Abstract

Background: Clinical evidence shows that muscle-strengthening exercise (MSE) is important for the treatment and management of hypertension. However, the links between MSE and hypertension in epidemiological research are currently poorly understood. This study examines the association between MSE duration and volume with clinically assessed hypertension.

Methods: Cross-sectional data (*n* = 10,519, adults ≥16 years) were pooled from the Health Survey for England (2012, 2016). Self-reported MSE mode (own bodyweight; gym-based), duration, and volume were tested for associations with sphygmomanometer measured hypertension (SBP ≥130 mmHg or DBP ≥ 80 mmHg). Poisson regressions with robust error variance were used to calculate the prevalence ratios (PR) of hypertension (outcome variable) across MSE (exposure variables: duration (minutes (0 [reference]; 10-20; 21-59; ≥60/session); and volume (0 [reference]; low <mean; high ≥mean/week) for each mode and the modes combined.

Results: Most adults (81.1%) did no MSE. However, in those who did (n=1,984), undertaking any MSE, regardless of mode, duration or volume, was associated with a reduced likelihood of hypertension (adjusted prevalence ratios (APRs) 0.61-0.90). When compared to the reference groups (no MSE), some modes had more favourable associations (e.g., ≥60 minutes/session of own bodyweight MSE; ≥mean minutes/week of gym-based MSE).

Conclusions: Irrespective of duration or volume, MSE was associated with a lower prevalence of clinically assessed hypertension. Public-health campaigns and other interventions that successfully promote small-to-moderate increases in MSE participation may reduce the prevalence of hypertension.

Keywords: resistance exercise, prevalence, blood pressure, physical activity, duration

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Background

Hypertension and cardiovascular disease are globally among the leading causes of morbidity and mortality [1] and are associated with over 10 million deaths annually [2]. Regular physical activity is a key non-pharmacological and relatively side-effect-free treatment option for the prevention and management of hypertension. For overall health and well-being, including blood pressure control, the 2020 World Health Organisation (WHO) 'Guidelines on physical activity and sedentary behaviour' state that adults (18–64 years) should undertake "*at least 150-300 minutes of moderate-intensity aerobic physical activity"* or do *"at least 75-150 minutes of vigorous-intensity aerobic physical activity"* or *"an equivalent combination of moderate- and vigorous-intensity activity*" throughout the week [3] and muscle-strengthening exercise "*at moderate or greater intensity*" targeting "*all the major muscle groups ... on two or more days a week*" [3]. At present, the epidemiological evidence on linking physical activity to a reduced risk of hypertension is largely based on studies of aerobic physical activity, i.e. walking, running or cycling [4,5]. Meta-analysis of cohort studies shows a negative dose-response association between aerobic moderate-to-vigorous physical activity (aerobic MVPA: walking, cycling, running etc.) and risk of hypertension [4,5].

More recently, several meta-analyses of evidence from clinical exercise studies suggest that muscle-strengthening exercise may also be important in the treatment management of hypertension. For example, a meta-analyses by MacDonald et al [6] found positive dose-response associations between dynamic muscle-strengthening exercise and reductions in blood pressure in hypertensive, prehypertensive and normotensive

populations. Similarly, Cornelissen and Smart [7] found the strongest dose-response associations within prehypertensive participants rather than in hypertensive/normotensive participants. Furthermore, Ashton et al., [8] identified negative blood pressure associations amongst participants who undertook muscle-strengthening exercise [8].

While these studies provide insights into the benefits of muscle-strengthening exercise on hypertension in controlled laboratory settings, few studies have examined these associations at the population level. A recent large cross-sectional study showed that among a sample of 1.5 million adults, compared to those doing none, any muscle-strengthening exercise was associated with a lower prevalence of hypertension [9]. However, the key limitations of that study were the sole focus on the frequency of muscle-strengthening exercise participation (times/week), self-reported hypertension, and non-reporting of anti-hypertensive medications [9]. Therefore, at the population level, there is a limited understanding of the links to other muscle-strengthening exercise participation parameters (i.e., duration, volume) and the association with clinically assessed blood pressure. It is important to develop an understanding of the dose-dependent associations between the duration and volume of different muscle-strengthening exercise modes, and associations with blood pressure. Such information will be essential for future adjunct therapy recommendations in the treatment and management of hypertension. Moreover, this research may be used to develop physical activity guidelines aimed at reducing the risk of hypertension at the population level.

Therefore, the aim of this study is to describe the association between duration and volume of muscle-strengthening exercise and the prevalence of clinically assessed hypertension, among a large population-based sample of adults.

Methods

Sample

In this cross-sectional study, we drew data from The Health Survey for England (HSE). Since the background information on the HSE has been described elsewhere [10], we will provide details relevant to the current study. Since 1991 the HSE has collected health and related data from free-living members of the English public [11,12]. Physical activity-related data are assessed every four years from a targeted national representative population sample of English-speaking children, and adults aged 16 years and older, living in private households [13]. Each iteration of the HSE is subject to ethical approval [10,13]. Data are collected face-to-face by trained researchers using a standard survey instrument, and informed consent was obtained from all participants [13], with data subsequently made available for research purposes. In the current study, we used the data from the two most recent HSE waves (2012 and 2016) (n = 20,400).

Data inclusion/exclusion

Data from participants aged 16 years and older, who undertook a clinical blood pressure assessment, were included in our study. Participants were excluded if they had missing demographic (age) information (20.1%, n = 4,099) or they did not respond to the question about taking prescribed drugs for blood pressure (28.3%, n = 5,782). The final

sample in the present study, therefore, contained 10,519 participants (see Supplemental Digital Content 1, for the participant flow diagram).

Exposure variable: Muscle-strengthening exercise (mode, frequency, and duration)

Self-reported muscle-strengthening exercise was assessed using an interview-led questionnaire [10,13]. Participants were shown a card (see Supplemental Digital Content 2) [14] and asked: *"Can you tell me if you have done any activities on this card during the last 4 weeks?"* including *"teaching, coaching, training and practice sessions".* In the current study, we selected the responses: *"Workout at a gym/Exercise bike/Weight training"* and *"Exercises (e.g. press-ups, sit-ups)"* for inclusion. The frequency of participation was assessed by asking *"Can you tell me on how many separate days you did (name of activity) for at least 10 minutes a time during the past four weeks?"*; and duration (reported in minutes) was assessed by asking *"How much time did you usually spend doing (name of activity) on each day?"* Participants were asked to only include "*times you did it for at least 10 minutes".*

Participants who reported *"Workout at a gym/Exercise bike/Weight training"* were then shown a card (see Supplemental Digital Content 3) [14] and asked: *"What did you do specifically?"* (options included: (i) strength work out at the gym using machines or free weights; (ii) exercise bike; (iii) spinning classes; (iv) stepping machine, rowing machine or cross trainer; and (v) treadmill running). Participants reporting *"Strength work out at a gym using machines or free weights"* were included in our study, along with their frequency (number of separate days) and duration (time [reported in minutes] spent doing the activity on each day, for at least 10 minutes) data. While the reliability and

validity of the muscle-strengthening items contained within the HSE surveillance instrument have not been examined [15], similar items have shown evidence of excellent test-retest reliability (Cohen's kappa (κ) = 0.85; 95% CI: 0.71-0.99) and moderate validity (κ = 0.40; 95% CI: 0.20-0.60) [16].

Based on the above questions, we categorised muscle-strengthening exercise into two modes: (i) 'own bodyweight exercises', or (ii) 'gym-based strength work' (working out with weights). We then combined these data to create a third category 'all muscle-strengthening exercise' (all MSE).

Classification of muscle-strengthening exercise (duration and volume)

Data for muscle-strengthening exercise session duration (minutes) were collapsed into one of four groups: (i) none/0 minutes; (ii) low duration (10-20 minutes); (iii) moderate duration (21-59 minutes); or (iv) high duration (≥60 minutes) for each muscle-strengthening exercise mode (own bodyweight exercises, gym-based strength work, and all MSE) (see Table 2, Figure 1, and Supplemental Digital Content 4).

To classify the weekly volume of muscle-strengthening exercise (own bodyweight exercises and gym-based strength work), we first multiplied the reported frequency (days in the last four weeks) by the reported duration (session), then divided this result by four to obtain the average weekly volume for each mode respectively. For all MSE, we combined the total volume for each mode (own bodyweight exercises and gym-based strength work), then divided this result by four to arrive at the average weekly figure. We then derived the mean volume values (minutes/week) for each of the three

exposure variables: (i) own bodyweight exercises (76.5 minutes/week); (ii) gym-based strength work (96.3 minutes/week); and (iii) all MSE (106.2 minutes/week). Data for each of the three exposure variables were then collapsed into one of three groups: (i) none (0); (ii) low volume (< mean minutes/week); or (iii) high volume (≥ mean) (see Table 2, Figure 2, and Supplemental Digital Content 4).

Outcome variable: Clinically assessed blood pressure (Hypertension)

Following standard protocols, resting blood pressure was measured three times by a trained research nurse. Using an Omron HEM 907 monitor, systolic (SBP) and diastolic (DBP) blood pressure was measured in millimetres of mercury (mmHg) [10]. The mean values for each measure (SBP and DBP) were computed and reported in the available research data.

Based on existing research and established cut points [17], we classified blood pressure as follows: (i) normal (<120 mmHg SBP and <80 mmHg DBP); (ii) elevated (120-129 mmHg SBP and <80 mmHg DBP); (iii) hypertensive (≥130 mmHg SBP or ≥80 mmHg DBP). We categorised the mean values for SBP (as either <130 mmHg or ≥ 130 mmHg) and DBP (as either <80 mmHg or ≥ 80 mmHg). According to the established cut points [17], we combined these data and then collapsed them further, categorising each participant as either: (i) not hypertensive (SBP <130 mmHg and DBP <80 mmHg) or (ii) hypertensive (SBP ≥130 mmHg or DBP ≥80 mmHg).

Covariates/confounders

Sociodemographic factors, modifiable lifestyle factors, aerobic MVPA, and sedentary behaviour were selected a priori because previous literature has highlighted their potential influence on participation in muscle-strengthening exercise and hypertension [18-23]. Self-reported data included: (i) sex, (either male or female); (ii) age in 10-year brackets; (iii) education (assessed as the highest level obtained or level of qualification), and (iv) total household income before tax (equivalised into income tertiles). Additionally, data for the consumption of alcohol were collapsed into those who reported either (i) 'less than weekly/not at all/non-drinkers', or (ii) 'weekly alcohol consumption'. Smoking status was collapsed into those who (i) 'never smoked cigarettes at all', (ii) 'ex-smoker', or (iii) 'current cigarette smoker'. Data for the taking of medication due to high blood pressure were collapsed into those either (i) 'not taking drug' or (ii) 'taking drug'. Concerning longstanding illness, participants were asked "*Do you have any physical or mental health conditions or illnesses lasting or expected to last 12 months or more?"*, with response options either (i) 'yes' or (ii) 'no'.

Anthropometric measures were assessed by a nurse using standard measurement protocols and included: (i) height (using a portable stadiometer, recorded to the nearest millimetre) and (ii) weight (using SECA 877 scales, and recorded in kilograms and grams) [10]. Body mass index (BMI) was calculated by dividing participant weight by their height in metres squared [12]. Standard classifications for BMI were applied: (i) underweight <18.5 kg/m^2; (ii) normal weight ≥18.5 kg/m^2 to <25 kg/m^2; (iii) overweight 25 kg/m^2 to <30 kg/m^2; (iv) obese ≥30 kg/m^2 [12].

For minutes/week of aerobic MVPA (including activities such as heavy housework, gardening, work-based occupational activities, brisk walking, athletics, aerobic, and swimming) [24], based on current global guidelines, we classified participants as either: (i) 'inactive'(<30 minutes/week), (ii) 'insufficiently active' (30-149 minutes/week) and not meeting the aerobic MVPA guideline; or (iii) 'active' (≥ 150 minutes/week) [12]. To assess sedentary time, participants were asked to report their average daily time spent: (i) watching TV (including DVDs and videos) and (ii) in any other sitting (reading, studying, and computer use). High levels of sedentary time are often classified within the literature as those with sitting time ≥480 minutes a day [25]. Therefore, we combined the data for these two contexts (watching TV, and other sitting) then collapsed them into either (i) low sedentary behaviour (<480 mins/day) or (ii) high sedentary behaviour (≥480 mins/day).

Statistical analysis

We pooled data from two existing HSE data sets (2012 and 2016), and harmonised and reviewed the data for missing values prior to our analysis. To improve the population representativeness of our analysis we weighted the data, with weighting factors provided by the HSE [12], to account for clustering and non-response. Descriptive statistics were used to describe the profile of the sample according to the outcome variable and covariates (see Table 1) and the three respective muscle-strengthening exercise exposure variables (see Table 2). Significance was set at $p < 0.05$ throughout our analyses.

The associations of having hypertension with each muscle-strengthening exercise mode (for duration/session and volume/week) were assessed using Poisson regression analysis, with robust error variance to calculate prevalence ratios (PR) with 95% confidence intervals. Poisson regression examined the PR for clinically assessed hypertension (outcome variable) according to the three muscle-strengthening exercise categories (exposure variable). In all regression models, the reference category was those doing no muscle-strengthening exercise (0 minutes = duration; and none = volume). We conducted four models to examine the potential effects of covariates: Model A 'unadjusted', Model B (adjusted for sociodemographic factors: sex; age; education; and income tertiles); Model C (adjusted for Model B and lifestyle factors: BMI; weekly alcohol consumption; smoking status; taking blood pressure medication; and longstanding illness); and Model D (adjusted for Model C in addition to weekly aerobic MVPA and weekly sedentary time). Prior to our analysis, we tested for multicollinearity among the potential covariates, using tests for the variance inflation factor (VIF). A VIF ≥2 indicates multicollinearity [26]. The VIF values ranged from 1.04 to 1.30, indicating no evidence of multicollinearity.

To enable a more robust interpretation of the results, we performed several sensitivity analyses. First, given that hypertension [27,28] and muscle-strengthening exercise have been shown to differ by sex and age [8,9,29], we conducted sex (males vs females) and age (16-54 years vs ≥55 years) stratified analyses. Second, since BMI [30] and smoking [31] can impact both hypertension and muscle-strengthening exercise [9], we also stratified the sample by BMI (underweight/normal vs overweight/obese) and smoking status (never smoked vs current smoker). Third, as the presence of having a

longstanding illness [18] is likely to affect muscle-strengthening exercise participation, to minimise the risk of reverse causation, we stratified the sample by reporting having a longstanding illness ('no' vs 'yes'). Last, to compare the effects of participation in aerobic MVPA [6], we created two groups (i) 'insufficiently active' (<149 minutes/week); and (ii) 'sufficiently active' (≥150 minutes/week).

In further analysis we compared the HSE data using the American [17] and European [32] hypertension cut points. For this analyses we applied the established European cut points [32] which classify blood pressure as: (i) optimal (<120 mmHg SBP and <80 mmHg DBP); (ii) normal (120-129 mmHg SBP and/or 80-84 mmHg DBP); (iii) high normal (130-139 mmHg SBP and/or 85-89 mmHg DBP); hypertensive (≥140 mmHg SBP and/or ≥90 mmHg DBP). We categorised the mean values for SBP (as either <140 mmHg or ≥ 140 mmHg) and DBP (as either <90 mmHg or ≥ 90 mmHg). According to the established cut points [32] we combined these data and then collapsed them further, categorising each participant as either: (i) not hypertensive (SBP <140 mmHg and DBP <90 mmHg) or (ii) hypertensive (SBP ≥140 mmHg or DBP ≥90 mmHg). Furthermore, additional analysis was conducted using mean values for SBP and DBP. All data analyses were conducted using Statistical Package for the Social Sciences version 26 (SPSS Inc., an IBM Company, Armonk, NY).

<Insert Table 1 here>

Results

Sample description

Data from 10,519 adults aged ≥16 years were included in our analysis. The sample characteristics are shown in Table 1. In brief, over half were female (56.3%), one-third were either aged between 35-54 years (32.8%) or 55-74 years (34.5%), and 35.3% represented in the highest household income. Over half were classified as either overweight or obese (64.8%), reported weekly alcohol consumption, approximately half had never smoked, and just over a quarter self-reported having a longstanding illness. Over half (60%) reported sufficient MVPA, and most (86.9%) had low levels of sedentary behaviour. Just under half were classified as hypertensive (according to the ACC/AHA guidelines), with is number reducing to ~22% when adopting the ESC/ESH classification for hypertension, with under a quarter of the sample taking prescribed medication of blood pressure (18.6%) (see Table 1).

<Insert Table 2 here>

The muscle-strengthening exercise behaviour characteristics of the sample are described in Table 2. In brief, over 85% of participants reported doing no own bodyweight exercise, with just over 90% reporting doing no gym-based strength work. Some participants (18.9%) reported doing both modes of muscle-strengthening. The highest prevalence of those who reported doing either mode (own bodyweight or gym-based strength work) or the modes combined (all MSE) was for bouts of between 10-20 minutes/session.

Prevalence ratios for clinically assessed hypertension

The unadjusted and adjusted prevalence ratios (APRs) for hypertension are shown in Supplemental Digital Content 4. Since the prevalence ratios (PRs) were similar, after adjusting for sociodemographic characteristics, sedentary time, and MVPA, we will only present the results of the most adjusted model (Model D) here (all data shown in Supplemental Digital Content 4).

Figure 1 shows the associations between the session duration categories of the three muscle-strengthening exercise exposure modes and hypertension. When compared to the reference group (0 minutes), the APRs for each muscle-strengthening exercise mode followed an inverse linear-gradient for own bodyweight (APRs 0.78; 0.75; 0.61), gym-based strength (APRs 0.90; 0.76; 0.66); and all MSE (APRs 0.83; 0.78; 0.65) for 10-20; 21-59; and 60+ minutes/session respectively.

<Insert Figure 1 here>

Figure 2 shows the associations between muscle-strengthening exercise volume (none, <mean, ≥mean) and hypertension. An inverse linear-gradient (< mean; ≥ mean respectively) was observed for the total weekly volumes for gym-based strength (APRs 0.84; 0.70) and all MSE (APRs 0.79; 0.74) with the lowest APRs observed when undertaking high volumes (≥mean), compared to those doing none (reference group). However, a linear trend was observed among those doing own bodyweight exercise (APRs 0.74; 0.80) with the lowest APRs for undertaking < mean (low volume) when compared to the reference group (none).

<Insert Figure 2 here>

Analyses using mean data

Furthermore, we completed unadjusted analyses using the calculated mean values for both SBP and DBP (Supplemental Digital Content 4.3). Overall, the inverse linear trends remained similar for each muscle-strengthneing exercise mode (own bodyweight and gym-based strength), and the modes combined. However, the most favourable reductions in combined SBP and DBP were seen amongst those who reported ≥ 60 minutes/session of gym-based strength exercise. We observed an overall difference in SBP of 4.99 mmHg in this group, when compared to those who did none (0 minutes/session), and a difference of 5.61 mmHg in DBP. The most favourable reductions in SBP and DBP were also seen in those reporting ≥mean/week of gym-based strength exercise, compared to those reporting none (-4.26 mmHg SBP, and -4.98 mmHg DBP).

Sensitivity analyses

Analyses stratified for sex, age, BMI, smoking status, longstanding illness, and aerobic MVPA variables are shown in the supplemental digital content files (Supplemental Digital Content 5 and Supplemental Digital Content 6). In brief, similar associations between 'all MSE' (duration/session) and hypertension were observed among males (APR range: 0.64-0.92) vs. females (APR range: 0.58-0.72), younger (16-54 years) (APR range: 0.77-0.90) vs. older adults (≥55 years) (APR range: 0.76-0.98), and underweight/normal BMI (≤ 24.99 kg/m^2) (APR range 0.63-0.70) vs. overweight/obese (BMI ≥ 25.0 kg/m^2) (APR range 0.73-0.99).

When compared to those who had never smoked (APR range: 0.62-0.84), the associations between all MSE (duration/session) and hypertension were generally stronger among current smokers (APR range: 0.57-0.72). Compared to those who reported having a longstanding illness, (APR range: 0.73-1.05), the associations were mixed, with only those who reported having no longstanding illness and a duration/session greater than 60 minutes (APR 0.61; 95% CI: 0.47-0.76) showing the strongest association. Amongst those assessed as either sufficiently active (≥150 MVPA minutes/week) (APR range 0.68-0.87), or insufficiently active (≤149 MVPA minutes/week), all APRs were lower (APR range 0.66-0.84). For all MSE durations/session (compared to those doing none), with the strongest associations for both groups (sufficient/insufficient) amongst those reporting ≥60 minutes of all MSE.

For volume per week of all MSE, for the sensitivity analyses, we found similar associations with hypertension as those for duration/session. Briefly, the associations were stronger in females (APR range 0.59-0.69) vs males (APR range 0.74-0.85), younger (APR range 0.79-0.84) vs. older adults (APR range 0.92-0.97), underweight/normal BMI (APR range 0.63-0.76) vs. overweight/obese (0.80-0.94), current smokers (APR range 0.51-0.72) vs. those who had never smoked (APR range 0.78-0.79), without longstanding illness (APR range 0.72-0.81) vs. reporting having a longstanding illness (APR range 0.76-0.92), and those assessed as sufficiently active (APR range 0.76-0.82) vs. insufficiently active (APR range 0.78-1.10).

Additional stratified analyses were completed using the ESC/ESH classification for hypertension [32], with adjustments for sex, age, BMI, smoking status, longstanding illness, and aerobic MVPA variables shown in the supplemental digital content files (Supplemental Digital Content 5.1 and Supplemental Digital Content 6.1). In brief, similar associations between 'all MSE' (duration/session; volume/week) and hypertension were found, with the trends remaining similar using the American and European classifications, except for age (duration per session and volume per week) and smoking status (duration per session) (see Supplemental Digital Content 5.2 and 6.2).

Discussion

Among a large community sample of adults, any muscle-strengthening exercise, irrespective of mode, duration or volume, was associated with a lower prevalence of clinically assessed hypertension. In addition, there was evidence for a dose-dependent association between the duration and volume of muscle-strengthening exercise and hypertension. Moreover, all associations remained after the adjustment for key confounding factors (e.g. age, sex, income, aerobic MVPA, sedentary behaviour). Additionally, associations between muscle-strengthening exercise remained overall similar regardless of the classification used to define hypertension, and when SBP and DBP were expressed as mean values. While these findings need to be replicated in future prospective studies, our results suggest that undertaking any muscle-strengthening exercise (regardless of mode, duration or volume) may be protective against hypertension.

The epidemiological evidence describing the relationship between hypertension and the volume and duration of aerobic MVPA is well established [4,5,33]. However, despite the strong clinical evidence linking muscle-strengthening exercise to a reduced risk of hypertension [7,18,20], few epidemiological studies have examined this relationship at the population level. In comparison to the limited previous research, we found similar associations between muscle-strengthening exercise and prevalent hypertension as those from large cross-sectional studies by Bennie et al., [9] and Loprinzi and Loenneke [34] . However, those studies only focused on muscle-strengthening exercise frequency (times/week). Our study is important because it is the first to assess the additional components of duration and volume of muscle-strengthening exercise and their relationship with prevalent hypertension.

Due to the cross-sectional nature of this study, we are not able to comment on the length of time that participants have been undertaking muscle-strengthening exercise (data not provided). However, in comparison to a recent review and meta-analysis [8], on the effects of muscle-strengthening exercise on cardiometabolic health outcomes, our data showed similar reductions in SBP and DBP compared to those reporting no muscle-strengthening exercise. These results add to the body of knowledge regarding the positive effects of undertaking muscle-strengthening exercise on clinically assessed blood pressure. Reaffirming the benefit of this exercise modality as possible adjunct therapy in the treatment and management of hypertension.

The multiple sensitivity analyses (sex, age, BMI, smoking status, longstanding illness, and aerobic MVPA) suggested that with very few exceptions most associations between

muscle-strengthening exercise and the risk of hypertension were similar. Amongst our sample, however, those with a longstanding illness (undertaking all MSE for a duration/session of ≥60 minutes), or those reporting insufficient aerobic MVPA (undertaking all MSE at volumes >106 minutes/week), were at an increased risk of hypertension (APR range 1.05-1.10). This possible negative relationship between hypertension, insufficient aerobic MVPA and higher volumes of muscle-strengthening exercise was also evident in the study by Bennie et al. [35]. Despite this, overall our results add further support to future health promotion messaging that doing some muscle-strengthening exercise is better than none. Additionally, these findings support the continued prescription of muscle-strengthening exercise might be a valid adjunct therapy in the prevention and treatment management of hypertension.

There are several physiological mechanisms that may explain the relationship between muscle-strengthening exercise and hypertension observed in the current study. However, it should be acknowledged that there is limited, and often conflicting, evidence concerning the specific mechanisms of this exercise mode and its hypotensive effect [36,37]. Some studies report mixed findings concerning changes in endothelial function (e.g., altered sympathetic tone) [38], arterial compliance [39], sympathetic activity [40-42], variability in cardiac output [42], and arterial elasticity [36,43] as potential mechanisms explaining the relationship between muscle-strengthening exercise and hypertension. Importantly, however from a health promotion perspective, within these studies [36,39,40,43,44] there is no evidence of harm linked with doing muscle-strengthening exercise. Moreover, it has been argued that the additional physiological benefits of doing muscle-strengthening exercise (increase in lean body

mass, improved VO_2max, reduced abdominal fat [8,45], and improved insulin sensitivity [8]) may provide for alternative mechanisms in reducing blood pressure in prehypertensive and hypertensive populations.

While most physical activity guidelines include recommendations for undertaking muscle-strengthening exercise "*on at least two days a week*" [46], currently they do not include recommendations for duration nor volume. This ongoing gap in research, that there need to be more studies examining the dose-response association between MSE and health outcomes, was highlighted in the 2020 WHO guidelines [3]. The largest portion of our sample undertook own bodyweight exercise for session durations between 10-20 minutes, and at a lower total weekly volume. However, it should be highlighted that over 85% of our sample did no own bodyweight exercise, which suggests most adults do not routinely engage in this exercise mode.

From a public health promotion perspective, our findings suggest that among those currently doing none, small to moderate increases in muscle-strengthening exercise may have a positive influence on hypertension, regardless of muscle-strengthening exercise mode (own body weight vs gym-based). Globally the level of participation in muscle-strengthening exercise is low when compared to other exercise modes such as aerobic MVPA [35,47,48]. Therefore, a way to increase participation in muscle-strengthening exercise, at the population level, could be to include messaging that highlights the relative simplistic nature of performing such exercise, such as own bodyweight exercises (i.e. no; special equipment; facilities; knowledge; or support required from trained professionals). Our results may suggest that future promotion of muscle-

strengthening exercise should also contain the message that "doing some is better than doing none", and this is consistent with the 2020 WHO 'good practice statements' [49]. As the world continues to face the challenges associated with the COVID-19 pandemic, it is timely that simple health promotion messaging is at the forefront, as many people may have had to modify their usual work and or exercise behaviours due to periods of lockdown or restrictions. Therefore, this portion of the population may be more receptive to what could be considered simple changes to their exercise behaviours that may indeed have a long-lasting and positive benefit on their health.

Strengths and limitations

A key strength of this study is that it is the first to explore the relationship between specific modes of muscle-strengthening exercise and clinically assessed hypertension, in a large population sample of adults. The use of data that has been gathered through standardised recruitment and data collection procedure is another strength, as our findings will be able to be compared with future HSE data and other large population surveillance studies.

Limitations of this study primarily include the use of cross-sectional data, this precluding statements regarding causality [50]. A further limitation includes the risks associated with using self-reported data, as the responses may have been influenced by responder recall bias (e.g., social desirability or over/under reporting of actual behaviour). The HSE survey instrument limits participant responses to those undertaking muscle-strengthening exercise bouts of at least 10 minutes or more, hence, we were not able to analyse if bouts of less than 10 minutes influenced the prevalence of

hypertension. Furthermore, the HSE does not assess muscle-strengthening exercise parameters such as sets, repetitions, target muscle-groups, tempo, or rest periods between exercises, which further limits the understanding of the benefits of this exercise modality and hypertension at the population level. Additionally, the indicator of having hypertension does not account for the temporality or severity of the condition, or for participant management of their condition. A further limitation was that our sample had a higher prevalence of those meeting the aerobic MVPA recommendations [24]. Additional research, amongst large populations, that includes the measurement of muscle-strengthening exercise intensity is also needed, as exercising at a lower intensity may have greater hypotensive effects than performing muscle-strengthening exercise at higher intensities [42].

Conclusion

Among a large sample of adults, compared to those doing no muscle-strengthening exercise, engaging in any (irrespective of mode, duration, or volume) was associated with a lower prevalence of clinically assessed hypertension. While prospective cohort studies are needed to confirm these preliminary findings, among those currently doing no muscle-strengthening exercise, small-to-moderate increase in participation in this exercise mode are likely to be beneficial in the prevention and management of hypertension at the population level.

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Authors' contributions

JSD, KDC, SJHB, and JAB conceptualised the study and developed the research plan. JSD conducted the data analysis. JSD drafted the initial manuscript. JAB, KDC, and SJHB provided guidance on the study and critically reviewed the manuscript. All authors read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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Table 1: Characteristics of participants included in the analysis [a]

Total sample of 2012 and 2016 Health Survey for England (n = 10,519)	
	Total sample % (n)
Sex	
Male	43.7 (4,594)
Female	56.3 (5,925)
Age (years)	
16-34	20.6 (2,171)
35-54	32.8 (3,452)
55-74	34.5 (3,625)
≥75	12.1 (1,271)
Education	
Graduate /degree	26.0 (2,732)
Higher education (below degree)	47.1 (4, 955)
No qualification	21.7 (2,277)
Student (full-time)	5.2 (546)
Income Tertiles	
Highest	35.3 (3,026)
Middle	34.0 (2,917)
Lowest	30.7 (2,638)
Body Mass Index (kg/m^2)	
Underweight (<18.5)	1.4 (132)
Normal (≥18.5-<25)	33.9 (3,184)
Overweight (25– <30)	37.7 (3,541)

Obese (≥30)	27.1 (2,548)
Smoking status	
Never smoked	50.3 (5,271)
Ex-smoker	33.5 (3,505)
Current smoker	16.2 (1,701)
Alcohol	
None (0)/less than weekly	45.9 (4,805)
Weekly	54.1 (5,670)
Hypertension (≥130 mmHg or ≥80 mmHg)[b]	
Yes	45.2 (4,003)
No	54.8 (4,858)
Prescribed medication for blood pressure	
Yes	18.6 (1,960)
No	81.4 (8,559)
Longstanding illness	
Yes	27.3 (2,865)
No	72.7 (7,647)
Aerobic MVPA level (minutes/week)	
<30 minutes/week 'inactive'	23.2 (2,438)
30-149 minutes/week 'insufficiently active'	16.6 (1,724)
≥ 150 minutes/week 'active'	60.0 (6,233)
Sedentary behavior (min/ day)	
Low (<480 minutes/day)	86.9 (9,114)
High (≥480 minutes/day)	13.1 (1,369)

[a] Numbers vary slightly because of missing data for some characteristic variables

Missing data equated to: education 0.1% (n=9), household income 18.4% (n=1,938), BMI 10.6% (n=1,114), alcohol consumption 0.4% (n=44), smoking status 0.4% (n=42), hypertension 15.8% (n=1,658), longstanding illness 0.1% (n=7), aerobic MVPA 1.2% (n=124), and sedentary behaviour 0.3% (n=36).

[b] Defined in 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: A report of the American college of cardiology/American heart association task force on clinical practice guidelines.

Table 2: Muscle-strengthening exercise behaviour characteristics of participants included in the analysis

Total sample of 2012 and 2016 Health Survey for England (n = 10,519)	
	Total Sample % (n)
Muscle- strengthening exercise – Duration (minutes/session)	
Own Bodyweight	
0 minutes	85.6 (9,006)
10-20 minutes	9.1 (960)
21-59 minutes	3.4 (355)
60+ minutes	1.9 (198)
Gym-based strength	
0 minutes	90.6 (9,530)
10-20 minutes	3.9 (406)
21-59 minutes	3.4 (362)
60+ minutes	2.1 (221)
All MSE [a]	
0 minutes	81.1 (8,533)
10-20 minutes	8.3 (875)
21-59 minutes	6.1 (637)
60+ minutes	4.5 (474)
Muscle- strengthening exercise – Volume (minutes/week)	
Own Bodyweight	
None	85.6 (9,006)
Low < mean [b]	10.8 (1,141)
High ≥ mean [b]	3.5 (372)
Gym-based strength	
None	90.6 (9,533)

Low < mean [c]	6.6 (694)
High ≥ mean [c]	2.8 (292)
All MSE [a]	
None	81.1 (8,535)
Low < mean [d]	13.9 (1,459)
High ≥ mean [d]	5.0 (525)

[a] All MSE: Own bodyweight and gym-based strength combined

[b] Mean value: Own bodyweight 76.5 minutes/week

[c] Mean value: Gym-based strength 96.3 minutes/week

[d] Mean value: All MSE 106.2 minutes/week

Figure 1

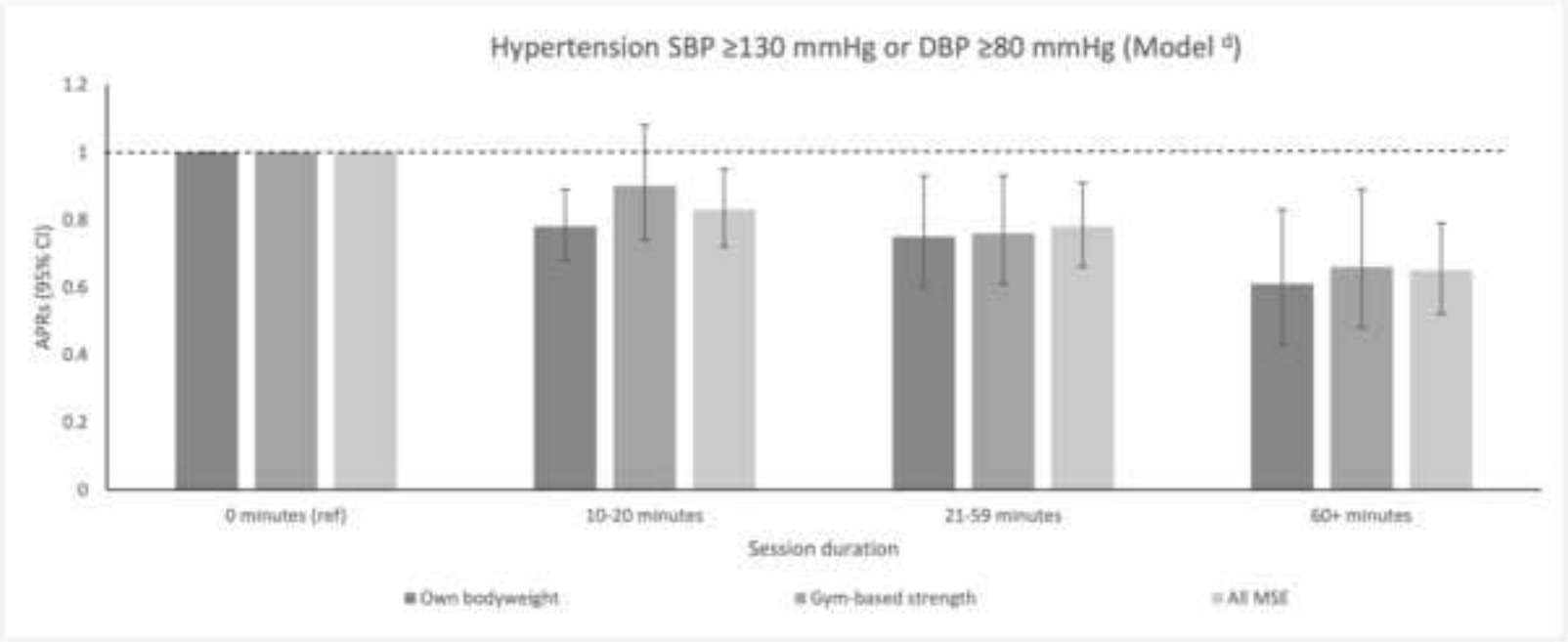


Figure 1. Analysis of the relationship between muscle-strengthening exercise (duration/ session) between clinically assessed hypertension relative to two specific modes of muscle-strengthening exercise, and modes combined (APRs; 95% CI).

APRs:	adjusted prevalence ratios, with 95% Confidence Interval (CI)
All MSE:	Own bodyweight and Gym-based strength combined
Model [d]	adjusted for sociodemographic factors (sex, age, education, income tertiles) and lifestyle factors (BMI, weekly alcohol consumption, smoking status, blood pressure medication, longstanding illness), weekly aerobic MVPA, and weekly sedentary time

Figure 2

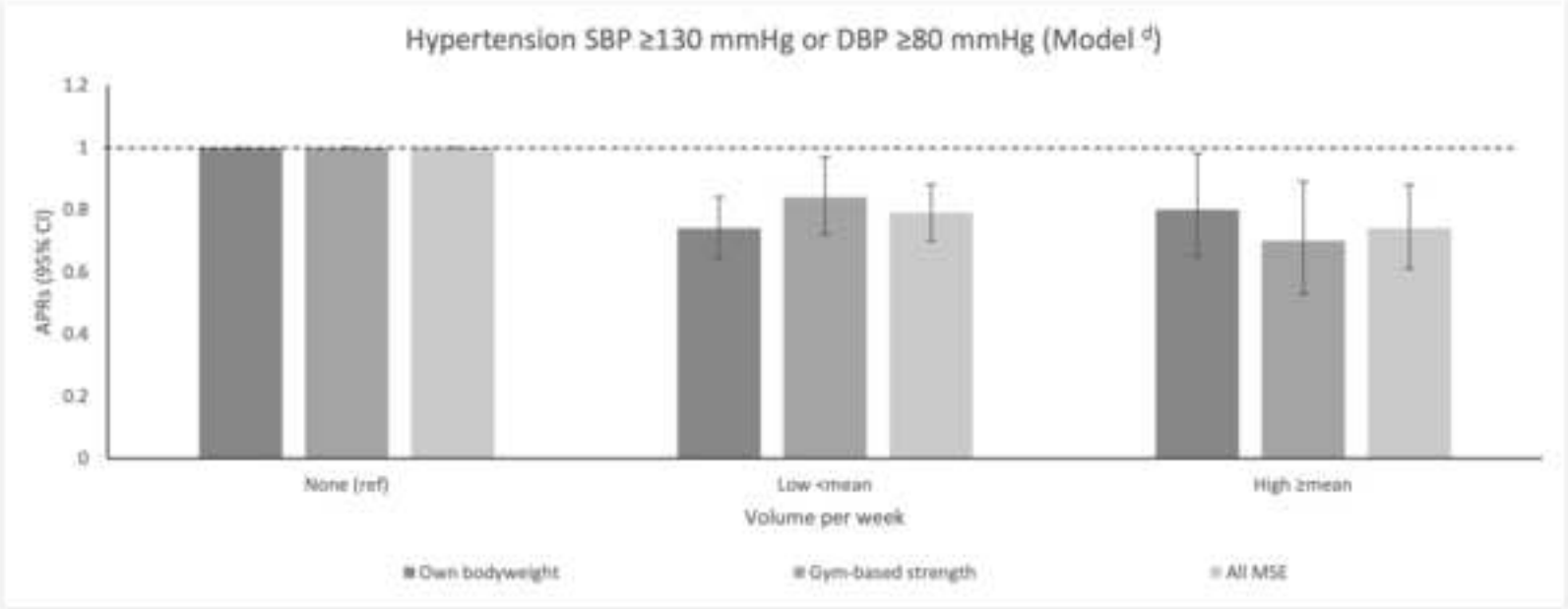
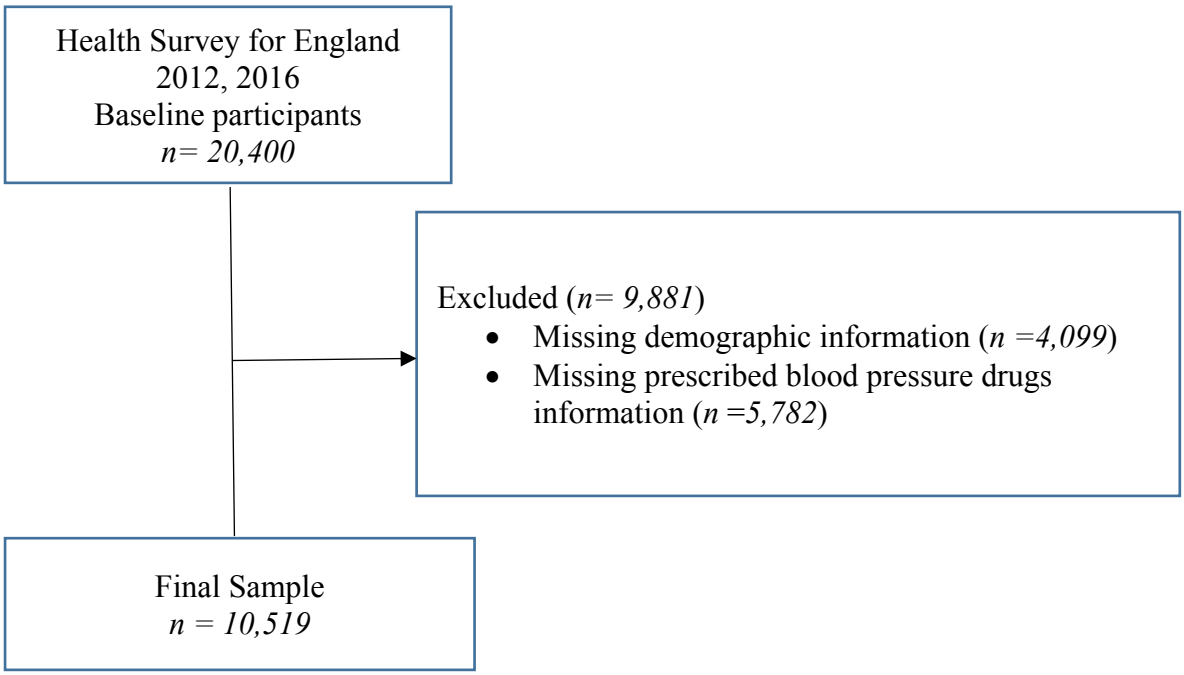


Figure 2. Analysis of the relationship between muscle-strengthening exercise (volume/week: frequency/week x duration/session) between clinically assessed hypertension relative to two specific modes of muscle-strengthening exercise, and modes combined (APRs; 95%CI).

APRs: adjusted prevalence ratios and 95% Confidence Intervals (CI)
All MSE: Own bodyweight and Gym-based strength combined
Model [d] adjusted for sociodemographic factors (sex, age, education, income tertiles) and lifestyle factors (BMI, weekly alcohol consumption, smoking status, blood pressure medication, longstanding illness), weekly aerobic MVPA, and weekly sedentary time
Mean values: own bodyweight 76.5 minutes/week, gym-based strength 96.3 minutes/week, all MSE 106.2 minutes/week

Supplemental Digital Content 1. Health Survey for England 2012 and 2016 participant flow diagram.



Supplemental Digital Content 2. Health Survey for England exercise show card E6

CARD E6

1 Swimming

2 Cycling

3 Workout at a gym/Exercise bike/Weight training

4 Aerobics/Keep fit/Gymnastics/ Dance for fitness

5 Any other type of dancing

6 Running/Jogging

7 Football/Rugby

8 Badminton/tennis

9 Squash

10 Exercises (e.g. press-up, sit-ups)

ActPhy/WhtAct

Supplemental Digital Content 3. Health Survey for England exercise show card E7

CARD E7

1 Strength work out at the gym using machines or free weights

2 Exercise Bike

3 Spinning Classes

4 Stepping machine, rowing machine or cross trainer

5 Treadmill running

WorkOut

Supplemental Digital Content 4. Analysis of the relationship between muscle-strengthening exercise (duration per session and volume per week) between hypertension according to two specific modes of muscle-strengthening exercise, and both modes combined (PRs; APRs; 95% CI).

Duration per session				
Own bodyweight exercises	Model A[a]	Model B[b]	Model C[c]	Model D[d]
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.80 (0.71-0.89)	0.80 (0.70-0.91)	0.78 (0.68-0.89)	0.78 (0.68-0.89)
21-59 minutes	0.78 (0.64-0.94)	0.78 (0.62-0.96)	0.76 (0.61-0.94)	0.75 (0.60-0.93)
60+ minutes	0.69 (0.52-0.89)	0.65 (0.48-0.87)	0.61 (0.43-0.83)	0.61 (0.43-0.83)
Gym-based strength exercises				
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.86 (0.72-1.01)	0.87 (0.72-1.04)	0.90 (0.74-1.08)	0.90 (0.74-1.08)
21-59 minutes	0.73 (0.60-0.89)	0.77 (0.62-0.94)	0.76 (0.61-0.93)	0.76 (0.61-0.93)
60+ minutes	0.70 (0.53-0.89)	0.65 (0.47-0.87)	0.66 (0.47-0.88)	0.66 (0.48-0.89)
All MSE				
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.83 (0.74-0.93)	0.85 (0.74-0.96)	0.83 (0.72-0.95)	0.83 (0.72-0.95)
21-59 minutes	0.77 (0.67-0.89)	0.78 (0.67-0.91)	0.78 (0.66-0.92)	0.78 (0.66-0.91)
60+ minutes	0.70 (0.59-0.83)	0.67 (0.55-0.82)	0.65 (0.52-0.79)	0.65 (0.52-0.79)
Volume per week (frequency x duration)				
Own bodyweight exercises [e]				
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.76 (0.68-0.84)	0.76 (0.67-0.85)	0.74 (0.65-0.84)	0.74 (0.64-0.84)
High ≥ mean	0.84 (0.70-1.00)	0.84 (0.69-1.01)	0.81 (0.65-0.98)	0.80 (0.65-0.98)
Gym-based strength exercises				
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.82 (0.71-0.93)	0.82 (0.71-0.95)	0.84 (0.72-0.97)	0.84 (0.72-0.97)
High ≥ mean	0.69 (0.55-0.86)	0.71 (0.55-0.90)	0.70 (0.53-0.90)	0.70 (0.53-0.89)
All MSE [e]				
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.78 (0.71-0.86)	0.80 (0.72-0.89)	0.79 (0.70-0.88)	0.79 (0.70-0.88)
High ≥ mean	0.78 (0.66-0.90)	0.76 (0.63-0.91)	0.74 (0.61-0.89)	0.74 (0.61-0.88)

MSE = muscle-strengthening exercise, PRs = prevalence ratios, APRs = adjusted prevalence ratios, CI = confidence interval

[a] Unadjusted model (Model A)

[b] Model B - adjusted for sociodemographic factors (sex, age groups in 10 years brackets, education, income tertiles)

[c] Model C - adjusted for sociodemographic factors (sex, age groups in 10 years brackets, education, income tertiles) and lifestyle factors (BMI, weekly alcohol consumption, smoking status, blood pressure medication, longstanding illness)

[d] Model D adjusted for sociodemographic factors (sex, age groups in 10 years brackets, education, income tertiles) and lifestyle factors (BMI, weekly alcohol consumption, smoking status, blood pressure medication, longstanding illness) and weekly aerobic MVPA and weekly sedentary time

[e] mean value: own bodyweight 76.5 minutes/week, gym-based strength 96.3 minutes/week, all MSE 106.2 minutes/week [low = below the mean, high = above the mean]

Supplemental Digital Content 4.3 Analysis of the relationship between muscle-strengthening exercise (duration per session and volume per week) between hypertension (mean values for SBP and DBP) according to two specific modes of muscle-strengthening exercise, and both modes combined (SD).

Duration per session		
Own bodyweight exercises	Mean SBP mmHg (SD)	Mean DBP mmHg (SD)
0 minutes	126.99 (17.48)	73.21 (10.88)
10-20 minutes	123.55 (15.91)	71.41 (10.34)
21-59 minutes	123.57 (16.24)	71.46 (11.88)
60+ minutes	121.49 (13.43)	70.42 (9.99)
Gym-based strength exercises		
0 minutes	126.79 (17.49)	73.15 (10.79)
10-20 minutes	123.97 (15.40)	72.56 (11.28)
21-59 minutes	123.34 (14.83)	71.07 (11.32)
60+ minutes	121.80 (13.41)	67.54 (10.91)
All MSE		
0 minutes	127.19 (17.57)	73.31 (10.83)
10-20 minutes	123.86 (16.61)	72.09 (10.46)
21-59 minutes	123.41 (15.51)	71.89 (11.40)
60+ minutes	122.40 (13.82)	69.33 (10.81)
Volume per week (frequency x duration)		
Own bodyweight exercises [e]		
None	126.99 (17.48)	73.21 (10.88)
Low < mean	123.09 (15.71)	71.25 (10.47)
High ≥ mean	123.86 (15.63)	71.42 (11.25)
Gym-based strength exercises		
None	126.79 (17.49)	73.15 (10.79)
Low < mean	123.57 (14.96)	72.05 (11.32)
High ≥ mean	122.53 (14.36)	68.17 (11.03)
All MSE [e]		
None	127.18 (17.57)	73.30 (10.83)
Low < mean	123.39 (15.80)	71.83 (10.69)
High ≥ mean	123.37 (15.24)	70.10 (11.38)

SBP = Systolic Blood Pressure
DBP = Diastolic Blood Pressure
MSE = muscle-strengthening exercise, SD = standard deviation

[e] mean value: own bodyweight 76.5 minutes/week, gym-based strength 96.3 minutes/week, all MSE 106.2 minutes/week [low = below the mean, high = above the mean]

Supplemental Digital Content 5. Adjusted Prevalence ratios (APR)[a] of hypertension[b] according to duration per session of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

	Hypertension[b]	
	Sex	
	Males	**Females**
All MSE	APR[c] (95% CI)	APR[c] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.92 (0.76-1.09)	0.72 (0.58-0.88)
21-59 minutes	0.83 (0.68-1.02)	0.65 (0.49-0.84)
60+ minutes	0.64 (0.49-0.82)	0.58 (0.40-0.82)
	Age	
	16-54 years	**≥55 years**
All MSE	APR[d] (95% CI)	APR[d] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.80 (0.65-0.98)	0.98 (0.82-1.17)
21-59 minutes	0.90 (0.72-1.10)	0.92 (0.70-1.19)
60+ minutes	0.77 (0.59-0.99)	0.76 (0.52-1.07)
	Body Mass Index (kg/m^2)	
	≤ 24.99 (underweight/normal)	**≥25.0 (overweight/obese)**
All MSE	APR[e] (95% CI)	APR[e] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.70 (0.53-0.91)	0.99 (0.84-1.15)
21-59 minutes	0.64 (0.45-0.88)	0.89 (0.74-1.07)
60+ minutes	0.63 (0.42-0.89)	0.73 (0.56-0.94)
	Smoking	
	Never smoked [i]	**Current smoker**
All MSE	APR[f] (95% CI)	APR[f] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.84 (0.70-1.01)	0.57 (0.31-0.96)
21-59 minutes	0.82 (0.65-1.01)	0.72 (0.39-1.20)
60+ minutes	0.62 (0.46-0.82)	0.69 (0.33-1.27)
	Longstanding illness	
	No	**Yes**
All MSE	APR[g] (95% CI)	APR[g] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.87 (0.74-1.01)	0.74 (0.51-1.03)
21-59 minutes	0.80 (0.67-0.96)	0.73 (0.48-1.08)
60+ minutes	0.61 (0.47-0.76)	1.05 (0.63-1.63)
	Aerobic physical activity level	
	Insufficiently active (0-149 MVPA minutes/week)	**Sufficiently active (≥150 MVPA minutes/week)**
All MSE	APR[h] (95% CI)	APR[h] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.84 (0.60-1.14)	0.87 (0.74-1.01)
21-59 minutes	0.74 (0.36-1.35)	0.82 (0.69-0.97)
60+ minutes	0.66 (0.24-1.42)	0.68 (0.54-0.84)

[a] PR calculated using Poisson regression with a robust error variance.

[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥130mmHg or DBP ≥80mmHg.

[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness and weekly sedentary behaviour.

[i] excludes ex-smokers

Supplemental Digital Content 5.1 Adjusted Prevalence ratios (APR)[a] of hypertension[b] according to duration per session of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

	Hypertension[b] European classification	
	Sex[c]	
	Males	**Females**
All MSE	APR[c] (95% CI)	APR[c] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.91 (0.70-1.16)	0.67 (0.48-0.90)
21-59 minutes	0.55 (0.38-0.77)	0.60 (0.39-0.88)
60+ minutes	0.47 (0.30-0.70)	0.28 (0.12-0.54)
	Age[d]	
	16-54 years	**≥55 years**
All MSE	APR[d] (95% CI)	APR[d] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.66 (0.44-0.94)	1.06 (0.83-1.33)
21-59 minutes	0.62 (0.40-0.91)	0.92 (0.63-1.29)
60+ minutes	0.54 (0.31-0.86)	0.59 (0.33-0.98)
	Body Mass Index (kg/m^2)[e]	
	≤ 24.99 (underweight/normal)	**≥25.0 (overweight/obese)**
All MSE	APR[e] (95% CI)	APR[e] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.55 (0.34-0.82)	1.02 (0.81-1.27)
21-59 minutes	0.41 (0.21-0.71)	0.71 (0.52-0.94)
60+ minutes	0.42 (0.20-0.76)	0.48 (0.30-0.73)
	Smoking[f]	
	Never smoked [i]	**Current smoker**
All MSE	APR[f] (95% CI)	APR[f] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.85 (0.65-1.10)	0.60 (0.25-1.18)
21-59 minutes	0.57 (0.38-0.82)	0.54 (0.19-1.17)
60+ minutes	0.41 (0.24-0.65)	0.30 (0.05-0.94)
	Longstanding illness[g]	
	No	**Yes**
All MSE	APR[g] (95% CI)	APR[g] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.85 (0.68-1.05)	0.74 (0.45-1.16)
21-59 minutes	0.57 (0.41-0.76)	0.79 (0.44-1.29)
60+ minutes	0.37 (0.23-0.56)	0.86 (0.39-1.62)
	Aerobic physical activity level[h]	
	Insufficiently active (0-149 MVPA minutes/week)	**Sufficiently active (≥150 MVPA minutes/week)**
All MSE	APR[h] (95% CI)	APR[h] (95% CI)
0 minutes	1 (reference)	1 (reference)
10-20 minutes	0.96 (0.61-1.42)	0.84 (0.67-1.05)
21-59 minutes	0.31 (0.05-0.97)	0.68 (0.51-0.89)
60+ minutes	0.25 (0.01-1.10)	0.49 (0.33-0.70)

[a] APR calculated using Poisson regression with a robust error variance.

[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥140mmHg or DBP ≥90mmHg (Defined in 2018 ESC/ESH Guidelines for the management of arterial hypertension: The task force for the management of arterial hypertension of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH)).

[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness and weekly sedentary behaviour.

[i] excludes ex-smokers

Supplemental Digital Content 5.2 Adjusted Prevalence ratios (APR)[a] of hypertension[b] and hypertension[j] according to duration per session of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

	Sex			
	Males		**Females**	
	Hypertension[b] US classification	**Hypertension[j] European classification**	**Hypertension[b] US classification**	**Hypertension[j] European classification**
All MSE	APR[c] (95% CI)	APR[c] (95% CI)	APR[c] (95% CI)	APR[c] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.92 (0.76-1.09)	0.91 (0.70-1.16)	0.72 (0.58-0.88)	0.67 (0.48-0.90)
21-59 minutes	0.83 (0.68-1.02)	0.55 (0.38-0.77)	0.65 (0.49-0.84)	0.60 (0.39-0.88)
60+ minutes	0.64 (0.49-0.82)	0.47 (0.30-0.70)	0.58 (0.40-0.82)	0.28 (0.12-0.54)
	Age			
	16-54 years		**≥55 years**	
All MSE	APR[d] (95% CI)	APR[d] (95% CI)	APR[d] (95% CI)	APR[d] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.80 (0.65-0.98)	0.66 (0.44-0.94)	0.98 (0.82-1.17)	1.06 (0.83-1.33)
21-59 minutes	0.90 (0.72-1.10)	0.62 (0.40-0.91)	0.92 (0.70-1.19)	0.92 (0.63-1.29)
60+ minutes	0.77 (0.59-0.99)	0.54 (0.31-0.86)	0.76 (0.52-1.07)	0.59 (0.33-0.98)
	Body Mass Index (kg/m^2)			
	≤ 24.99 (underweight/normal)		**≥25.0 (overweight/obese)**	
All MSE	APR[e] (95% CI)	APR[e] (95% CI)	APR[e] (95% CI)	APR[e] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.70 (0.53-0.91)	0.55 (0.34-0.82)	0.99 (0.84-1.15)	1.02 (0.81-1.27)
21-59 minutes	0.64 (0.45-0.88)	0.41 (0.21-0.71)	0.89 (0.74-1.07)	0.71 (0.52-0.94)
60+ minutes	0.63 (0.42-0.89)	0.42 (0.20-0.76)	0.73 (0.56-0.94)	0.48 (0.30-0.73)
	Smoking			
	Never smoked [i]		**Current smoker**	
All MSE	APR[f] (95% CI)	APR[f] (95% CI)	APR[f] (95% CI)	APR[f] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.84 (0.70-1.01)	0.85 (0.65-1.10)	0.57 (0.31-0.96)	0.60 (0.25-1.18)
21-59 minutes	0.82 (0.65-1.01)	0.57 (0.38-0.82)	0.72 (0.39-1.20)	0.54 (0.19-1.17)
60+ minutes	0.62 (0.46-0.82)	0.41 (0.24-0.65)	0.69 (0.33-1.27)	0.30 (0.05-0.94)
	Longstanding illness			
	No		**Yes**	
All MSE	APR[g] (95% CI)	APR[g] (95% CI)	APR[g] (95% CI)	APR[g] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.87 (0.74-1.01)	0.85 (0.68-1.05)	0.74 (0.51-1.03)	0.74 (0.45-1.16)
21-59 minutes	0.80 (0.67-0.96)	0.57 (0.41-0.76)	0.73 (0.48-1.08)	0.79 (0.44-1.29)
60+ minutes	0.61 (0.47-0.76)	0.37 (0.23-0.56)	1.05 (0.63-1.63)	0.86 (0.39-1.62)
	Aerobic physical activity level			
	Insufficiently active (0-149 MVPA minutes/week)		**Sufficiently active (≥150 MVPA minutes/week)**	
All MSE	APR[h] (95% CI)	APR[h] (95% CI)	APR[h] (95% CI)	APR[h] (95% CI)
0 minutes	1 (reference)	1 (reference)	1 (reference)	1 (reference)
10-20 minutes	0.84 (0.60-1.14)	0.96 (0.61-1.42)	0.87 (0.74-1.01)	0.84 (0.67-1.05)
21-59 minutes	0.74 (0.36-1.35)	0.31 (0.05-0.97)	0.82 (0.69-0.97)	0.68 (0.51-0.89)
60+ minutes	0.66 (0.24-1.42)	0.25 (0.01-1.10)	0.68 (0.54-0.84)	0.49 (0.33-0.70)

[a] APR calculated using Poisson regression with a robust error variance.
[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥130mmHg or DBP ≥80mmHg (Defined in 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: A report of the American college of cardiology/American heart association task force on clinical practice guidelines).
[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.
[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.
[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.
[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.
[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, and weekly sedentary behaviour.
[i] excludes ex-smokers
[j] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥140mmHg or DBP ≥90mmHg (Defined in 2018 ESC/ESH Guidelines for the management of arterial hypertension: The task force for the management of arterial hypertension of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH)).

Supplemental Digital Content 6. Adjusted Prevalence ratios (APR)[a] of hypertension[b] according to volume per week (frequency x duration) of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

	Hypertension[b]	
	Sex	
	Males	**Females**
All MSE [j]	APR[c] (95% CI)	APR[c] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.85 (0.74-0.99)	0.69 (0.58-0.82)
High ≥ mean	0.74 (0.59-0.92)	0.59 (0.40-0.83)
	Age	
	16-54 years	**≥55 years**
All MSE [j]	APR[d] (95% CI)	APR[d] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.84 (0.72-0.99)	0.92 (0.78-1.07)
High ≥ mean	0.79 (0.61-1.01)	0.97 (0.72-1.27)
	Body Mass Index (kg/m^2)	
	≤ 24.99 (underweight/normal)	**≥25.0 (overweight/obese)**
All MSE [j]	APR[e] (95% CI)	APR[e] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.63 (0.50-0.79)	0.94 (0.82-1.06)
High ≥ mean	0.76 (0.54-1.04)	0.80 (0.63-0.99)
	Smoking	
	Never smoked [i]	**Current smoker**
All MSE [j]	APR[f] (95% CI)	APR[f] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.78 (0.67-0.91)	0.72 (0.47-1.05)
High ≥ mean	0.79 (0.61-1.01)	0.51 (0.24-0.93)
	Longstanding illness	
	No	**Yes**
All MSE [j]	APR[g] (95% CI)	APR[g] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.81 (0.71-0.91)	0.76 (0.57-0.99)
High ≥ mean	0.72 (0.59-0.89)	0.92 (0.56-1.40)
	Aerobic physical activity level	
	Insufficiently active (0-149 MVPA minutes/week)	**Sufficiently active (≥150 MVPA minutes/week)**
All MSE [j]	APR[h] (95% CI)	APR[h] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.78 (0.57-1.03)	0.82 (0.73-0.93)
High ≥ mean	1.10 (0.39-2.37)	0.76 (0.62-0.92)

[a] PR calculated using Poisson regression with a robust error variance.

[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥130mmHg or DBP ≥80mmHg.

[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness and weekly sedentary behaviour.

[i] excludes ex-smokers

[j] Mean value 106.2 minutes/week

Supplemental Digital Content 6.1 Adjusted Prevalence ratios (APR)[a] of hypertension[b] according to volume per week (frequency x duration) of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

	Hypertension[b] European classification	
	Sex[c]	
	Males	**Females**
All MSE [j]	APR[c] (95% CI)	APR[c] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.72 (0.57-0.89)	0.59 (0.45-0.76)
High ≥ mean	0.59 (0.40-0.82)	0.49 (0.26-0.82)
	Age[d]	
	16-54 years	**≥55 years**
All MSE [j]	APR[d] (95% CI)	APR[d] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.61 (0.45-0.81)	0.95 (0.77-1.17)
High ≥ mean	0.63 (0.39-0.96)	0.91 (0.60-1.32)
	Body Mass Index (kg/m^2)[e]	
	≤ 24.99 (underweight/normal)	**≥25.0 (overweight/obese)**
All MSE [j]	APR[e] (95% CI)	APR[e] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.44 (0.30-0.64)	0.84 (0.69-1.01)
High ≥ mean	0.56 (0.30-0.94)	0.67 (0.46-0.94)
	Smoking[f]	
	Never smoked [i]	**Current smoker**
All MSE [j]	APR[f] (95% CI)	APR[f] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.65 (0.51-0.82)	0.59 (0.30-1.04)
High ≥ mean	0.69 (0.46-0.99)	0.33 (0.08-0.87)
	Longstanding illness[g]	
	No	**Yes**
All MSE [j]	APR[g] (95% CI)	APR[g] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.68 (0.56-0.82)	0.73 (0.49-1.04)
High ≥ mean	0.55 (0.38-0.76)	0.98 (0.50-1.69)
	Aerobic physical activity level[h]	
	Insufficiently active (0-149 MVPA minutes/week)	**Sufficiently active (≥150 MVPA minutes/week)**
All MSE [j]	APR[h] (95% CI)	APR[h] (95% CI)
None	1 (reference)	1 (reference)
Low < mean	0.72 (0.46-1.06)	0.73 (0.60-0.88)
High ≥ mean	1.25 (0.31-3.25)	0.64 (0.46-0.86)

[a] APR calculated using Poisson regression with a robust error variance.

[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥140mmHg or DBP ≥90mmHg (Defined in 2018 ESC/ESH Guidelines for the management of arterial hypertension: The task force for the management of arterial hypertension of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH)).

[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness and weekly sedentary behaviour.

[i] excludes ex-smokers

[j] Mean value 106.2 minutes/week

Supplemental Digital Content 6.2 Adjusted Prevalence ratios (APR)[a] of hypertension[b] and hypertension[k] according to volume per week (frequency x duration) of all muscle-strengthening exercise (MSE) among Health Survey for England (2012-2016): stratified by sex, age, body mass index, smoking, long standing illness, and aerobic physical activity level.

Sex				
	Males		**Females**	
	Hypertension[b]	**Hypertension[k]**	**Hypertension[b]**	**Hypertension[k]**
	US classification	**European Classification**	**US classification**	**European Classification**
All MSE [j]	APR[c] (95% CI)	APR[c] (95% CI)	APR[c] (95% CI)	APR[c] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.85 (0.74-0.99)	0.72 (0.57-0.89)	0.69 (0.58-0.82)	0.59 (0.45-0.76)
High ≥ mean	0.74 (0.59-0.92)	0.59 (0.40-0.82)	0.59 (0.40-0.83)	0.49 (0.26-0.82)
Age				
	16-54 years		**≥55 years**	
All MSE [j]	APR[d] (95% CI)	APR[d] (95% CI)	APR[d] (95% CI)	APR[d] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.84 (0.72-0.99)	0.61 (0.45-0.81)	0.92 (0.78-1.07)	0.95 (0.77-1.17)
High ≥ mean	0.79 (0.61-1.01)	0.63 (0.39-0.96)	0.97 (0.72-1.27)	0.91 (0.60-1.32)
Body Mass Index (kg/m^2)				
	≤ 24.99 (underweight/normal)		**≥25.0 (overweight/obese)**	
All MSE [j]	APR[e] (95% CI)	APR[e] (95% CI)	APR[e] (95% CI)	APR[e] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.63 (0.50-0.79)	0.44 (0.30-0.64)	0.94 (0.82-1.06)	0.84 (0.69-1.01)
High ≥ mean	0.76 (0.54-1.04)	0.56 (0.30-0.94)	0.80 (0.63-0.99)	0.67 (0.46-0.94)
Smoking				
	Never smoked [i]		**Current smoker**	
All MSE [j]	APR[f] (95% CI)	APR[f] (95% CI)	APR[f] (95% CI)	APR[f] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.78 (0.67-0.91)	0.65 (0.51-0.82)	0.72 (0.47-1.05)	0.59 (0.30-1.04)
High ≥ mean	0.79 (0.61-1.01)	0.69 (0.46-0.99)	0.51 (0.24-0.93)	0.33 (0.08-0.87)
Longstanding illness				
	No		**Yes**	
All MSE [j]	APR[g] (95% CI)	APR[g] (95% CI)	APR[g] (95% CI)	APR[g] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.81 (0.71-0.91)	0.68 (0.56-0.82)	0.76 (0.57-0.99)	0.73 (0.49-1.04)
High ≥ mean	0.72 (0.59-0.89)	0.55 (0.38-0.76)	0.92 (0.56-1.40)	0.98 (0.50-1.69)
Aerobic physical activity level				
	Insufficiently active (0-149 MVPA minutes/week)		**Sufficiently active (≥150 MVPA minutes/week)**	
All MSE [j]	APR[h] (95% CI)	APR[h] (95% CI)	APR[h] (95% CI)	APR[h] (95% CI)
None	1 (reference)	1 (reference)	1 (reference)	1 (reference)
Low < mean	0.78 (0.57-1.03)	0.72 (0.46-1.06)	0.82 (0.73-0.93)	0.73 (0.60-0.88)
High ≥ mean	1.10 (0.39-2.37)	1.25 (0.31-3.25)	0.76 (0.62-0.92)	0.64 (0.46-0.86)

[a] APR calculated using Poisson regression with a robust error variance.

[b] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥130mmHg or DBP ≥80mmHg (Defined in 2017 ACC/AHA/AAPA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: A report of the American college of cardiology/American heart association task force on clinical practice guidelines).

[c] Adjusted for age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[d] Adjusted for sex, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[e] Adjusted for sex, age, education, income, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[f] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, prescription medication for blood pressure, longstanding illness, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[g] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, aerobic moderate-to-vigorous physical activity, and weekly sedentary behaviour.

[h] Adjusted for sex, age, education, income, BMI, weekly alcohol consumption, smoking, prescription medication for blood pressure, longstanding illness, and weekly sedentary behaviour.

[i] excludes ex-smokers

[j] Mean value 106.2 minutes/week

[k] To be classified as having hypertension, a respondent had to have clinically assessed blood pressure of SBP ≥140mmHg or DBP ≥90mmHg (Defined in 2018 ESC/ESH Guidelines for the management of arterial hypertension: The task force for the management of arterial hypertension of the European Society of Cardiology (ESC) and the European Society of Hypertension (ESH)).