Published in final edited form as:

Blood Press Monit. 2018 August ; 23(4): 185–190. doi:10.1097/MBP.0000000000000325.

The Influence of Resting Blood Pressure on Muscle Strength in Healthy Adults:

Resting Blood Pressure and Muscle Strength

Adam R. Blanchard, MS^{1,2}, Beth A. Taylor, PhD^{1,2,3}, Paul D. Thompson, MD³, Lindsey K. Lepley, PhD¹, C. Michael White, Pharm.D.^{3,4}, Lauren M. Corso, MS^{1,2}, Amanda L. Zaleski, MS^{1,2,3}, and Linda S. Pescatello, PhD^{1,2}

¹Department of Kinesiology, University of Connecticut, Storrs, CT, United States of America

²Institute for Collaboration on Health, Intervention and Policy, University of Connecticut, Storrs, CT, United States of America

³Henry Low Heart Center, Department of Cardiology, Hartford Hospital, Hartford, CT, United States of America

⁴School of Pharmacy, University of Connecticut, Storrs, CT, United States of America

Abstract

Adverse alterations in the skeletal muscle response to exercise have been noted among adults with hypertension. The influence of resting blood pressure (BP) on muscle strength is unknown. We hypothesized adults with high BP would exhibit lower muscular strength than adults with normal BP. An isokinetic dynamometer tested 21 measures of isometric and isokinetic muscle strength. BP was measured by auscultation. Subjects were categorized into having normal (<120&<80mmHg) or high (≥120&/or ≥80mmHg) BP. Height (cm) and weight (kg) were measured to calculate body mass index (BMI, kg·m⁻²). Analysis of covariance tested differences in muscle strength between BP groups with sex, age and height as covariates. Subjects (n=420, 49% men) were middle-aged (44.1±16.1yr) and overweight (26.4±4.8kg·m⁻²) with 187 having normal (107.7±7.3/68.3±6.3mmHg) and 233 high (127.8±9.8/80.8±8.1mmHg) BP. For upper body, three of five extension and five of five flexion measures, as well as handgrip, were greater in the high than normal BP group (*p* 0.05). For lower body, five of five extension measures were greater in the high than normal BP group, while there were no differences between BP groups for the five flexion measures (*p*>0.05). Contrary to our hypothesis, adults with high BP displayed greater muscle strength than adults with normal BP. Reasons for our findings are unclear but may be due to shifts in muscle fiber type from Type I to Type IIb/x and oxidative to glycolytic metabolism;

Address for Correspondence: Adam R. Blanchard, MS, ACSM EP-C, Department of Kinesiology, College of Agriculture, Health, and Natural Resources, University of Connecticut, Gampel Pavilion Room 206, 2095 Hillside Rd, U-1110, Storrs, CT 06269-1110, United States of America, Phone: (203) 232-0396, adam.blanchard@uconn.edu.

Conflicts of Interest

None

Declaration

The present results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

alterations that may result in a more strength-adapted phenotype among adults with high BP such as we observed.

Keywords

Dynamometer; Exercise; Hypertension; Prehypertension

INTRODUCTION

Hypertension is the most common, costly, and preventable cardiovascular disease (CVD) risk factor with 80 million adults (32.6%) in the United States (U.S.) having hypertension and an additional 36.3% having prehypertension, according to the Joint National Committee Seven on the Prevention, Detection, Evaluation, and Treatment of High Blood Pressure (JNC 7) [1,2]. Using the JNC 7 blood pressure (BP) thresholds, one in five people with prehypertension will develop hypertension within four years of being diagnosed with prehypertension, and the lifetime risk for developing hypertension is 90% [1,2]. By 2030, it is estimated about 41.4% of adults in the U.S. will have hypertension [1]. Adults with high BP have a higher risk for stroke, myocardial infarction, and CVD death [1]. Due to the significant public health burden of having high BP, all professional organizations recommend lifestyle interventions such as exercise to prevent, manage, and treat hypertension [3–6].

Resistance training has been shown to be beneficial for cardiometabolic health, and has gained in popularity as an efficacious mode of exercise to prevent, manage, and control high BP [3,7–9]. Resistance training has been recently reported to elicit BP reductions of as large as 5–8 mmHg among adults with hypertension [10], and is currently recommended as an adjuvant lifestyle therapy to aerobic exercise for its antihypertensive benefits. Interestingly, evidence from epidemiological studies suggest there is an inverse association between muscle strength and BP [11–13].

Several primary level studies also exist that show adverse physiological alterations in the skeletal muscle response to an acute muscle contraction among individuals with hypertension compared to those with normal BP that includes exaggerated sympathetic nervous activity, increased vasoconstriction, and a greater release of reactive oxygen species [14–18]. These alterations create a state of hypoxia in the skeletal muscle which augments oxidative stress, eventually leading to vascular wall thickening and skeletal muscle damage [16,17,19]. This pathological chain of events has been shown to be associated with decreased muscle strength among those with congestive heart failure and chronic obstructive pulmonary disease [16,19]. Surprisingly, the influence of resting BP status on muscle strength among adults has not been examined.

Therefore, the purpose of this study was to examine the relationship between resting BP and measures of muscle strength among healthy, adult men and women equally distributed across the lifespan. We hypothesized that adults with high BP would exhibit decreased upper and lower body muscle strength compared to those with normal BP due to underlying negative physiological alterations in the skeletal muscle that is associated with high BP.

METHODS

Subjects

This study is a sub study from a larger, multi-site, randomized double-blind clinical trial entitled, *Effects of Statins on Skeletal Muscle Function and Performance* (STOMP) (NIH Grant R01HL081893-01A2) [20] that was approved by the Institutional Review Boards of Hartford Hospital, the University of Massachusetts-Amherst, and the University of Connecticut-Storrs. All subjects signed an informed consent form. All data reported for the STOMP sub study were collected at baseline among 420 healthy men (49%) and women (51%) equally distributed across the lifespan (ages 20–39 year [n=143], 40–54 year [n=142], and 55 year [n=135] with a mean $\pm$ standard deviation (SD) age of 44.1 ± 16.1 year and resting systolic BP (SBP)/diastolic BP (DBP) of $118.9 \pm 13.3/75.3 \pm 9.6$ mmHg.

Anthropometrics

Body weight (kg) was measured with a calibrated beam scale, while a wall-mounted tape measure was used to measure height (cm) for the calculation of body mass index (BMI, $\text{kg}\cdot\text{m}^{-2}$) [3]. Waist circumference (cm) was measured using a non-distensible Gulick tape measure [3,20].

Blood Pressure

Resting BP was determined according to American Heart Association guidelines [21] with a Welch Allyn floor sphygmomanometer after subjects were seated for 5 min of rest with both feet flat on the floor, legs uncrossed, and their back supported. A minimum of two readings, 1 min apart, were taken in each arm at heart level. If there was a >5 mmHg difference between the first and second readings, additional readings were taken until three measurements agreed within 5 mmHg. The average of the readings in the non-dominant arm were recorded as resting BP [20].

Upper and Lower Body Muscle Strength

Dominant isometric handgrip strength was measured using a handgrip dynamometer by taking the average of three, 3 sec maximal contractions with 1 min rest in between [20]. Elbow isometric and isokinetic flexion/extension and knee flexion/extension in the dominant limb were measured using a Biodex System 3 dynamometer (Biodex Medical, Shirley, NY) [20]. Prior to each test, participants warmed up by performing three submaximal contractions. For elbow isometric flexion and extension strength, participants performed three maximal contractions with the elbow flexed at an angle of 90° . After a 5 min rest, elbow isokinetic flexion and extension strength were determined by four maximal contractions in succession at 1.05 rad/s or $60^\circ/\text{s}$ followed by an additional 5 min rest and then four maximal contractions were performed in succession at 3.14 rad/s or $180^\circ/\text{s}$. For knee isometric flexion and extension strength, participants performed three maximal contractions with the knee flexed at an angle of 110° . After 5 min rest, knee isokinetic flexion and extension strength were determined by four maximal contractions in succession at 1.05 rad/s or $60^\circ/\text{s}$ followed by an additional 5 min rest and then four maximal contractions were performed in succession at 3.14 rad/s or $180^\circ/\text{s}$. The average peak torque

(Nm) and average power (Nm) was calculated with the Biodex System 3 Software (Biodex Medical, Shirley, NY) for upper and lower body muscle strength measurements.

Cardiorespiratory Fitness

Cardiorespiratory fitness (i.e., maximal oxygen uptake; $\text{VO}_{2\text{max}}$) was assessed using a breath-by-breath analysis of expired gas via a Parvomedics TrueOne 2400 metabolic cart (ParvoMedics Corporation, Sandy, Utah). Subjects completed a modified Balke treadmill protocol after an 8–12 hr fast. Subjects began walking at 2 mph on a 0% incline for 2 min. Following this warm-up, the treadmill speed was increased to a pace that the subject could maintain for the remainder of the test, while the treadmill incline increased 1% every min [20]. The test was terminated when one or more of the following conditions were met: the subject reported a rating of perceived exertion of 18, the subject had a respiratory exchange ratio >1.1 , the subject achieved their age predicted maximum heart rate, there was a plateau in VO_2 , and/or the subject self-terminated due to fatigue or discomfort [3,20].

Physical Activity

Physical activity and type of physical activity was assessed using Question 6 of the Paffenbarger Physical Activity Questionnaire [22], which has been validated for use in both healthy and individuals with hypertension [22,23]. This question determined how many times per week, if any, does the subject engage in regular activity (i.e., brisk walking, jogging, bicycling) and asked the subject to state what type of activity was performed. Type of activity was categorized into either none, resistance, aerobic, or other.

Statistical Analyses

Muscle strength variables were not normally distributed so that all muscle strength measures were initially log-transformed for purposes of statistical analysis, and then back-transformed from the mean of the log transform for the purpose of reporting our findings. For the purpose of statistical analysis, the sample was dichotomized into two groups by resting BP: a group with normal BP (SBP <120 mmHg and DBP <80 mmHg; $n=187$) and a group with pre- to established hypertension (SBP ≥ 120 mmHg and/or DBP ≥ 80 mmHg; $n=233$). Subject characteristics for the total sample and between BP groups and sex were tested using one-way analysis of variance (ANOVA). To test the relationship between resting BP status and baseline muscle strength an analysis of covariance (ANCOVA) was performed with BP group as a fixed factor and age, sex, and to account for body size [24,25], height as covariates. Statistical significance was set at an alpha level of $p \leq 0.05$. All analyses were performed using SPSS Statistics 19.0 (IBM Corporation, New York).

RESULTS

Blood Pressure and Muscle Strength

Subject Characteristics (Table 1)—On average subjects ($n=420$) were middle-aged, overweight, and had normal BP (23, 26). The sample was approximately evenly divided by resting BP status, with 45% having normal BP and 55% classified as having high BP (i.e., pre-hypertension [42%] or established hypertension [13%]). Only 6% ($n=24$) subjects were taking antihypertensive medications. When stratified by resting BP status, the group with

normal BP was younger, shorter, and had lower BMI and waist circumference than those with high BP ($p<0.001$). In the normal BP group 30% ($n=56$) participated in no physical activity, 8% ($n=15$) participated in resistance training, 55% ($n=102$) participated in aerobic activity, and 7% ($n=14$) participated in other types. In the high BP group, 27% ($n=63$) participated in no physical activity, 9% ($n=21$) participated in resistance training, 52% ($n=121$) participated in aerobic activity, and 11% ($n=26$) participated in other types. There was no difference between BP groups among participation in the four types of physical activity ($p>0.05$). Women were shorter, had a lower BMI, waist circumference, SBP, DBP, and VO_{2max} than the men ($p<0.05$). Men were significantly stronger in every measure of muscle strength than the women ($p<0.001$).

Isokinetic Muscle Strength Measures at 180°/sec (Table 2)

Upper Body: Of the four isokinetic upper body strength measures performed at 180°/sec, which is an indicator of predominately Type II muscle fiber recruitment [26], the high BP group had greater muscular strength for elbow extension average peak torque (adjusted mean difference $\pm$ SD; 1.6 ± 14.8 ; $p=0.03$) and elbow flexion average peak torque (1.8 ± 13.2 ; $p=0.001$) compared to the normal BP group. There were no statistically significant differences between BP groups for elbow extension average power or elbow flexion average power ($p>0.05$).

Lower Body: Of the four isokinetic lower body strength measures performed at 180°/sec, the high BP group had greater muscular strength for knee extension average peak torque (7.3 ± 46.6 ; $p=0.009$) and knee extension average power (13.7 ± 98.9 ; $p=0.027$) compared to the normal BP group. There were no statistically significant differences between BP groups for the two lower body flexion measures ($p>0.05$).

Isometric Strength Measures and Isokinetic Muscle Strength Measures at 60°/sec (Table 3)

Upper Body: Of the two isometric and four isokinetic upper body strength measures performed at 60°/sec, an indicator of mixed Type I and II muscle fiber recruitment (26), the high BP group had greater muscular strength for isometric flexion average peak torque (1.9 ± 24.6 ; $p=0.02$); extension average peak torque (1.8 ± 18.9 ; $p=0.014$); and extension average power (1.3 ± 14.8 ; $p=0.003$) compared to the normal BP group. In addition, handgrip strength (1.5 ± 17.7 ; $p=0.001$) was greater in the high BP group compared to the normal BP group.

Lower Body: Of the two isometric and four isokinetic lower body strength measures performed at 60°/sec, the high BP group had greater muscular strength for all knee extension measures including: isometric extension average peak torque (16.2 ± 95.9 ; $p=0.003$); extension average peak torque (9.0 ± 61.2 ; $p=0.014$); and extension average power (6.4 ± 43.5 ; $p=0.002$). There were no differences between BP groups for the three knee flexion measures ($p>0.05$).

DISCUSSION

The present study examined the relationship between resting BP and muscle strength among healthy adults across the lifespan, of which 45% had normal BP and 55% had high BP. Due to reports in the literature of adverse muscle function alterations among individuals with hypertension, we hypothesized that individuals with high BP would exhibit reduced muscle strength compared to those with normal BP. Unexpectedly, we found that adults with pre- to established hypertension generally had greater muscle strength than those with normal BP in the biceps, triceps, and quadriceps as well as handgrip. More specifically, the high BP group had greater muscle strength in four out of the eight upper and lower body isokinetic measures performed at 180°/sec, a speed of contraction that reflects Type II muscle fiber recruitment [26]; one out of the two extension and flexion upper body isometric measures, four out of eight upper and lower body isokinetic measures performed at 60°/sec, a speed of contraction that reflects mixed Type I and Type II muscle fiber recruitment; and one out of two lower body isometric measures. Our unanticipated findings suggest that otherwise healthy adults in the early stages of hypertension appear to have a more muscle strength adapted phenotype than adults with normal BP.

Our findings are consistent with those of Dong et al. who recently examined the association between handgrip strength and resting BP in 44,240 adolescent boys (mean $\pm$ SD; 15.0 ± 1.4 yr) and 44,625 adolescent girls (15.0 ± 1.4 yr) with normal BP [27]. Adolescents were stratified by BMI as being thin, normal, overweight, or obese according to sex- and age-specific normative values [28]. Dong et al. [27] found a positive relationship between handgrip strength and resting BP after stratifying by and/or adjusting for BMI in their sample of adolescents ($p < 0.05$).

Several primary level studies exist that may lend support and mechanistic insight into our findings and those of Dong et al. [27]. There are physiological differences in the structure and function of the skeletal muscle during exercise in those with high compared to normal BP that may be associated with greater muscle strength as we found in our study [15,18,29–31]. Recently, Dipla et al. [32] found that untreated newly, diagnosed adults with hypertension had impaired muscle oxygenation both at rest and during exercise compared to age-, sex-, and BMI-matched individuals with normal BP. During submaximal handgrip exercise, the adults with hypertension had a greater BP/ tissue saturation index ratio than those with normal BP, indicating decreased muscle oxygenation levels during exercise possibly due to mitochondrial dysfunction and impaired vasodilation [32].

Additional studies have reported impaired skeletal muscle oxygenation during exercise among adults with hypertension compared to those with normal BP. For example, Vongpatanasin et al. sought to examine if functional sympatholysis is impaired among otherwise healthy 13 middle aged men and women with hypertension compared to 17 middle aged men and women with normal BP [33]. They measured muscle oxygenation and forearm blood flow in response to increases in sympathetic nerve activity evoked by lower body negative pressure at rest and during moderate intensity handgrip exercise [33]. Among the subjects with hypertension, the ability to combat the increase in sympathetic vasoconstriction during acute moderate intensity via functional sympatholysis was blunted

compared to the subjects with normal BP limiting the blood flow and oxygen delivery to the working skeletal muscles. These findings provide evidence that vascular function in the skeletal muscle and consequently oxygen delivery are impaired during exercise among adults with high BP [33]. Similarly Nyberg et al. found decreased leg blood flow and oxygen delivery during 10, 20, and 30 watts of knee-extensor exercises ($p < 0.05$) among 10 middle aged adults with hypertension compared to 11 middle aged adults with normal BP [34].

There is also evidence of alterations in skeletal muscle metabolism and muscle fiber type recruitment during acute resistance exercise in individuals with high BP. Several investigative teams have found that there is a shift from oxidative to glycolytic metabolism under hypoxic conditions in the skeletal muscle in individuals with high BP [17,19,29,35]. Therefore, the increased reliance on glycolytic metabolism may result in a shift in muscle fiber type recruitment from Type I to an increase in Type IIb/x; a phenomenon that has been documented in disease states such as chronic obstructive pulmonary disease and chronic heart failure [19]. In addition, Batool et al. [36] found women with hypertension had higher levels of testosterone compared to women with normal BP. Collectively, the evidence of impaired oxygenation of skeletal muscle [32–34], an increased reliance on glycolytic metabolism [17,29,34], and a shift in muscle fiber type recruitment from Type I to an increase in Type IIb/x [19] during acute resistance exercise, and greater testosterone levels among adults with hypertension [36] are consistent with our findings of a more muscle strength adapted phenotype among adults with high than normal BP.

There were limitations to our study. Our investigation was a sub study of the larger STOMP clinical trial (NIH Grant R01HL081893-01A2) so that the data collected in the larger STOMP study were not intended to test the hypothesis of this sub study. This sub study was not mechanistic in nature so that we can only speculate on reasons for our unanticipated findings. Measurements such as muscle biopsies or testing muscle strength at higher and lower isokinetic speeds than 60°/sec and 180°/sec may have confirmed our speculation into selected muscle fiber recruitment at certain velocities. Additional measurements such as electromyography, magnetic resonance imaging, ultrasound, and muscle sympathetic nervous activity may have provided a more comprehensive picture of muscular architecture and neural activation associated with having high BP, and how these changes may have affected muscle strength. Last, the associations we found among high resting BP and 14 out of 21 measures of upper and lower body muscle strength, although provocative, do not demonstrate causality.

Strengths of our sub study include a large sample of 420 healthy adults evenly distributed across the lifespan, and we were able to account for height in our statistical analyses which has been shown to be correlated to BP. The larger STOMP methods used gold standard measurement protocols for both resting BP [21] and upper and lower body muscle strength. In addition we assessed baseline physical activity levels to determine if participation in resistance training could have influenced our findings, and found no differences in physical activity among the BP groups. Lastly, subjects were absent of chronic disease or health conditions other than high BP that could have confounded our muscular strength outcomes.

To conclude, we found that multiple dimensions of upper and lower body muscle strength were greater among adults with pre- to established hypertension than adults with normal BP. Future studies are needed to confirm our findings, and if confirmed, investigate possible mechanisms to explain the influence high BP may have on muscle strength among adults in the early stages of hypertension.

Acknowledgments

Support: NIH Grant R01HL081893-01A2

References

1. Benjamin EJ, Blaha MJ, Chiuve SE, Cushman M, Das SR, Deo R, et al. Heart Disease and Stroke Statistics-2017 Update: A Report From the American Heart Association. *Circulation*. 2017; 135:e146–e603. [PubMed: 28122885]
2. Chobanian AV, Bakris GL, Black HR, Cushman WC, Green LA, Izzo JL Jr, et al. Seventh report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. *Hypertension*. 2003; 42:1206–1252. [PubMed: 14656957]
3. Pescatello, LS., Arena, R., Riebe, D., Thompson, PD. ACSM's Guidelines for Exercise Testing and Prescription. 9. Lippincott Williams & Wilkins; Baltimore (MD): 2014.
4. Pescatello LS, Franklin BA, Fagard R, Farquhar WB, Kelley GA, Ray CA, et al. American College of Sports Medicine position stand. Exercise and hypertension. *Med Sci Sports Exerc*. 2004; 36:533–553. [PubMed: 15076798]
5. Eckel RH, Jakicic JM, Ard JD, de Jesus JM, Houston Miller N, Hubbard VS, et al. 2013 AHA/ACC guideline on lifestyle management to reduce cardiovascular risk: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. *J Am Coll Cardiol*. 2014; 63:2960–2984. [PubMed: 24239922]
6. Pescatello LS, MacDonald HV, Lamberti L, Johnson BT. Exercise for Hypertension: A Prescription Update Integrating Existing Recommendations with Emerging Research. *Curr Hypertens Rep*. 2015; 17 87-015-0600-y.
7. Williams MA, Haskell WL, Ades PA, Amsterdam EA, Bittner V, Franklin BA, et al. Resistance exercise in individuals with and without cardiovascular disease: 2007 update: a scientific statement from the American Heart Association Council on Clinical Cardiology and Council on Nutrition, Physical Activity, and Metabolism. *Circulation*. 2007; 116:572–584. [PubMed: 17638929]
8. Martel GF, Hurlbut DE, Lott ME, Lemmer JT, Ivey FM, Roth SM, et al. Strength training normalizes resting blood pressure in 65- to 73-year-old men and women with high normal blood pressure. *J Am Geriatr Soc*. 1999; 47:1215–1221. [PubMed: 10522955]
9. Cornelissen VA, Fagard RH, Coeckelberghs E, Vanhees L. Impact of resistance training on blood pressure and other cardiovascular risk factors: a meta-analysis of randomized, controlled trials. *Hypertension*. 2011; 58:950–958. [PubMed: 21896934]
10. MacDonald HV, Johnson BT, Huedo-Medina TB, Livingston J, Forsyth KC, Kraemer WJ, et al. Dynamic Resistance Training as Stand-Alone Antihypertensive Lifestyle Therapy: A Meta-Analysis. *J Am Heart Assoc*. 2016; 5doi: 10.1161/JAHA.116.003231
11. Maslow AL, Sui X, Colabianchi N, Hussey J, Blair SN. Muscular strength and incident hypertension in normotensive and prehypertensive men. *Med Sci Sports Exerc*. 2010; 42:288–295. [PubMed: 19927030]
12. Artero EG, Lee DC, Ruiz JR, Sui X, Ortega FB, Church TS, et al. A prospective study of muscular strength and all-cause mortality in men with hypertension. *J Am Coll Cardiol*. 2011; 57:1831–1837. [PubMed: 21527158]
13. Lawman HG, Troiano RP, Perna FM, Wang CY, Fryar CD, Ogden CL. Associations of Relative Handgrip Strength and Cardiovascular Disease Biomarkers in U.S. Adults, 2011–2012. *Am J Prev Med*. 2015

14. Greaney JL, Matthews EL, Boggs ME, Edwards DG, Duncan RL, Farquhar WB. Exaggerated exercise pressor reflex in adults with moderately elevated systolic blood pressure: role of purinergic receptors. *Am J Physiol Heart Circ Physiol*. 2014; 306:H132–41. [PubMed: 24163081]
15. Greaney JL, Edwards DG, Fadel PJ, Farquhar WB. Rapid onset pressor and sympathetic responses to static handgrip in older hypertensive adults. *J Hum Hypertens*. 2015; 29:402–408. [PubMed: 25471615]
16. Umbrello M, Dyson A, Feelisch M, Singer M. The key role of nitric oxide in hypoxia: hypoxic vasodilation and energy supply-demand matching. *Antioxid Redox Signal*. 2013; 19:1690–1710. [PubMed: 23311950]
17. Nyberg M, Gliemann L, Hellsten Y. Vascular function in health, hypertension, and diabetes: effect of physical activity on skeletal muscle microcirculation. *Scand J Med Sci Sports*. 2015; 25(Suppl 4):60–73.
18. Clanton TL. Hypoxia-induced reactive oxygen species formation in skeletal muscle. *J Appl Physiol*. 2007; 102:2379–2388. 1985. [PubMed: 17289907]
19. Gosker HR, Wouters EF, van der Vusse GJ, Schols AM. Skeletal muscle dysfunction in chronic obstructive pulmonary disease and chronic heart failure: underlying mechanisms and therapy perspectives. *Am J Clin Nutr*. 2000; 71:1033–1047. [PubMed: 10799364]
20. Thompson PD, Parker BA, Clarkson PM, Pescatello LS, White CM, Grimaldi AS, et al. A randomized clinical trial to assess the effect of statins on skeletal muscle function and performance: rationale and study design. *Prev Cardiol*. 2010; 13:104–111. [PubMed: 20626664]
21. Pickering TG, Hall JE, Appel LJ, Falkner BE, Graves J, Hill MN, et al. Recommendations for blood pressure measurement in humans and experimental animals: Part 1: blood pressure measurement in humans: a statement for professionals from the Subcommittee of Professional and Public Education of the American Heart Association Council on High Blood Pressure Research. *Hypertension*. 2005; 45:142–161. [PubMed: 15611362]
22. Paffenbarger RS Jr, Wing AL, Hyde RT. Physical activity as an index of heart attack risk in college alumni. *Am J Epidemiol*. 1978; 108:161–175. [PubMed: 707484]
23. Paffenbarger RS Jr, Wing AL, Hyde RT, Jung DL. Physical activity and incidence of hypertension in college alumni. *Am J Epidemiol*. 1983; 117:245–257. [PubMed: 6829553]
24. Dyer AR, Elliott P, Shipley M. Body mass index versus height and weight in relation to blood pressure. Findings for the 10,079 persons in the INTERSALT Study. *Am J Epidemiol*. 1990; 131:589–596. [PubMed: 2180281]
25. Voors AW, Harsha DW, Webber LS, Berenson GS. Relation of blood pressure to stature in healthy young adults. *Am J Epidemiol*. 1982; 115:833–840. [PubMed: 7091142]
26. MacIntosh BR, Herzog W, Suter E, Wiley JP, Sokolosky J. Human skeletal muscle fibre types and force: velocity properties. *Eur J Appl Physiol Occup Physiol*. 1993; 67:499–506. [PubMed: 8149928]
27. Dong B, Wang Z, Arnold L, Song Y, Wang HJ, Ma J. The association between blood pressure and grip strength in adolescents: does body mass index matter? *Hypertens Res*.
28. Cole TJ, Flegal KM, Nicholls D, Jackson AA. Body mass index cut offs to define thinness in children and adolescents: international survey. *BMJ*. 2007; 335:194. [PubMed: 17591624]
29. Jones AM, Ferguson SK, Bailey SJ, Vanhatalo A, Poole DC. Fiber Type-Specific Effects of Dietary Nitrate. *Exerc Sport Sci Rev*. 2016; 44:53–60. [PubMed: 26829247]
30. Marshall JM. Adenosine and muscle vasodilatation in acute systemic hypoxia. *Acta Physiol Scand*. 2000; 168:561–573. [PubMed: 10759593]
31. Delaney EP, Greaney JL, Edwards DG, Rose WC, Fadel PJ, Farquhar WB. Exaggerated sympathetic and pressor responses to handgrip exercise in older hypertensive humans: role of the muscle metaboreflex. *Am J Physiol Heart Circ Physiol*. 2010; 299:H1318–27. [PubMed: 20802135]
32. Diplá K, Triantafyllou A, Koletsos N, Papadopoulos S, Sachpekidis V, Vrabas IS, et al. Impaired Muscle Oxygenation and Elevated Exercise Blood Pressure in Hypertensive Patients: Links With Vascular Stiffness. *Hypertension*. 2017; 70:444–451. [PubMed: 28607132]

33. Vongpatanasin W, Wang Z, Arbique D, Arbique G, Adams-Huet B, Mitchell JH, et al. Functional sympatholysis is impaired in hypertensive humans. *J Physiol.* 2011; 589:1209–1220. [PubMed: 21224235]
34. Nyberg M, Jensen LG, Thaning P, Hellsten Y, Mortensen SP. Role of nitric oxide and prostanoids in the regulation of leg blood flow and blood pressure in humans with essential hypertension: effect of high-intensity aerobic training. *J Physiol.* 2012; 590:1481–1494. [PubMed: 22271868]
35. Boushel R. Muscle metaboreflex control of the circulation during exercise. *Acta Physiol(Oxf).* 2010; 199:367–383. [PubMed: 20353495]
36. Batool AI, Rehman M, Unab S, Naveed N, Arshad M, Jabeen SH, et al. Reproductive Endocrinopathy among Cardiovascular Hypertensive Patients. *Saudi Journal of Biomedical Research.* 2016; 1:13.

Table 1Baseline characteristics (Mean $\pm$ SD) for the total sample and by resting blood pressure status and sex

Variable	Total (n=420)	Men (n=204)	Women (n=216)	Normal BP (n=187)	High BP (n=233)
Age (yr)	44.1 $\pm$ 16.1	43.7 $\pm$ 15.8	44.5 $\pm$ 16.5	41.0 $\pm$ 15.6	46.61 $\pm$ 16.2 [‡]
Height (cm)	171.5 $\pm$ 9.6	178.5 $\pm$ 7.1	165.0 $\pm$ 6.5**	170.4 $\pm$ 9.4	172.4 $\pm$ 9.6 [†]
Weight (kg)	78.1 $\pm$ 16.9	87.5 $\pm$ 15.5	69.3 $\pm$ 13.0**	73.7 $\pm$ 15.7	81.6 $\pm$ 17.0 [‡]
BMI (kg·m ⁻²)	26.4 $\pm$ 4.8	27.4 $\pm$ 4.5	25.5 $\pm$ 5.0**	25.3 $\pm$ 4.2	27.3 $\pm$ 5.1 [‡]
WC (cm)	86.2 $\pm$ 13.9	92.8 $\pm$ 13.0	80.3 $\pm$ 12.0**	82.5 $\pm$ 12.5	89.2 $\pm$ 14.3 [‡]
Systolic BP (mmHg)	118.9 $\pm$ 13.3	121.7 $\pm$ 12.7	116.3 $\pm$ 13.3**	107.7 $\pm$ 7.3	127.8 $\pm$ 9.8 [‡]
Diastolic BP (mmHg)	75.3 $\pm$ 9.6	76.4 $\pm$ 9.4	74.1 $\pm$ 9.8*	68.3 $\pm$ 6.3	80.8 $\pm$ 8.1 [‡]
Maximal oxygen uptake (ml·kg·min ⁻¹)	33.9 $\pm$ 9.7	38.2 $\pm$ 8.9	29.9 $\pm$ 8.8**	34.7 $\pm$ 9.5	33.3 $\pm$ 9.9

Note: *Abbr:* BMI= body mass index; BP= blood pressure; WC= waist circumference, SD= standard deviation

Sex difference, *p 0.05, **p 0.001.

Resting BP status difference, †p 0.05, ‡p 0.001.

Table 2

Adjusted baseline muscle strength measures performed at 180°/sec (Adjusted Mean $\pm$ SD) by resting blood pressure status

Muscle Strength Measures at 180°/sec	Normal BP (<i>n</i> =187)	High BP (<i>n</i> =233)
Upper Body (N-M)		
Isokinetic Extension ¹	31.0 $\pm$ 6.9	32.6 $\pm$ 7.7*
Isokinetic Flexion ¹	29.1 $\pm$ 6.9	30.9 $\pm$ 6.1**
Isokinetic Extension ²	56.2 $\pm$ 16.4	60.0 $\pm$ 16.8
Isokinetic Flexion ²	48.6 $\pm$ 12.3	50.6 $\pm$ 12.2
Lower Body (N-M)		
Isokinetic Extension ¹	95.7 $\pm$ 23.3	103.0 $\pm$ 23.0**
Isokinetic Flexion ¹	53.6 $\pm$ 15.1	57.2 $\pm$ 15.3
Isokinetic Extension ²	179.7 $\pm$ 49.3	193.4 $\pm$ 49.0*
Isokinetic Flexion ²	93.1 $\pm$ 35.6	98.3 $\pm$ 35.2

Note: Normal vs High BP status adjusted for age, sex, and height.

* *p* 0.05, ** *p* 0.01.

¹ average peak torque; ² average power; BP, blood pressure

Table 3

Adjusted baseline isometric and isokinetic muscle strength measure performed at 60°/sec (Adjusted Mean $\pm$ SD) by resting blood pressure status

Muscle Strength Measures	Normal BP (n=187)	High BP (n=233)
Handgrip (kg)	38.5 $\pm$ 8.2	40.0 $\pm$ 9.2**
Upper Body (N-M)		
Isometric Extension ¹	43.1 $\pm$ 12.3	44.7 $\pm$ 12.2
Isometric Flexion ¹	51.0 $\pm$ 12.3	52.9 $\pm$ 12.2*
Isokinetic Extension ¹	38.7 $\pm$ 9.6	40.5 $\pm$ 9.2*
Isokinetic Flexion ¹	34.0 $\pm$ 6.9	35.0 $\pm$ 7.7
Isokinetic Extension ²	29.2 $\pm$ 6.9	30.5 $\pm$ 7.7**
Isokinetic Flexion ²	25.9 $\pm$ 5.5	26.5 $\pm$ 6.1
Lower Body (N-M)		
Isometric Extension ¹	186.7 $\pm$ 48.0	202.9 $\pm$ 47.4**
Isometric Flexion ¹	82.6 $\pm$ 19.2	86.5 $\pm$ 18.4
Isokinetic Extension ¹	145.5 $\pm$ 30.1	154.5 $\pm$ 30.6*
Isokinetic Flexion ¹	73.2 $\pm$ 23.3	77.0 $\pm$ 24.5
Isokinetic Extension ²	100.8 $\pm$ 21.9	107.2 $\pm$ 21.4**
Isokinetic Flexion ²	56.4 $\pm$ 13.7	57.9 $\pm$ 13.8

Note: Normal vs High BP status adjusted for age, sex, and height.

* $p < 0.05$, ** $p < 0.01$.

¹ average peak torque; ² average power; BP, blood pressure