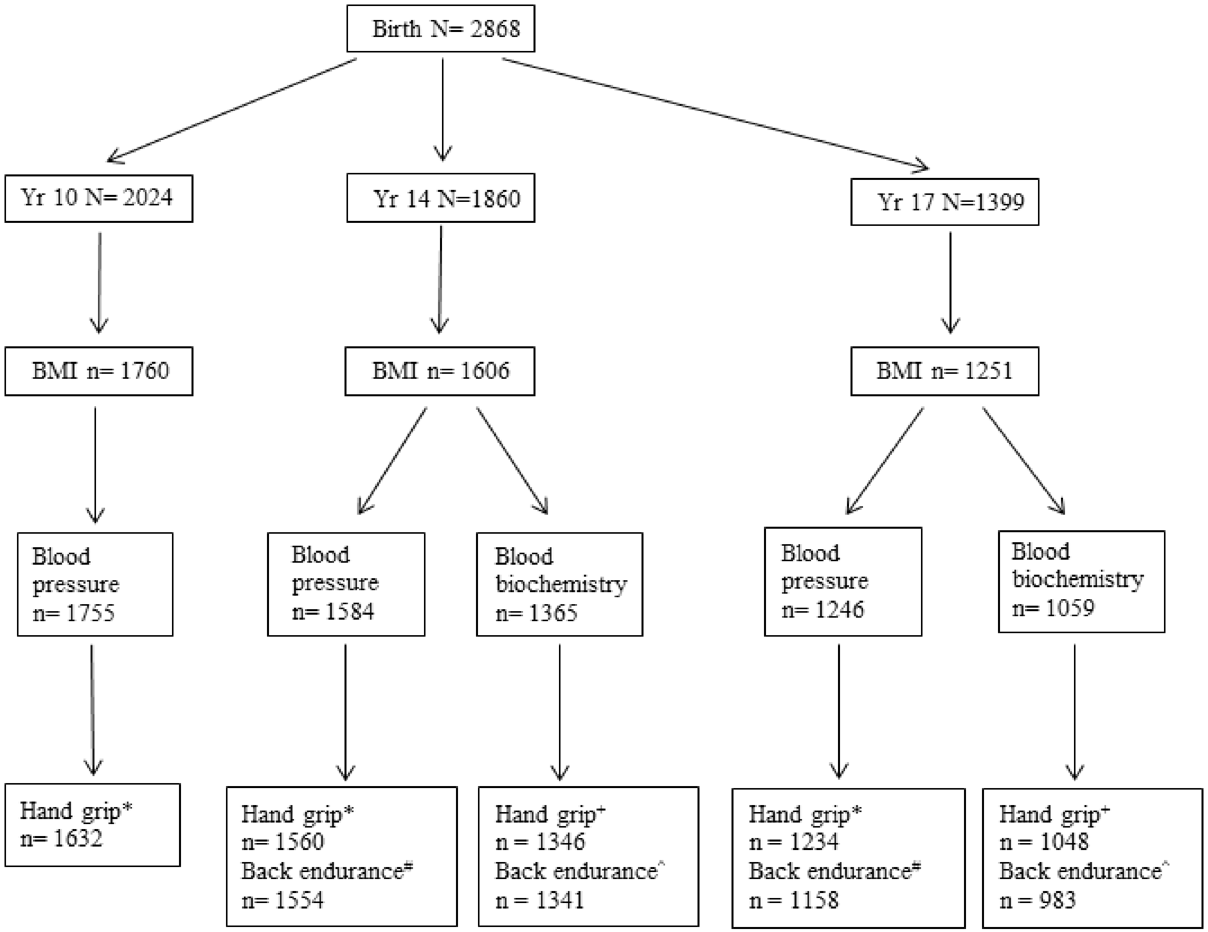
Figure 2. Handgrip strength and systolic BP at 10, 14 and 17 years after adjustment for BMI (mean and 95% CI's represented) generated from longitudinal linear mixed models

Figure 3. Back muscle endurance and systolic BP at 14 and 17 years after adjustment for BMI (mean and 95% CI's represented) generated from longitudinal linear mixed models

Supplemental Digital Content 1. Tables that illustrate longitudinal linear mixed models of handgrip strength or back endurance with the individual cardio-metabolic risk factors.pdf

Supplemental Digital Content 2. Figures that illustrate handgrip strength or back muscle endurance and systolic BP in unadjusted models.pdf

Figure 1. Flow diagram of Raine Study participants attending the 10, 14 and 17 year follow-up with complete handgrip strength and back muscle endurance data



* Multiple assessments on n= 1522
\# Multiple assessments on n= 1025
\+ Multiple assessments on n= 888
^ Multiple assessments on n= 833

Figure 2. Handgrip strength and systolic BP at 10, 14 and 17 years after adjustment for BMI (mean and 95% CI's represented) generated from longitudinal linear mixed models

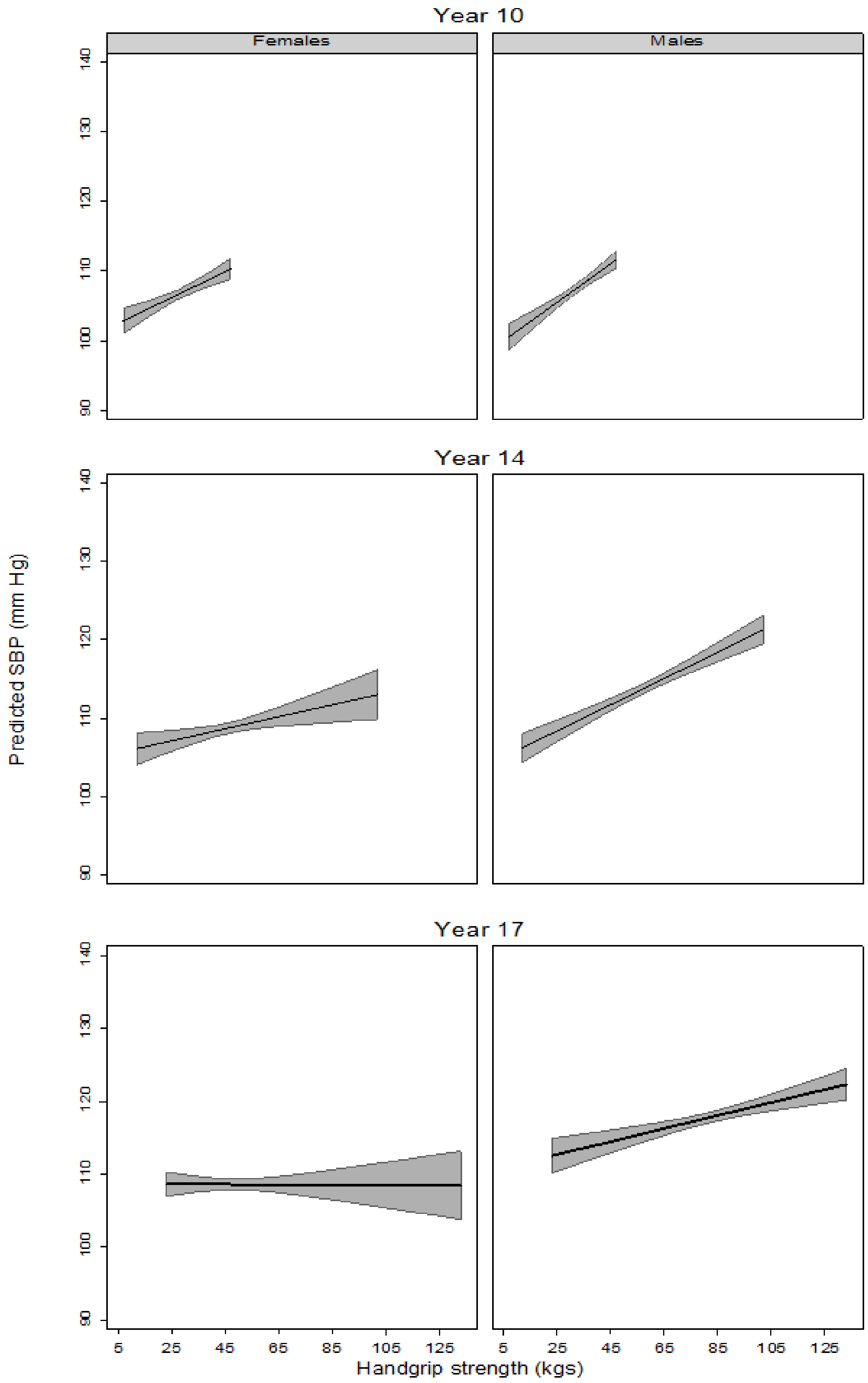
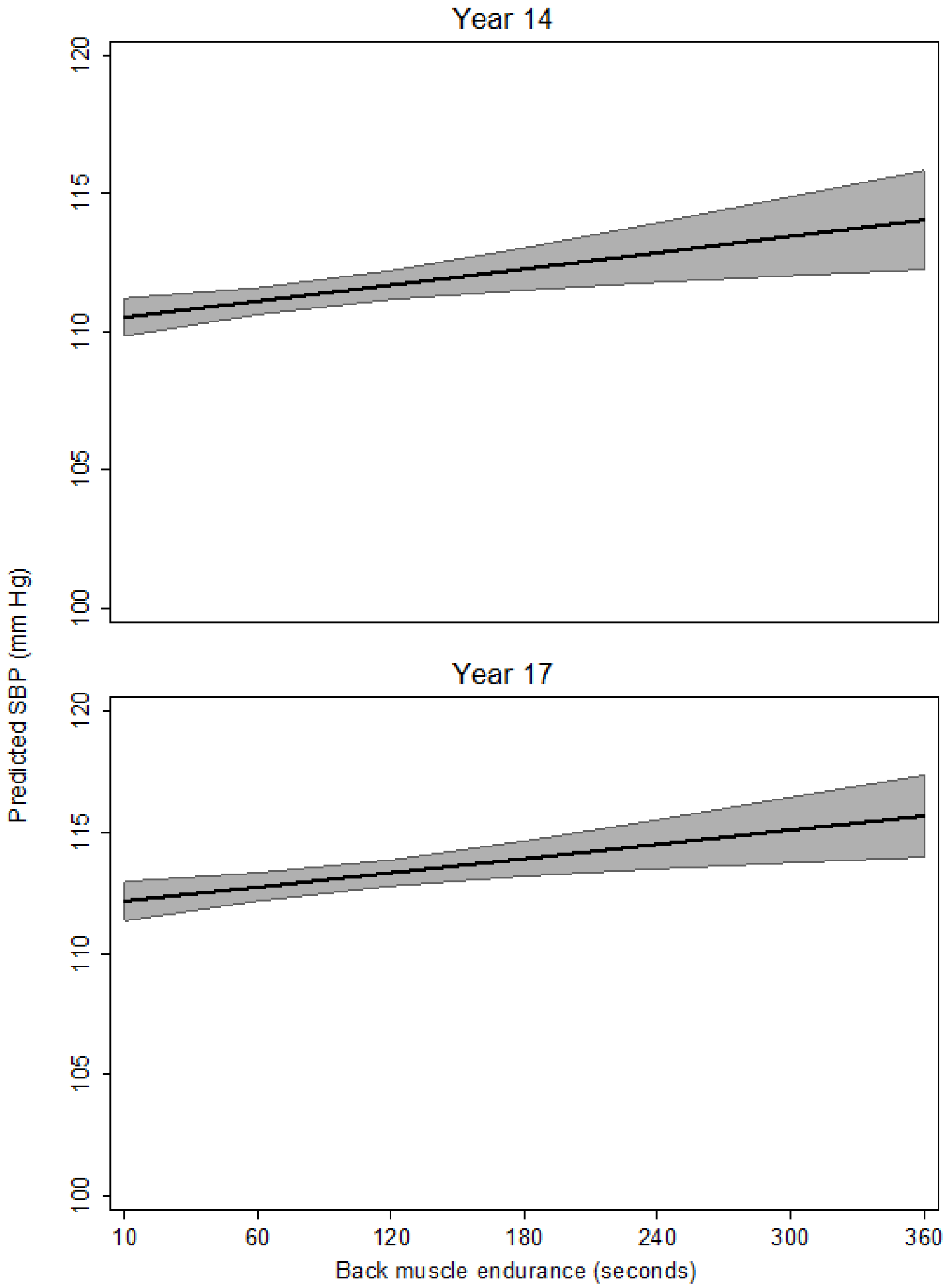


Figure 3. Back muscle endurance and systolic BP at 14 and 17 years after adjustment for BMI (mean and 95% CI's represented) generated from longitudinal linear mixed models



Supplementary Table 1a. Raw handgrip strength with systolic BP

	Unadjusted for adiposity				Adjusted for adiposity			
Systolic BP	**Coefficient**	**P Value**	**95% CI**		**Coefficient**	**P value**	**95% CI**	
Year (ref 10)								
14	1.80	0.154	-0.67	4.27	0.04	0.977	-2.42	2.50
17	2.71	0.031	0.25	5.17	-0.44	0.726	-2.93	2.04
Handgrip strength	0.30	<0.001	0.25	5.17	0.22	<0.001	0.15	0.29
Year*handgrip strength								
14	-0.08	0.026	-0.15	-0.01	-0.04	0.282	-0.12	0.03
17	-0.11	0.001	-0.18	-0.04	-0.05	0.124	-0.12	0.01
Sex (ref females)	1.58	<0.001	0.84	2.33	2.22	<0.001	1.49	2.95
BMI	N/A	N/A	N/A	N/A	0.52	<0.001	0.44	0.60
Constant	97.12	<0.001	95.02	99.22	89.55	<0.001	87.17	91.93
AIC	31919.38				31768.82			

N= 4425 observations from 1916 participants

Supplementary Table 1b. Height adjusted handgrip strength with systolic BP

		Unadjusted for adiposity				Adjusted for adiposity			
Systolic BP		**Coefficient**	**P Value**	**95% CI**		**Coefficient**	**P value**	**95% CI**	
Year (ref 10)									
	14	-0.22	0.884	-3.25	2.80	-1.37	0.371	-4.36	1.63
	17	0.15	0.92	-2.88	3.18	-2.12	0.168	-5.13	0.89
Handgrip strength		0.14	0.001	0.05	0.22	0.06	0.172	-0.02	0.14
Year*handgrip strength									
	14	0.03	0.471	-0.05	0.12	0.05	0.198	-0.03	0.14
	17	0.02	0.619	-0.06	0.10	0.06	0.161	-0.02	0.14
Sex (ref females)		3.34	<0.001	2.60	4.07	3.90	<0.001	3.20	4.61
BMI		N/A	N/A	N/A	N/A	0.60	<0.001	0.52	0.68
Constant		101.34	<0.001	98.86	103.82	92.29	<0.001	0.52	0.68
AIC		32130.51				31939.96			

N= 4425 observations from 1916 participants

Supplementary Table 1c. Weight adjusted handgrip strength with systolic BP

		Unadjusted for adiposity				Adjusted for adiposity			
Systolic BP		**Coefficient**	**P Value**	**95% CI**		**Coefficient**	**P value**	**95% CI**	
Year (ref 10)									
	14	-3.15	0.036	-6.10	-0.20	-6.03	<0.001	-8.93	-3.13
	17	-3.12	0.035	-6.03	-0.21	-7.56	<0.001	-10.44	-4.68
Handgrip strength		0.01	0.806	-0.07	0.09	0.06	0.132	-0.02	0.14
Year*handgrip strength									
	14	0.14	0.001	0.06	0.22	0.13	0.001	0.05	0.22
	17	0.14	0.001	0.06	0.23	0.13	0.002	0.05	0.21
Sex (ref females)		2.94	<0.001	2.16	3.71	2.72	<0.001	2.00	3.45
BMI		N/A	N/A	N/A	N/A	0.77	<0.001	0.69	0.85
Constant		105.38	<0.001	2.16	3.71	89.62	<0.001	86.72	92.52
AIC		32137.14				31809.22			

N= 4425 observations from 1916 participants

Supplementary Table 2: Longitudinal linear mixed model for the association between handgrip strength and systolic BP over time

	Unadjusted model		**BMI adjusted model**		**BMI and PWC_{170} adjusted model**	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**	**Coefficient (95% CI)**	**P value**
Year						
14 yrs	3.35 (0.70, 6.00)	0.013	1.99 (-0.62, 4.61)	0.135	Reference group	Reference group
17 yrs	6.69 (3.87, 9.52)	<0.001	4.52 (1.72, 7.32)	0.002	3.70 (1.25, 6.14)	0.003
Sex Male	-2.23 (-4.22, -0.22)	0.030	-2.86 (-4.82, -0.90)	0.004	-0.34 (-3.67, 2.99)	0.842
Year*sex						
14 yrs	2.24 (0.65, 3.83)	0.006	2.19 (0.63, 3.75)	0.006	Reference group	Reference group
17 yrs	4.40 (2.08, 6.72)	<0.001	4.95 (2.68, 7.22)	<0.001	3.25 (1.49, 5.00)	<0.001
Handgrip strength	**0.29 (0.21, 0.37)**	**<0.001**	**0.18 (0.11, 0.26)**	**<0.001**	**0.12 (0.06, 0.19)**	**<0.001**
Year*handgrip strength						
14 yrs	**-0.14 (-0.21, -0.07)**	**<0.001**	**-0.11 (-0.18, -0.04)**	**0.003**	**Reference group**	**Reference group**
17 yrs	**-0.22 (-0.29, -0.15)**	**<0.001**	**-0.19 (-0.26, -0.11)**	**<0.001**	**-0.10 (-0.15, -0.06)**	**<0.001**
Sex*handgrip strength						
Males	**0.06 (-0.0004, 0.12)**	**0.051**	**0.09 (0.03, 0.15)**	**0.002**	**0.09 (0.02, 0.15)**	**0.008**
BMI	N/A	N/A	0.58 (0.50, 0.67)	<0.001	0.50 (0.40, 0.59)	<0.001

PWC_{170}	N/A	N/A	N/A	N/A	-0.02 (-0.03, -0.007)	0.003
Constant	90.61 (88.08, 93.13)	<0.001	90.61 (88.08, 93.13)	<0.001	94.09 (90.79, 97.40)	97.40

N (unadjusted and BMI adjusted model) = 4425 observations from 1916 participants; (BMI and PWC_{170} adjusted model) =2617 observations from 1649 participants

Supplementary Table 3: Longitudinal linear mixed model for the association between handgrip strength and log HOMA-IR over time

	Unadjusted model		**BMI adjusted model**	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	-0.38 (-0.44, -0.31)	<0.001	-0.46 (-0.52, -0.40)	<0.001
Sex Male	-0.12 (-0.19, -0.05)	0.001	-0.01 (0.08, -0.05)	0.663
Year*sex				
17 yrs	-0.06 (-0.16, 0.04)	0.221	0.06 (-0.03, 0.15)	0.210
Handgrip strength	**0.003 (0.0006, 0.005)**	**0.013**	**-0.003 (-0.005, -0.002)**	**0.001**
BMI	N/A	N/A	0.06 (0.05, 0.07)	<0.001
Constant	0.72 (0.61, 0.83)	<0.001	-0.39 (-0.53, -0.24)	<0.001

N= 2392 observations from 1505 participants

Supplementary Table 4: Longitudinal linear mixed model for the association between handgrip strength and HDL-C over time

	Unadjusted model		**BMI adjusted model**	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	-0.15 (-0.22, -0.08)	<0.001	-0.12 (-0.18, -0.05)	0.001
Sex Male	-0.02 (-0.06, 0.01)	0.181	-0.05 (-0.09, -0.02)	0.001
Year*sex				
17 yrs	-0.11 (-0.15, -0.06)	<0.001	-0.14 (-0.18, -0.02)	<0.001
Handgrip strength	**-0.004 (-0.006, -0.003)**	**<0.001**	**-0.003 (-0.004, -0.002)**	**<0.001**
Year*handgrip strength				
17 yrs	**0.003 (0.001, 0.004)**	**<0.001**	**0.003 (0.001, 0.004)**	**<0.001**
BMI	N/A	N/A	-0.02 (-0.02, -0.01)	<0.001
Constant	1.64 (1.58, 1.70)	<0.001	2.02 (1.94, 2.09)	<0.001

N= 2396 observations from 1506 participants

Supplementary Table 5: Random effects tobit model for the association between handgrip strength and log hs-CRP over time

	Unadjusted model		BMI adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	0.43 (0.30, 0.56)	<0.001	0.35 (0.23, 0.48)	<0.001
Sex Male	0.06 (-0.09, 0.22)	0.439	0.22 (0.08, 0.37)	0.003
Year*sex				
17 yrs	-0.73 (-0.94, -0.53)	<0.001	-0.50 (-0.70, -0.31)	<0.001
Handgrip strength	**0.005 (0.001, 0.01)**	**0.013**	**-0.006 (-0.01, -0.002)**	**0.007**
BMI	N/A	N/A	0.11 (0.10, 0.13)	<0.001
Constant	-0.84 (-1.06, -0.62)	<0.001	-2.89 (-3.18, -2.59)	<0.001

N= 1967 observations from 1363 participants

Supplementary Table 6: Longitudinal linear mixed model for the association between back muscle endurance and systolic BP over time

	Unadjusted model		BMI adjusted model		BMI and PWC_{170} adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**	**Coefficient (95% CI)**	**P value**
Year*						
17 yrs	-0.34 (-1.17, 0.50)	0.429	-1.34 (-2.18, -0.51)	0.002	-1.40 (-2.27, -0.52)	0.002
Sex Male	4.99 (4.05, 5.95)	<0.001	5.39 (4.47, 6.31)	<0.001	5.55 (4.54, 6.57)	<0.001
Year*sex						
17 yrs	4.33 (3.17, 5.49)	<0.001	4.07 (2.93, 5.21)	<0.001	3.90 (2.67, 5.14)	<0.001
Back muscle endurance	**-0.001 (-0.007, 0.005)**	**0.723**	**0.01 (0.004, 0.02)**	**0.002**	**0.01 (0.003, 0.02)**	**0.003**
BMI	N/A	N/A	0.61 (0.52, 0.71)	<0.001	0.62 (0.52, 0.72)	<0.001
PWC_{170}	N/A	N/A	N/A	N/A	0.003 (-0.01, 0.02)	0.654
Constant	108.86 (107.99, 109.72)	<0.001	94.69 (92.32, 97.07)	<0.001	94.21 (91.66, 96.76)	<0.001

N (unadjusted and BMI adjusted model) = 2712 observations from 1687 participants; (BMI and PWC_{170} adjusted model) =2557 observations from 1638 participants

Supplementary Table 7: Longitudinal linear mixed model for the association between back muscle endurance and log HOMA-IR over time

	Unadjusted model		BMI adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	-0.36 (-0.43, -0.30)	<0.001	-0.46 (-0.52, -0.39)	<0.001
Sex Male	-0.10 (-0.17, -0.04)	0.002	-0.06 (-0.12, -0.004)	0.036
Year*sex				
17 yrs	0.04 (-0.05, 0.12)	0.403	0.01 (-0.07, 0.10)	0.768
Back muscle endurance	**-0.002 (-0.002, -0.001)**	**<0.001**	**-0.001 (-0.001, -0.0006)**	**<0.001**
BMI	N/A	N/A	0.06 (0.05, 0.10)	<0.001
Constant	1.02 (0.97, 1.08)	<0.001	-0.29 (-0.44, -0.14)	<0.001

N= 2325 observations from 1491 participants

Supplementary Table 8: Longitudinal linear mixed model for the association between back muscle endurance and log triglycerides over time

	Unadjusted model		BMI adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	-0.0001 (-0.04, 0.04)	0.996	-0.04 (-0.08, -0.004)	0.033
Sex Male	-0.09 (-0.13, -0.04)	<0.001	-0.07 (-0.11, -0.03)	0.001
Year*sex				
17 yrs	0.10 (0.04, 0.15)	<0.002	0.09 (0.03, 0.14)	0.002
Back muscle endurance	**-0.0009 (-0.001, -0.0006)**	**<0.001**	**-0.0004 (-0.0007, -0.0001)**	**0.007**
BMI	N/A	N/A	0.03 (0.02, 0.03)	<0.001
Constant	0.03 (-0.007, 0.07)	0.112	-0.58 (-0.69, -0.47)	<0.001

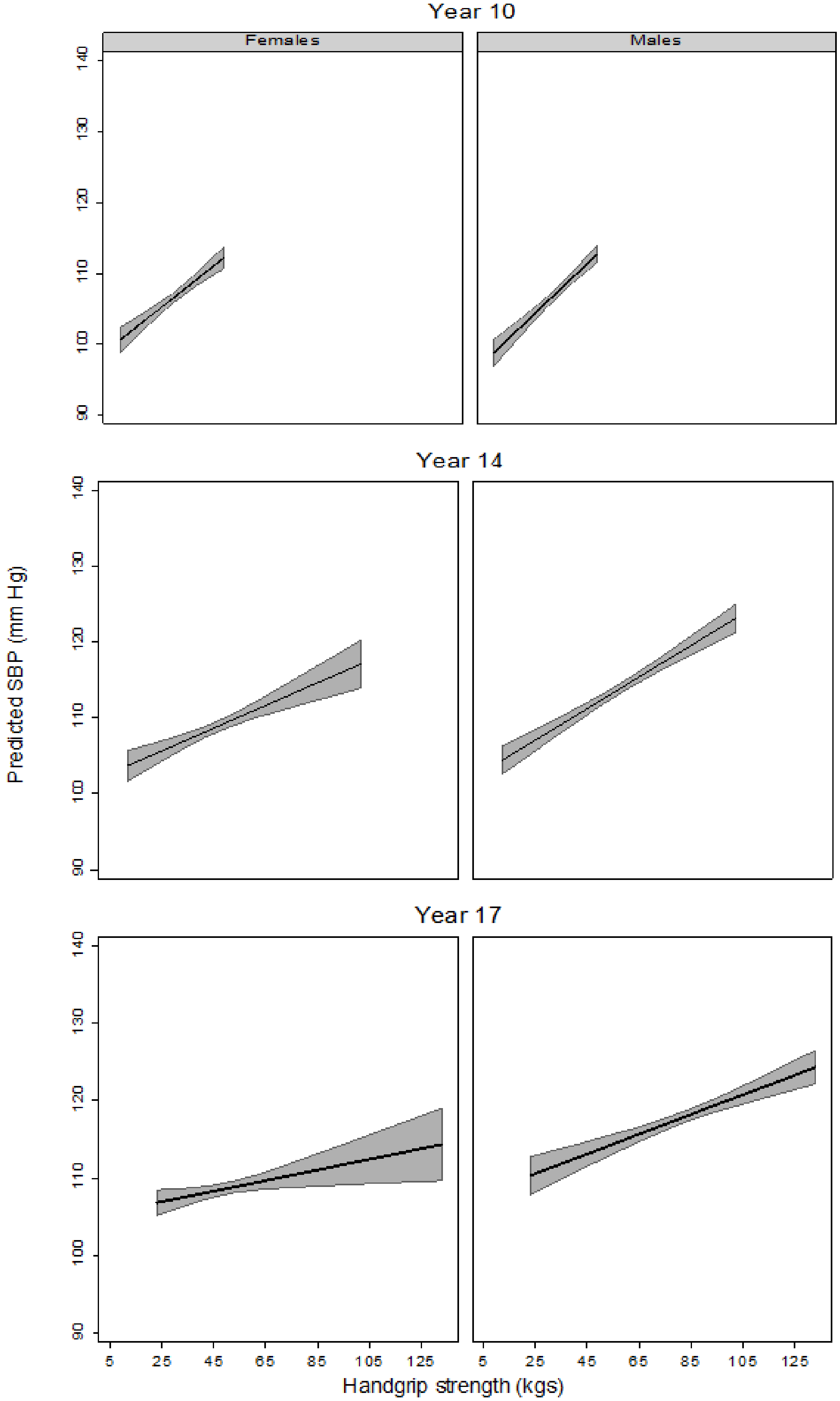
N= 2325 observations from 1491 participants

Supplementary Table 9: Random effects tobit model for the association between back muscle endurance and log hs-CRP over time

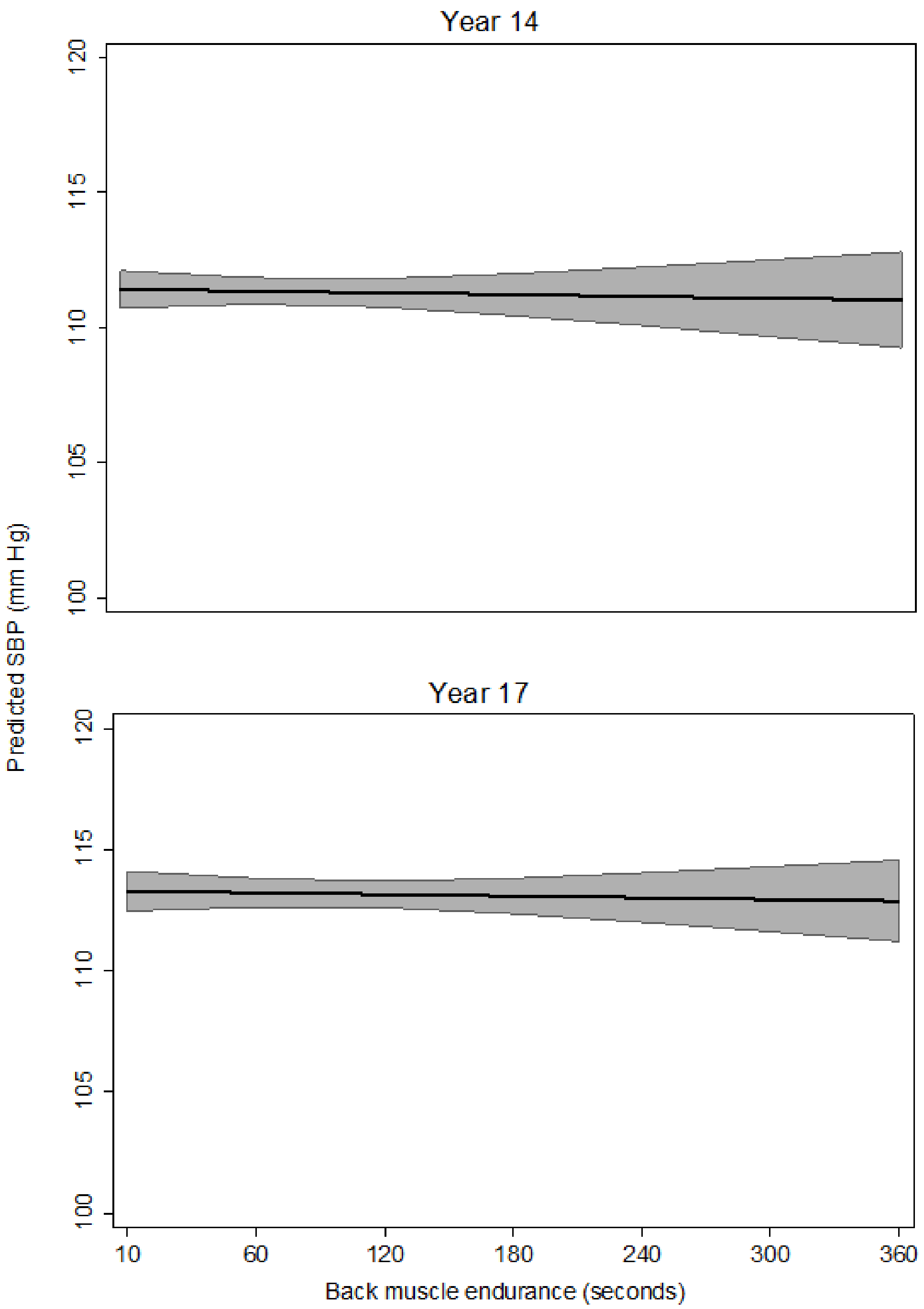
	Unadjusted model		BMI adjusted model	
	Coefficient (95% CI)	**P value**	**Coefficient (95% CI)**	**P value**
Year				
17 yrs	0.45 (0.32, 0.59)	<0.001	0.34 (0.21, 0.46)	<0.001
Sex Male	0.10 (-0.04, 0.25)	0.169	0.15 (0.02, 0.29)	0.029
Year*sex				
17 yrs	-0.58 (-0.76, -0.39)	<0.001	-0.60 (-0.78, -0.43)	<0.001
Back muscle endurance	**-0.003 (-0.004, -0.002)**	**<0.001**	**-0.001 (-0.002, -0.0002)**	**0.018**
BMI	N/A	N/A	0.10 (0.09, 0.12)	<0.001
Constant	-0.31 (-0.44, -0.18)	<0.001	-2.81 (-3.14, -2.49)	<0.001

N= 1895 observations from 1337 participants

Supplementary Figure 1. Handgrip strength and systolic BP at 10, 14 and 17 years (mean and 95% CI's represented) generated from longitudinal linear mixed models



Supplementary Figure 2. Back muscle endurance and systolic BP at 14 and 17 years (mean and 95% CI's represented) generated from longitudinal linear mixed models



Supplementary Figure 1. Handgrip strength and systolic BP at 10, 14 and 17 years (mean and 95% CI's represented) generated from longitudinal linear mixed models

Supplementary Figure 2. Back muscle endurance and systolic BP at 14 and 17 years (mean and 95% CI's represented) generated from longitudinal linear mixed models