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

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

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Master of Science Thesis

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

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Chapter 1. Introduction

1.1. Background and Significance

Cardiovascular disease (CVD) is the leading cause of death in the United States (U.S.) and the world (1, 22). In 2012, it was estimated that about 85.6 million adults in the U.S. had CVD which is equivalent to more than 1 in every 3 persons (33%) (22). Furthermore, CVD places a significant financial strain on the U.S. economy and healthcare system contributing an estimated \$316.6 billion in direct and indirect costs, making CVD one of the most costly medical conditions (22). By 2030, the total direct medical costs attributable to CVD are projected to triple to ~\$900 billion (22). About half of U.S. adults have at least one risk factor for CVD, the most common of which is hypertension (22).

Hypertension is defined as blood pressure (BP) levels ≥ 140 mmHg systolic and/or ≥ 90 mmHg diastolic BP, taking antihypertensive medication, or being told by a physician on two separate occasions a person has high BP (4). Currently, 80 million adults (~32.6%) in the U.S. have hypertension (22). The lifetime risk for developing hypertension is 90%, and by 2030, it is estimated that about 41.4% of U.S. adults will have hypertension (22). Moreover, hypertension is the leading cause of death in women and the second-leading cause of death in men, only behind smoking (22). From 2003 to 2013, the number of deaths directly related to hypertension in the U.S. increased by 34.7% (22). Overall, due to the numerous adverse health outcomes associated with hypertension such as increased risk of stroke, CVD, and kidney failure, many professional organizations recommend lifestyle interventions such as exercise to prevent, manage, and treat hypertension (2, 4, 9, 10, 21, 24).

1.2 Exercise and Hypertension

Exercise is recommended by many professional health organizations as a safe and

effective antihypertensive lifestyle therapy to prevent, manage, and control hypertension (2, 4, 9, 10, 21, 24). The American College of Sports Medicine (ACSM) recommends primarily moderate intensity (40-<60% maximal oxygen consumption reserve) aerobic exercise on most days of the week supplemented by moderate intensity [60-80% 1-repetition maximum (1-RM)] resistance training 2-3 days per week to lower BP 5-7 mmHg among adults with hypertension (2, 24).

Muscular strength and blood pressure

Resistance training has been shown to be beneficial for cardiovascular and metabolic health (19, 25, 27, 29). In fact, resistance training has risen in popularity as an efficacious mode of exercise to prevent, manage, and control hypertension (5, 7, 24, 29). For example there are several epidemiological studies that show the positive association between muscle strength and BP (3, 17, 20).

Maslow et al. examined the association between muscular strength and hypertension cases across 19 years in 4,147 men (age, 43 ± 9 years) (20). At baseline 1,951 men had normal BP [systolic BP (SBP)/diastolic BP (DBP) $108.3 \pm 6.7/71.4 \pm 4.8$ mmHg] and 2,196 men had prehypertension ($120.2 \pm 8.1/80.4 \pm 5.1$ mmHg). Subjects were followed from baseline until the date they were diagnosed with hypertension or until June 30, 2004. Baseline muscular strength was assessed via a 1-RM supine bench press for upper body strength, and a 1-RM seated leg press for lower body strength. The authors found a significant relationship ($p < 0.01$) among hypertension incidence rates across categories of muscle strength. After follow-up, hypertension rates in those in the high and middle strength categories were 27% and 20% lower than those in the low muscular strength category, respectively (20). These findings suggest that muscular strength is inversely associated with the development of hypertension.

Artero et al. examined the impact of muscular strength on mortality in 1,506 men [age,

50.2 ± 7.4 years; body mass index (BMI), 26.9 ± 3.7] with hypertension (131.7 ± 13.9/89.9 ± 8.5 mmHg) from baseline assessment until their death or until December 31, 2003 (3). Participants were placed into tertiles based on muscular strength. After controlling for potential confounders including cardiorespiratory fitness, a higher level of muscular strength was significantly associated with a lower risk of all-cause mortality in men with hypertension (3). Furthermore those in the highest strength tertile had a significantly lower risk (~41%) of all-cause mortality compared to the lower third of muscular strength (3). These results not only support that greater muscular strength can be protective for the development of hypertension in healthy individuals, but also can be protective for premature mortality in individuals that already have hypertension (3).

In addition to the prospective studies above, Lawman et al. examined associations of grip strength with biomarkers of CVD risk that include serum lipids, plasma insulin, glucose, and BP in 4,221 participants from the National Health and Nutrition Examination Survey (2011-2012) (17). On average participants were middle aged (age, 47.5 ± 0.8 years) and had pre-hypertension (men: 123.1 ± 0.0/72.7 ± 0.6 mmHg); (women: 120.4 ± 0.8/70.6 ± 0.7 mmHg) (17). Isometric handgrip strength was measured using a hand-held dynamometer while the participant stood with the arm extended straight down to the side. Three measurements in each hand were recorded and absolute grip strength was calculated as the sum of the largest reading from each hand (kg). Relative grip strength was calculated as the absolute grip strength divided by the participant's BMI (17). Linear regression models demonstrated a higher relative grip strength was significantly associated with lower SBP, but not DBP when controlled for BMI ($p < 0.05$) (17).

Overall, the literature supports that higher upper and lower body muscular strength as measured by 1-RM as well as isometric handgrip strength is inversely associated with BP and the

development of hypertension (3, 17, 20). A higher muscular strength is also associated with a decreased incidence rate of early mortality in individuals with hypertension (3). These favorable associations between muscular strength and BP suggest that there are physiological differences as it relates to skeletal muscle between those with normal BP vs those with high BP.

1.3 Physiological Alterations in Skeletal Muscle in Those with High versus Normal BP during a Muscle Contraction

There are several physiological changes that occur in the skeletal muscle during a muscle contraction that include; an increase in heart rate, sympathetic nerve activity, and BP, regardless of resting BP status (13). The increase in BP during a muscle contraction is termed the exercise pressor reflex which is comprised of group III and IV skeletal muscle afferents that are regulated by mechanical and/or metabolic stimuli (8, 13, 14, 26). There are several studies that sought to determine differences in these physiological responses to a muscle contraction among those with high BP compared to individuals with normal BP (8, 12, 16).

Greaney et al. examined the BP and muscle sympathetic nerve activity responses at the immediate onset of muscle contraction in adults with hypertension as compared to normal BP (12). Heart rate, BP, and burst frequency (a measure of muscle sympathetic nerve activity) were measured in 15 individuals with hypertension (age, 62 ± 1 years; BP, $153 \pm 3/91 \pm 5$ mmHg) and 23 individuals with normal BP (age, 60 ± 1 years; BP, $112 \pm 1/67 \pm 2$ mmHg) during the first 30 seconds of isometric handgrip at 30% and 40% of the subjects' maximal voluntary contraction (12). For both intensities of handgrip, subjects with hypertension demonstrated a significantly greater increase in BP and burst frequency from rest within the first 10 seconds of exercise compared to subjects with normal BP ($p < 0.05$). Greaney et al. concluded that there are physiological differences in skeletal muscle based on resting BP due to the exaggerated pressor

response during the onset of exercise in those with hypertension versus those with normal BP (12).

Delaney et al. aimed to determine the contribution of the metabolic component of the exercise pressor reflex in response to static exercise in subjects with high versus normal BP (8, 12). Postexercise ischemia was used to trap the metabolites in the forearm produced during isometric handgrip exercise at 30% and 40% of the subjects' maximal voluntary contraction (8). Heart rate, BP, and muscle sympathetic nerve activity were measured at both handgrip intensities as well as during postexercise ischemia in 23 individuals with normal BP (age, 60 ± 1 years; BP, $112 \pm 1/67 \pm 2$ mmHg) and 15 individuals with hypertension (age, 63 ± 1 years; BP, $153 \pm 3/91 \pm 5$ mmHg) (8). By measuring muscle sympathetic nerve activity during postexercise ischemia, Delaney et al. was able to assess the influence of the metabolic component of the exercise pressor reflex, via trapped metabolites in the skeletal muscle. The group with hypertension exhibited a significantly higher change in mean arterial pressure as well as muscle sympathetic nerve activity during both 30% and 40% handgrip maximal voluntary contraction and also during the period of postexercise ischemia (8). Due to the exaggerated sympathetic and pressor responses to handgrip exercise that were maintained during postexercise ischemia in the group with hypertension compared to the normal BP group, the authors concluded that the metabolic component of the exercise pressor reflex is heightened in adults with hypertension (8).

In addition to exaggerated exercise pressor reflex and muscle sympathetic nerve activity, individuals with high BP also have increased vasoconstriction in the skeletal muscle vasculature compared to those with normal BP (23, 28). Increases in vasoconstriction and muscle sympathetic nerve activity ultimately lead to a state of hypoxia in the skeletal muscle due to having high BP, which further augments oxidative stress (11, 28). These negative physiological

alterations associated with high BP eventually lead to vascular wall thickening and skeletal muscle damage (11, 23, 28). Furthermore, during states of hypoxia there is evidence of changes in skeletal muscle metabolism from oxidative metabolism to an increase in glycolytic metabolism (11). Accompanying increases in glycolytic metabolism there is also a shift in skeletal muscle fiber recruitment from Type I to an increase in Type IIb/x muscle fibers due to hypoxia (11). This shift in muscle metabolism from oxidative to increased glycolytic and muscle fiber recruitment from Type I to increased Type IIb/x is associated with decreased muscle strength among those with congestive heart failure and chronic obstructive pulmonary disease (11). Clearly there are differences in the response to a muscle contraction in those with high BP vs those with normal BP which may affect muscle strength such as exaggerated exercise pressor reflex and muscle sympathetic nerve activity as well as increased vasoconstriction and changes in metabolism and muscle fiber recruitment (8, 12). In addition there is clear evidence showing an inverse relationship between muscular strength and resting BP, therefore one would assume an increased resting BP would be associated with decreased muscle strength (3, 17, 20). However the affect resting BP status has on muscular strength during a single muscle contraction has not been established.

1.4 Specific Aims and Hypotheses

The purpose of this study was to examine the relationship between resting BP and measures of muscle strength among healthy men and women distributed equally across the lifespan. Data for this study was from a larger study entitled, "The Effects of Statins on Muscle Performance" (STOMP) (NIH RO1 HL081893-01A2).

Specific Aim 1: To assess the relationship between resting BP and baseline muscle strength in healthy men and women distributed equally across the lifespan.

Hypothesis 1: Individuals with high BP (pre- to established hypertension) will exhibit decreased muscle strength during both isometric and isokinetic muscle strength measures compared to those with normal BP.

Alternative Hypothesis 1: Individuals with high BP will exhibit increased muscle strength during both isometric and isokinetic muscle strength measures compared to those with normal BP.

1.5 Significance of Study

Currently, ~32.6% of American adults have hypertension, making it the most prevalent risk factor for the development for CVD (22). Moreover, of those with hypertension, only 82.7% were aware of their condition, 76.5% of those who had been diagnosed were being treated, and only 54.1% are properly controlled to therapeutic levels (SBP < 120 and DBP < 80 mmHg) (22). Without intervention, the prevalence of hypertension is expected to increase to 41.4% of the U.S. adult population by 2030, and the total cost related to hypertension is expected to increase from \$48.6 billion to \$274 billion (22). Therefore, lifestyle interventions such as exercise including resistance training should be recommended in order to effectively lower BP among adults with hypertension (2, 18, 24).

In support of resistance training as an anti-hypertensive therapy, several longitudinal studies show an inverse relationship between muscular strength and rates of hypertension as well as mortality in those with hypertension (3, 17, 20). In addition multiple meta-analyses show that participating in a resistance training program lowers BP and supports the fact that those with high BP will have lower muscle strength (6, 15). Moreover there is evidence that the physiological responses to a muscle contraction are different in those with hypertension compared to those with normal BP, and that changes in muscle metabolism and muscle fiber

recruitment due to alterations in skeletal muscle vasculature may negatively affect muscle strength (8, 12, 13). To date no one has directly assessed the relationship between resting BP and muscle strength. This study could give insight into the affect that resting BP has on skeletal muscle strength during a single contraction by assessing differences in muscle strength across resting BP levels.

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Chapter 2
The Influence of Resting Blood Pressure on Muscle Strength in Healthy Adults

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2.1 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 has not been examined. **PURPOSE:** We hypothesized adults with high BP would exhibit lower muscular strength than adults with normal BP. **METHODS:** An isokinetic dynamometer tested 21 measures of upper and lower body isometric and isokinetic muscle strength. BP was measured by auscultation. Subjects were categorized as having normal (<120 & <80 mmHg) or high (≥ 120 & /or ≥ 80 mmHg) BP. Height (cm) and weight (kg) were measured to calculate body mass index (BMI, $\text{kg}\cdot\text{m}^{-2}$). Analysis of covariance tested differences in muscle strength between BP groups with gender, age and BMI as covariates. **RESULTS:** Subjects ($n=420$, 49% men) were middle-aged (44.1 ± 16.1 yr) and overweight (26.4 ± 4.8 $\text{kg}\cdot\text{m}^{-2}$) with 187 having normal ($107.7\pm 7.3/68.3\pm 6.3$ mmHg) and 233 high ($127.8\pm 9.8/80.8\pm 8.1$ mmHg) 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 ($p\leq 0.05$). 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 ($p>0.05$). **CONCLUSION:** Contrary to our hypothesis, adults with high BP displayed greater muscle strength than adults with normal BP, particularly in the biceps, triceps, and quadriceps. Reasons for our findings are unclear but may be due to a shift in muscle fiber type from Type I to Type IIb/x and oxidative to glycolytic metabolism. These alterations would result in a more strength-adapted phenotype that have been shown to occur in disease states with altered vascular control as is seen with hypertension.

Key Words: Dynamometer, Exercise, Hypertension, Prehypertension

2.2 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 (20). One in five people with prehypertension will develop hypertension within 4 year of the diagnosis of prehypertension, and the lifetime risk for developing hypertension is 90%. By 2030, it is estimated about 41.4% of adults in the U.S. will have hypertension (20). Adults with high blood pressure (BP) have a higher risk for stroke, myocardial infarction, and CVD death (20). 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 (9, 23-25).

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 (6, 18, 23, 30). Resistance training is reported to elicit BP reductions of 2-3 mmHg among adults with hypertension (6, 14, 23), and is 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 (1, 15, 19).

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 (4, 11, 12, 21, 28). These alterations create a state of hypoxia in the skeletal muscle which augments oxidative stress further, eventually leading to vascular wall thickening and skeletal muscle damage (10, 21, 28). 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 (10, 28). 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 the several negative physiological alterations in the skeletal muscle that is associated with high BP.

2.3 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) (27) that was approved by the Institutional Review Boards of Hartford Hospital, the University of Massachusetts-Amherst, and the University of Connecticut-Storrs. All data reported for this 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 (m) in order to calculate body mass index (BMI, $\text{kg}\cdot\text{m}^{-2}$) (23). Waist circumference (cm) was measured using a non-distensible Gulick tape measure (23, 27).

Blood Pressure

Resting BP was determined according to American Heart Association guidelines (26) 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 (27).

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 (27). 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) (27). 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°/s followed by an additional 5 min rest and then four maximal contractions were performed in succession at 3.14 rad/s or 180°/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°/s followed by an additional 5 min rest and then four maximal contractions were performed in succession at 3.14 rad/s or 180°/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; VO_{2max}) 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 (27). 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 (23, 27).

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. The sample was divided by resting BP into two groups: 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 gender were tested using one-way analysis of variance (ANOVA). To test the relationship between resting BP status and baseline muscle strength an ANCOVA was performed with BP group as a fixed factor and age, gender and BMI 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).

2.4 RESULTS

Blood Pressure and Muscle Strength

Subject Characteristics (Table 1)

On average subjects ($n=420$) were middle-aged, overweight, and had normal BP. The sample was approximately evenly divided by resting BP status, with 45% having normal BP and 55% having high BP (i.e., pre-hypertension [42%] or established hypertension [13%]). Only 24 (6%) subjects were taking antihypertensive medications. When stratified by resting BP status, the group with normal BP was younger, and had lower BMI and waist circumference than those with high BP ($p<0.001$). Women 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 (16), the high BP group had greater muscular strength for elbow flexion average peak torque (adjusted mean difference \pm SD; 1.4 ± 13.2 ; $p=0.01$) and elbow flexion average power (0.9 ± 24.7 ; $p<0.001$) compared to the normal BP group. There were no statistically significant differences between BP groups for the two upper body extension measures ($p>0.05$).

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 (6.8 ± 49.5 ; $p=0.02$) and knee extension average power (12.1 ± 99.0 ; $p=0.05$) 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, the high BP group had greater muscular strength for all elbow strength measures including: isometric extension average peak torque (0.0 ± 24.7 ; $p=0.02$); isometric flexion average peak torque (1.4 ± 26.3 ; $p<0.001$); extension average peak torque (1.1 ± 17.5 ; $p=0.02$); flexion average peak torque (0.3 ± 14.6 ; $p=0.01$); extension average power (1.2 ± 14.6 ; $p<0.001$); and flexion average power (0.2 ± 13.2 ; $p<0.001$) compared to the normal BP group. In addition, handgrip strength (1.1 ± 17.4 ; $p<0.001$) 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 (14.1 ± 96.1 ; $p=0.01$); extension average peak torque (6.8 ± 62.6 ; $p=0.02$); and extension average power (5.3 ± 46.6 ; $p<0.001$). There were no differences between BP groups for the three knee flexion measures ($p>0.05$).

2.5 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. 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 on 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 (16); all extension and flexion upper body isometric measures, six 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 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 \pm 1.4 yr) and 44,625 adolescent girls (15.0 \pm 1.4 yr) with normal BP (8). Adolescents were stratified by BMI as being thin, normal, overweight, or obese according to sex- and age-specific normative values (5). Dong et al. (8) found a positive relationship between handgrip strength and resting BP after stratifying by and/or adjusting for BMI in the adolescents ($p \leq 0.05$).

Several primary level studies exist that may lend support and mechanistic insight into our findings and those of Dong et al. (8). 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 affect muscle strength (4, 7, 11, 13, 17). For example, there is evidence showing vascular

function in the skeletal muscle is impaired during exercise with high BP (29). Vongpatanasin et al. sought to examine if functional sympatholysis is impaired among otherwise healthy 13 middle aged men and women with hypertension (SBP/DBP, $144 \pm 4/ 87 \pm 2$ mmHg) compared to 17 middle aged men and women with normal BP (SBP/DBP, $118 \pm 3/ 72 \pm 2$ mmHg) (29). 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 (29). 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.

Similarly Nyberg et al. examined leg blood flow regulation and oxygenation before and after eight weeks of aerobic training among 10 middle aged adults with hypertension (SBP/DBP, $183 \pm 7/ 101 \pm 5$ mmHg) compared to 11 middle aged adults with normal BP (SBP/DBP, $119 \pm 4/ 70 \pm 2$ mmHg) (22). At baseline, those with hypertension had decreased leg blood flow and oxygen delivery compared to the normal BP group during 10, 20, and 30 watts of knee-extensor exercise ($p \leq 0.05$) (22). Overall Nyberg et al. (22) findings support those of Vongpatanasin et al. (29) such that during acute bouts of resistance exercise oxygen delivery to the working skeletal muscles is reduced in those with high BP compared to those with normal BP.

There is further 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 (3, 10, 13, 21). The increased reliance on glycolytic metabolism can result in a shift in muscle fiber type recruitment

from Type I to an increase in Type IIb/x that has been documented in disease states such as chronic obstructive pulmonary disease and chronic heart failure (10). In addition, there is evidence demonstrating differences in hormonal responses to having high BP versus normal BP (2). Batool et al. (2) found women with hypertension had higher levels of testosterone compared to women with normal BP. Collectively, these findings provide mechanistic insight into 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 could have given more information about our speculation into muscle fiber recruitment. Additional measurements such as electromyography, magnetic resonance imaging, ultrasound, and muscle sympathetic nervous activity could have added 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 that allowed us to account for BMI in our statistical analyses, an important confounding factor to consider in the association between resting BP and muscle strength. The larger STOMP methods used gold standard measurement protocols for both resting BP (26) and upper and lower body

muscle strength. Also, 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.

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

| 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‡ |
| 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

Gender difference, * p \leq 0.05, ** p \leq 0.001; resting BP Status difference, ‡p \leq 0.001

2.7.2 Table 2. Adjusted baseline muscle strength measures performed at 180°/sec⁺

(Adjusted Mean ± SD) by resting blood pressure status

| Muscle Strength Measures at 180°/sec | Normal BP (n=187) | High BP (n=233) |
|--------------------------------------|----------------------|--------------------|
| Upper Body (N-M) | | |
| Isokinetic Extension ¹ | 31.1 ± 6.9 | 32.4 ± 7.7 |
| Isokinetic Flexion ¹ | 29.6 ± 6.9 | 31.0 ± 6.1** |
| Isokinetic Extension ² | 56.7 ± 16.4 | 59.3 ± 16.8 |
| Isokinetic Flexion ² | 49.4 ± 12.3 | 50.3 ± 12.2** |
| Lower Body (N-M) | | |
| Isokinetic Extension ¹ | 96.0 ± 24.7 | 102.8 ± 24.5* |
| Isokinetic Flexion ¹ | 52.7 ± 15.1 | 55.8 ± 15.3 |
| Isokinetic Extension ² | 175.9 ± 49.3 | 188.0 ± 49.0* |
| Isokinetic Flexion ² | 90.7 ± 34.3 | 96.6 ± 35.2 |

Note: Normal vs High BP status adjusted for age, gender, and BMI, * $p \leq 0.05$,

** $p \leq 0.01$. ⁺Accurate predictor of Type II muscle fiber recruitment; ¹ average peak torque;

² average power; BP, blood pressure.

2.7.3 Table 3. Adjusted baseline isometric and isokinetic muscle strength measure performed at 60°/sec

(Adjusted Mean ± SD) by resting blood pressure status

| Muscle Strength Measures | Normal BP (n=187) | High BP (n=233) |
|-----------------------------------|------------------------------|----------------------------|
| Handgrip (kg) | 38.8 ± 8.2 | 39.9 ± 9.2** |
| Upper Body (N-M) | | |
| Isometric Extension ¹ | 44.1 ± 12.3 | 44.1 ± 12.2* |
| Isometric Flexion ¹ | 51.5 ± 13.7 | 52.9 ± 12.2** |
| Isokinetic Extension ¹ | 38.7 ± 8.2 | 39.8 ± 9.2* |
| Isokinetic Flexion ¹ | 34.5 ± 6.9 | 34.8 ± 7.7** |
| Isokinetic Extension ² | 29.2 ± 6.9 | 30.4 ± 7.7** |
| Isokinetic Flexion ² | 26.1 ± 6.9 | 26.3 ± 6.1** |
| Lower Body (N-M) | | |
| Isometric Extension ¹ | 182.9 ± 48.0 | 197.0 ± 47.4** |
| Isometric Flexion ¹ | 80.2 ± 19.2 | 83.9 ± 19.9 |
| Isokinetic Extension ¹ | 143.7 ± 31.5 | 150.5 ± 30.6* |
| Isokinetic Flexion ¹ | 75.1 ± 19.2 | 77.6 ± 19.9 |
| Isokinetic Extension ² | 98.7 ± 23.3 | 104.0 ± 23.0** |
| Isokinetic Flexion ² | 55.6 ± 13.7 | 56.5 ± 13.8 |

Note: Normal vs High BP status adjusted for age, gender, and BMI,

* $p \leq 0.05$, ** $p \leq 0.01$. ¹ average peak torque; ² average power; BP, blood pressure.

Chapter 3. Methods

The present 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 RO1 HL081893-01A2). STOMP was approved by the Institutional Review Boards of Hartford Hospital, the University of Massachusetts-Amherst, and the University of Connecticut-Storrs (9). Written consent was obtained from all participants. The specific aims of STOMP were to examine the incidence rate of statin-induced myalgia and the effects of statins on muscle strength, endurance, and aerobic exercise performance in a healthy population taking 80 mg Atorvastatin or a placebo (9). Data used for the present study were collected at baseline prior to randomization to either a placebo or 80 mg of Atorvastatin among 204 healthy males and 216 females distributed equally across the lifespan with a mean \pm standard deviation (SD) age of 44.1 \pm 16.1 years (6).

3.1 Subject Recruitment: Inclusion and Exclusion

A total of 468 subjects were recruited over 4 years at three sites (Hartford Hospital, University of Massachusetts, and University of Connecticut) and were equally distributed into 3 age groups (20-39, 40-54, and >55 year) (6, 9). Subjects were excluded for the following reasons; 1) cancer diagnosis within 5 years, 2) renal disease (creatinine level >2 mg/L), 3) hepatic disease (alanine amino-transferase value >2 times the upper limit of normal), 4) abnormal thyroid-stimulating hormone level, 5) history of CVD, 6) abnormal or ischemic-appearing ECG during exercise, 7) diabetes mellitus, 8) subjective muscle complaints or weakness, 9) physical disabilities that would inhibit exercise testing, and 10) present or previous treatment with lipid lowering medications, or medications that would alter statin metabolism (6, 9). Women who were pregnant or planning to become pregnant were excluded. All women in the

study of child-bearing age agreed to use an established method of birth control throughout. Lastly, subjects with hypertension were included if their BP was controlled and $\leq 140/90$ mmHg at baseline (9). During the study, subjects were removed if their creatine kinase exceeded 10 times the upper limit of normal at any point or if their alanine amino-transferase exceeded 3 times the upper limit of normal on 2 measurements performed within 1 week of the first elevated value (6).

3.2 Study Overview

The study consisted of six visits over ~6 months. Prior to the first visit, if a potential subject expressed interest, a phone interview was performed to determine if the subject met the inclusion and exclusion criteria. If the subject met the eligibility, they attended an orientation session which was deemed visit 1 (V1) (9).

V1 involved the informed consent process, measurement of vital signs and anthropometrics, a brief physical examination by a physician, strength testing of the elbow, knee and handgrip, and a Bruce Protocol maximal treadmill exercise test to exclude those with documented cardiac ischemia (3). A fasting blood sample was taken for measurement of low-density lipoprotein cholesterol (LDL), high-density lipoprotein cholesterol (HDL), triglycerides, 25-hydroxy vitamin D, thyroid-stimulating hormone, alanine aminotransferase (ALT), creatinine, creatine kinase (CK), and creatine kinase MB (CKMB). Lastly subjects completed several surveys including the Paffenbarger Physical Activity questionnaire, the Short-Form McGill Pain questionnaire, and the Brief Pain Inventory (Short Form) (9).

Approximately 72 hr after the completion of V1 subjects completed visit 2 (V2). During V2 subjects performed strength testing via the Biodex System 3 Isokinetic Dynamometer (Biodex Medical, Shirley, NY) of the elbow and knee, as well as endurance testing of the knee.

A handgrip dynamometer was used to assess handgrip strength. Next, another maximal treadmill exercise test was performed, this time following a modified Balke protocol to assess VO_{2max} (1). After testing, subjects left the site with an Actical PA accelerometer (Mini Meter, a Respironics Inc., Bend, OR) which was worn for 96 consecutive hours to assess PA levels (9).

Visit 3 (V3) was performed at least 96 hours following V2 in order to obtain the Actical accelerometer data. Subjects then completed another assessment of muscle strength of the elbow and knee as well as handgrip. During V3, subjects were randomized to either Atorvastatin 80mg or placebo group in which a 3 month supply was dispensed. This visit was deemed week 0. Prior to visit 4 (V4), subjects received a telephone call from study investigators at weeks 2, 4, 6, 8, and 10 in order to assess medication compliance and any symptoms or adverse events (9).

Subjects returned to the testing site at week 12 for V4. A fasting blood draw was taken for measurement of ALT, CK, and CKMB. Medication compliance and any symptoms or adverse events were also assessed. During V4, a second 3 month medication supply was dispensed. After V4 subjects received phone calls from investigators at weeks 14, 16, 18, 20, and 22 in which medication compliance and any symptoms or adverse events were assessed (9).

Subjects returned to the testing site at week 24 which was visit 5 (V5). A fasting blood draw was taken for measurement of LDL, HDL, triglycerides, ALT, creatinine, CK, CKMB, and vitamin D. Vital signs and anthropometric measures were taken as well as another measure of muscle strength of the elbow and knee and handgrip. Subjects' VO_{2max} was assessed by performing a maximal graded exercise treadmill test using the modified Balke protocol (1). Subjects also completed the Paffenbarger physical activity questionnaire, the Short-Form McGill Pain questionnaire, and the Brief Pain Inventory (Short Form) (4, 5, 8). Lastly, subjects left V5 wearing the Actical accelerometer for another 96 hours (9).

The last visit was visit 6 (V6) approximately 96 hours after V5. The Actual data was downloaded while subjects performed another strength testing of the elbow and knee as well as handgrip (9).

3.3 Anthropometric Measurements

This sub-study used baseline anthropometrics measured at V1. Subjects' body weight (kg) was measured by a calibrated beam scale. A wall-mounted tape measure was used to measure height (in), after the removal of shoes and any heavy clothing, to calculate body mass index (BMI) ($\text{kg}\cdot\text{m}^{-2}$). Waist circumference (cm) was measured with a Gulick spring-loaded non-dispensable tape measure (Sammons Preston, Chicago, IL) at the narrowest part of the torso above the umbilicus and below the xiphoid process while the subject stood with their arms at their sides, feet together, and abdomen relaxed (1, 9). The average of two measurements were recorded, provided the measurements were within 5 mm of one another. If the two measurements were not within 5 mm of one another, the study investigator continued to take waist circumference measurements until there were two measurements that were within 5 mm of one another and these were averaged (9).

3.4 Muscle Strength

Muscle strength was measured through different measures including handgrip strength, elbow and knee flexion and extension. Strength testing during V1 was used to familiarize the subject with the equipment and the protocol used, and the strength measures from V2 and V3 were averaged and recorded (9). The average strength measures from V2 and V3 were taken prior to randomization and these measures were used in this sub-study.

Isometric handgrip strength was performed using a handgrip dynamometer. Subjects completed three maximal contractions in the dominant hand lasting 3 seconds each, seated with

the elbow flexed at 90 degrees. A total of three trials were performed with 1 minute of rest in between each contraction. The three trials were averaged and recorded in kg (9).

Elbow flexion/extension and knee flexion/extension isometric and isokinetic tests were measured using the Biodex System 3 Isokinetic Dynamometer (Biodex Medical, Shirley, NY) (9). Subjects warmed up by performing three submaximal contractions prior to each test.

For elbow isometric strength, subjects performed three isometric contractions for both flexion and extension with the elbow fixed at 90 degrees. Subjects were given a 1 minute rest in between each contraction. After 5 minutes of rest, elbow isokinetic strength was measured by first having the subjects perform four contractions at 1.05 rad/s (60 deg/s). After an additional 5 minutes of rest subjects performed four isokinetic contractions at 3.14 rad/s (180 deg/s) (9). Average peak torque and average power (Nm) was recorded.

For knee isometric strength, subjects performed three isometric contractions for both flexion and extension with the knee fixed at 110 degrees. Subjects were given a 1 minute rest in between each contraction. After 5 minutes of rest, knee isokinetic strength was measured by having the subjects perform four contractions at 1.05 rad/s (60 deg/s) followed by another 5 minutes of rest. Then subjects performed four isokinetic contractions at 3.14 rad/s (180 deg/s) (9). Average peak torque and average power (Nm) was recorded (9).

3.5 Resting Blood Pressure

Resting blood pressure (BP) was determined according to American Heart Association guidelines with a Welch Allyn floor manual sphygmomanometer after subjects were seated for 5 minutes of rest with both feet flat on the floor, legs uncrossed, and their back supported (7). A minimum of two readings 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 and were averaged. The first and last audible sounds were recorded as systolic (SBP) and diastolic (DBP) pressure, respectively (7, 9).

3.6 Cardiorespiratory Fitness (VO_{2max})

The cardiorespiratory fitness (VO_{2max}) data that was used for this sub-study was recorded at baseline from V2. VO_{2max} was assessed using a breath-by-breath analysis of expired gases by the Parvomedics True One 2400 Metabolic Cart (ParvoMedics Corp, Sandy, UT) (9). Prior to the start of the test subjects sat quietly for 5 minutes in order to ensure resting conditions. The subject then began to walk on the treadmill at 2 miles per hour with a 0% incline for 2 minutes. After choosing a speed that the subject could maintain comfortably throughout the remainder of the test, the treadmill incline increased 1% every minute following the initial 2 minute walk. BP, heart rate, and rating of perceived exertion (RPE) was measured throughout the test (2, 9). The test was terminated when one or more of the following conditions were met: the subject reported a RPE of 18, the subject had a respiratory exchange ratio greater than 1.1, the subject achieved their age predicted maximum heart rate, there was a plateau in oxygen uptake, and/or the subject self-terminated due to fatigue or discomfort (1, 9).

3.7 Data Administration

Data collected during STOMP was compiled into an online master database, which was maintained by the study coordinator at Hartford Hospital. Investigators from the three study sites manually entered STOMP data into the online database. The master database was only accessed by study personnel and was secured by confidential usernames and passwords (6).

3.8 Statistical Analyses

All statistical analyses were performed using SPSS Statistics 19.0 (IBM Corporation, New York). Since muscle strength variables were not normally distributed, all muscle strength

measures were log-transformed for analyses. For variables that were log transformed, the mean outcome was then back-transformed from the mean of the log transform for ease of clinical interpretation. For analyses, subjects were broken into two groups based on BP status: a group with normal BP (SBP <120 mmHg and DBP <80 mmHg; n=187) and a group with pre- to established hypertension (SBP \geq 120 mmHg and/or DBP \geq 80 mmHg; n=233). Subject descriptive statistics between genders and BP status were compared using one-way analysis of variance (ANOVA). Subject descriptive results are displayed as mean \pm standard deviation (SD). To determine the relationship between BP and baseline muscle strength an ANCOVA was performed while controlling for age, gender, and BMI. All two-way interactions between variables were used in the ANCOVA models. Non-significant interactions were individually removed until only significant interactions remained in the model. Muscle strength results are displayed as mean \pm standard deviation (SD). Statistical significance was set at an alpha level of $p \leq 0.05$.

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Chapter 4. Discussion

The primary purpose of this thesis was to examine the relationship between resting BP and muscle strength. We sought to examine this relationship by testing the influence of resting BP on 21 measures of upper and lower body muscle strength in 420 healthy adults across the lifespan, of which 45% had normal BP and 55% had high BP. Initially the specific aims and hypotheses will be discussed followed by a summary of significant findings. I will then discuss methodological considerations, specifically related to the scientific method that may have led to our unexpected findings and how our findings add to the current literature. Finally, directions for future research pertaining to the findings will be suggested.

4.1 Specific Aims and Hypothesis

Specific Aim 1: To examine the relationship between resting BP and measures of muscle strength among healthy, adult men and women equally distributed across the lifespan.

Hypothesis 1: Adults with high BP would exhibit decreased upper and lower body muscle strength compared to those with normal BP. Contrary to our hypothesis we found adults with high BP had greater muscle strength than those with normal BP. The high BP group had greater muscle strength on four out of the eight upper ($p \leq 0.01$) and lower body ($p \leq 0.05$) isokinetic measures performed at 180°/sec, all extension and flexion upper body isometric measures ($p \leq 0.05$), six out of eight upper and lower body isokinetic measures performed at 60°/sec ($p \leq 0.05$), and one out of two lower body isometric measures ($p \leq 0.01$). Those with high BP appear to generally have a higher muscle strength phenotype than those with normal BP, particularly in the biceps, triceps, and quadriceps as well as handgrip.

4.2 Methodological Considerations: Importance of Implementing the Scientific Method

I examined methodological considerations and aspects of the scientific method to explain our unexpected findings. First, with the help of a medical librarian, I performed a literature search to locate available evidence on muscle strength and BP. Reference lists of qualified trials from the literature review were searched for additional studies of interest. Trials located by the search included the relationship between cardiovascular risk factors, specifically BP, and muscle strength among adults. These trials consistently demonstrated an inverse relationship between muscular strength and BP, in that higher muscle strength was associated with having a lower resting BP as well as associated with a delay in early mortality (1, 4, 5, 12). Also the negative effects of having high BP on skeletal muscle physiology and in turn exercise performance were apparent due to evidence of increases in the exercise pressor reflex, sympathetic nerve activity, and decreases in blood flow and oxygen delivery during a muscle contraction (3, 6, 9). Therefore, I formulated my hypothesis that adults with high BP would exhibit decreased muscular strength on the limited but available evidence in the literature.

Nonetheless, we found unexpected results that did not align with our initial hypothesis. We found adults with high BP generally had an increased muscle strength compared to those with normal BP. These are unexpected results because the literature we searched showed there exists an inverse relationship between BP and muscular strength. Also it is known the negative effects from having high BP reduces exercise capacity and more specifically skeletal muscle function (3, 7). As a result, there is a question as to what possible mechanisms would explain the positive association between resting BP and muscle strength that we found. Therefore we then had to perform an additional literature search in order to find evidence that might support our novel findings. Ultimately we found there alterations such as decreased blood flow and oxygen delivery to working skeletal muscles in those with high BP compared to those with normal BP,

which creates a state of hypoxia in the skeletal muscle (8, 11). Due to the state of hypoxia, there is some evidence suggesting a shift in muscle fiber type recruitment from Type I to Type IIb/x as well as a shift in energy metabolism from oxidative to an increase in glycolytic, creating an increased muscle strength adapted phenotype (3, 7). Now we as well as other authors are able to form additional questions and hypothesis based on our unexpected results and proposed mechanisms.

4.3 Impact on the Current Literature

To our knowledge, this is the first study to directly assess the impact of resting BP on muscle strength in healthy adults distributed across the lifespan. We are the first to show that adults with pre- to established hypertension exhibited an increased muscle strength in the upper and lower body compared to adults with normal BP. However, there is recent evidence that this positive relationship exists in adolescents with normal BP. Dong et al. (2) examined the association between BP and handgrip strength 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. After subjects were stratified by BMI into thin, normal, overweight, or obese Dong et al. (2) found that those with a higher resting BP displayed a higher muscular strength. This positive relationship existed after adjusting for BMI across both genders in the entire sample, as well as across BMI groups after stratification. This supports our findings albeit in a generally healthy adolescent population with normal BP (2).

In addition there is evidence of physiological alterations in the skeletal muscle of those with high compared to normal BP both at rest and during acute exercise that may affect muscle strength (6, 7, 10). However, none of these studies have examined the influence of BP on muscle strength directly, but rather what changes in skeletal muscle physiology and function exist

between individuals with normal compared to high BP. For example Vongpatanasin et al. (11) examined the difference in functional sympatholysis, via muscle oxygenation and forearm blood flow, among 13 middle aged men and women with hypertension compared to 17 middle aged men and women with normal BP. They found subjects with hypertension had a decreased muscle oxygenation and forearm blood flow, which was limited by an impaired functional sympatholysis compared to those with normal BP (11). Ultimately due to the decrease oxygen availability to working skeletal muscle, there is an increased reliance of glycolytic metabolism and in turn an increase recruitment of Type II muscle fibers.

Overall evidence exists that shows a positive association between resting BP and muscle strength in adolescents, as well as physiological changes that may influence a stronger muscle strength adapted phenotype in those with high BP compared to normal BP. Nonetheless, we were the first to examine and show that healthy adults distributed equally across the lifespan with high BP generally had an increased muscle strength compared to those with normal BP. Due to our unexpected and novel results, future studies are warranted to confirm this positive association as well as measure potential mechanisms.

4.4 Future Research

This thesis provides evidence that adults with high BP generally showed an increased muscle strength in both the upper and lower body. Potential mechanisms behind these unexpected findings were not measured and therefore can only be speculated at this time. Thus, future studies should assess the impact of resting BP on muscular strength while measuring potential mechanisms gaining insight into these relationships.

Also this study included otherwise healthy adults with the majority having prehypertension in the high BP group. Future studies should examine the relationship between

resting BP and muscle strength among equal numbers of individuals with normal BP, prehypertension, and hypertension to establish if there are potential differences in muscle strength among BP status.

4.5 Conclusion

To our knowledge we are the first to show that adults free from cardiovascular disease or conditions distributed across the lifespan demonstrated an increased muscular strength in the upper and lower body compared to adults with normal BP. Therefore future studies are needed to confirm our original findings, and also investigate possible mechanisms into why adults in the early stages of hypertension have an increased muscular strength during an acute muscle contraction.

4.6 References

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