Differences in Blood Flow Patterns and Endothelial Shear Stress at the Carotid Artery Using Different Exercise Modalities and Intensities.

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Data Availability: Data and Data analysis R scripts are available upon request.

Funding: Research reported in this publication was partially supported by the National Institute of General Medical Sciences of the National Institutes of Health under Award Number SC2GM140952.

Acknowledgments: The authors would like to thank the participants for their continued effort in the testing sessions.

# Abstract

Endothelial dysfunction is the first pathophysiological step of atherosclerosis, which is responsible for 90% of strokes. Exercise programs aim to reduce the risk of developing stroke; however, the majority of the beneficial factors of exercise are still unknown. Endothelial shear stress (ESS) is associated with endothelial homeostasis. Unfortunately, ESS has not been characterized during different exercise modalities and intensities in the carotid artery. Therefore, the purpose of this study was to determine exercise-induced blood flow patterns in the carotid artery. Fourteen apparently healthy young adults (males=7, females=7) were recruited for this repeated measures study design. Participants completed maximal oxygen consumption (VO2max) tests on a Treadmill, Cycle-ergometer, and Arm-ergometer, and 1-repetition maximum (1RM) tests of the Squat, Bench Press (Bench), and Biceps Curl (Biceps) on separate days. Thereafter, participants performed each exercise at 3 different exercise intensities (low, moderate, high) while a real-time ultrasound image of the carotid artery was obtained. Blood flow patterns were assessed by estimating ESS via Womersley’s estimation and turbulence via Reynold’s number (Re). Data were analyzed using a linear mixed-effects model. Pairwise comparisons with Holm-Bonferroni correction were conducted with Hedge’s g effect size to determine the magnitude of the difference. There was a main effect of intensity, exercise modality, and intensity \* exercise modality interaction on both ESS (p<0.001). Treadmill at a high intensity yielded the greatest ESS when compared to the other exercise modalities and intensities, while Bench Press and Biceps curls yielded the least ESS. All exercise intensities across all modalities resulted in turbulent blood flow. Clinicians must take into consideration how different exercise modalities and intensities affect ESS and Re of the carotid artery.

Keywords: Endothelial Shear Stress, Blood Flow Patterns, Aerobic Training, Resistance Training

# Introduction

Cardiovascular (CV) diseases, including coronary artery disease and stroke, are the leading cause of death worldwide. One in every 19 deaths are produced by a stroke, and there are more than 610,000 new cases of stroke per year. The total direct and indirect costs of stroke for the USA are estimated to be around 34 billion dollars (Benjamin et al., 2017). Atherosclerosis is responsible for 9 in every 10 cases of Stroke (Qaja & Bhimji, 2017); in addition, CV comorbidities are common features among stroke survivors (Tang et al., 2009).

Endothelial dysfunction is recognized as the first step for the development of almost all CV diseases (Benjamin et al., 2017), is a pathological condition characterized by an unbalance between vasodilatory and vasoconstrictory mechanisms (Flammer et al., 2012), and generally defined as the decrease in nitric oxide (NO) bio-availability within the endothelium (Harris et al., 2010). An underlying mechanism that regulates endothelial function in endothelial shear stress (ESS), which is the frictional force produced between blood flow and endothelial cells (Sriram et al., 2016); where increments of ESS (e.g. during exercise) are known to improve endothelial nitric oxide synthase (eNOS) gene expression (Ishibazawa et al., 2011) and NO bioavailability (ref). Exercise programs are one of the best suited approaches to prevent CV comorbidities and a subsequent stroke (Jurczak et al., 2014; Kirk et al., 2014; Marzolini et al., 2014; Prior et al., 2017; Tang et al., 2009), however, to the best of our knowledge, there are no studies regarding carotid ESS during different modalities of exercises and intensities.

The purpose of this study was to determine exercise-induced blood flow patterns across different exercise modalities at three different intensities in the carotid artery. It was hypothesized that ESS and turbulent flow in the carotid artery would increase in an intensity-dependent manner and that exercises involving larger and more muscle groups would have larger ESS and more turbulent flow.

# Methods

## Experimental Design

Twenty participants were recruited for a repeated-measures study design. Participation within the study involved 4 sessions for maximal testing and 2 sessions of ultrasonography testing. A priori power analysis was conducted in Rstudio using R statistical programing language and the “pwr” library; a total of 14 subjects with stratification by sex (7 per group) at an alpha level (α) of 0.05 with a large effect size (f) of 0.4, was determined to be enough to obtain power (β) of 0.80. All study protocols were in accordance with the Declaration of Helsinki and were approved by the Institution Review Board at the University of Texas at El Paso (Reference number: 1250657). All participants signed an informed consent form before engaging in their first testing session. Females were tested within a period that spanned four days before to four days after menses to reduce any hormonal influence on vascular reactivity (Adkisson et al., 2010; Mattu et al., 2020).

*Study Protocol*

Participants completed demographic and screening questionnaires to determine eligibility. Height and mass were taken using a calibrated stadiometer and scale, respectively (Detecto, STATE, USA). Then, resting blood pressure was obtained following the American Heart Association recommendations (BP760, Omnron Healthcare, Inc., Lake Forest, IL) (Francisco has this reference in his papers). In addition, and at the beginning of every visit, hematocrit (HemataStat II Hematocrit Analyzer, Separation Technology Inc., USA) and resting blood lactate (BLa) levels (Lactate Plus, Nova Inc., Boston, MA) were obtained from the lower end of the earlobe as previously described (Gurovich et al., 2021; Rascon et al., 2020). Then, for visit 1, subjects completed 3 maximal strength tests (Squat, Bench Press, and Biceps curls), then subjects rested for approximately 30 minutes and performed a VO2max treadmill (brand) test. On visit 2, participants performed a VO2max cycle-ergometer (Corival, Lode, The Netherlands) followed by 30 minutes rest to perform a VO2max on the Arm-ergometer (brand). Finally, ultrasound testing (Visit 3 and 4) happened within 24 to 48 hours of visit 2. These visits consisted of 3 repetitions of the squat, biceps curl, and bench press at low (45%1-RM), moderate (65%1-RM), and high intensity (85%1-RM) and 2-minutes workload steady-state exercise of cycling and running exercise test at low (≤= <2 mmol/L), moderate (= 2-4 mmol/L), and high intensity (≥ 4 mmol/L) (Rascon et al., 2020) (Figure 1).

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT FIGURE 1 ABOUT HERE\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Maximal oxygen consumption (VO2max) tests were conducted using a metabolic cart ((TrueOne 2400, Parvomedics Inc., Sandy, UT). A graded exercise test protocol was utilized with speed increased every 2-minutes (Beltz et al., 2016). At 30 seconds before the end of each stage, BLa was drawn from the participant’s earlobe, along with reported heart rate and rate of perceived exertion. A successful trial was considered if the following criteria were met: 1) BLa > 8.0 mmol/L, respiratory exchange ratio (RER) > 1.10, heart rate was within 10 bmp of estimated maximal heart rate (220 – age), and RPE > 17 (Beltz et al., 2016).

The 1-RM testing consisted of a familiarization and technique inspection of the individual's exercise execution. Thereafter, participants were asked to predict the maximal load they could achieve. Then, participants performed 5-10 repetitions of the predicted load at a comfortable pace. The load was increased by 20% for the following set and performed for 2-3 repetitions. Then load was increased 2.5-5 kg until participants reached failure (Montalvo et al., 2021; Seo et al., 2012). Technical execution analysis, as well as spotting, was performed by a Certified Strength and Conditioning Specialist (SM).

*Blood flow pattern testing*

On sub-maximal exercise testing (visits 3 and 4), real-time carotid longitudinal imaging was conducted with a cervical probe holder designed by the WM Keck Center for 3D Innovation at UTEP was placed on the subject’s neck, and images were recorded with a Doppler Ultrasound, Linear array, 12 MHz transducer (LA435, Esaote, (MyLab30 Gold, Esaote North America, Inc. in Fishers, IN) (Gurovich et al., 2021; Morales-Acuna, 2020) Ultrasound images and Doppler signals were analyzed with edge detection technology (Vascular Analysis Integrative System, Medical Imaging Applications, Coralville, IA) and data acquisition system (MP150WSW, BIOPAC Systems Inc., Goleta, CA) (Figure 2). ESS was obtained by Womersley’s approximation and presence of turbulent flow via Reynold’s number (Re) as previously described (Gurovich & Braith, 2012; Gurovich et al., 2021; Morales-Acuna et al., 2019; Rascon et al., 2020). The presence of laminar or turbulent flow was defined via Re, where undisturbed laminar flow values were <200, disturbed blood flow values between 200-1800, and turbulent flow values >2000 (Davies, 2009).

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT FIGURE 2 ABOUT HERE\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

## Statistical analysis

Data were compiled into a master data spreadsheet (Excel, Microsoft 2021). Data were then exported into Rstudio Integrative Development Environment (institution or reference) and analyzed using a custom-built script in R statistical programming language. The “dplyr” package was used for grammar data manipulation, “forecats” for factor re-leveling, “ggplot2” and “ggpurb” for data visualization ,“psych” for data descriptives, “cvcqv” for reliability analysis, “lm4” and “lmerTest” for linear mixed-effects models, “rstatix” for post-hoc pairwise comparisons, and effect sizes. Baseline demographic data were analyzed by a series of independent t-test between males and females. Reliability of baseline ESS and Re were analyzed using a coefficient of variation (CV) and interpreted as < 10% as very good, 10-20% as good, and 20-30% as acceptable, and >30% as poor. Differences between exercise modalities and intensities were assessed using a general linear mixed-effects model for repeated measures with adjusting for individual differences as a random effect; the model was as follows: dependent variable ~ exercise modality + exercise intensity + Sex + exercise modality\*exercise intensity + (1|Participant). Pairwise differences were analyzed post-hoc with a Holm-Bonferroni p-value correction (*p.adj*) when appropriate; the effect size was obtained through standardized mean differences using Cohen’s D with a Hedge’s g (ESg) correction for small sample size, and interpreted as follows: ESg < 0.2 as very small, 0.2-0.49 as small, 0.5-0.79 as moderate, and > 0.8 as large (Hopkins, 2009). Statistical significance was set *priori* at an alpha level of 0.05. Re was analyzed by visual analysis using a 95% confidence interval (CI) as previously described (Gurovich et al., 2021). Data and data analysis scripts are available at

# Results

Out of the 20 participants, 6 were unable to finish all 4 visits due to the COVID-19 lockdown. Hence, only 14 participants were able to complete the study. Demographics and descriptive data for final participants are provided in Table 1. Males were taller, had a higher VO2max on treadmill (t=2, p=0.002) 1-RM Bench Press (t=6, p<0.01), 1-RM Biceps than (t=3, p=0.02). Reliability analysis showed a good inter-testing reliability on ESS (CV=16.9 (95%CI=12.3-21.5)) and acceptable inter-testing reliability on Re (CV=22.7 (95%CI=16.4-29.1)).

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT TABLE 1 & 2 ABOUT HERE\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

The mixed effects model showed no interaction between sexes on ESS (F(1,12)= 2.01, p=0.18). There was a significant interaction of intensity (F(2,247)= 63.16, p<0.001), exercise modality (F(7,247)= 53.79, p<0.001), and exercise \* modality (F(10,247)= 2.99, p<0.01) on ESS. The model also showed an interaction of participants as a random effect on ESS (p<0.001). ESS significantly increased in an intensity dependent manner in all exercise modalities. Post-hoc pairwise analysis within exercise modalities showed that all exercise modalities were influenced by intensity (p<0.01) with large effect size between intensities (i.e. low vs moderate, moderate vs high, low vs high) (Figure 2 & Table 3). However, Squat at low intensity vs moderate intensity (t=-1.17, p.adj=0.26, ESg(*small*)=-0.29), Bench at low intensity vs high intensity (t=-2.08, p.adj=0.12, ESg(*moderate*)=-0.52), and Bench at moderate intensity vs high intensity (t=-0.81, p.adj=0.43, ESg(*small*)=-0.20) were not statistically different (Figure 3 & Table 3).

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT FIGURE 2 and TABLE 3 ABOUT HERE \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Pairwise comparisons for ESS during low-intensity exercise showed significant differences and large effects between Cycle-ergometer vs Bench and Squat vs Bench (Figure 4 and Table 4). Similarly, there were significant differences and large effects at moderate exercise intensity between Treadmill vs Arm-ergometer, Treadmill vs Squat, Treadmill vs Bench, Treadmill vs Biceps, and Squat vs Biceps (Figure 4 and Table 4). Finally, there were significant differences and large effects at high exercise intensity between Cycle-ergometer vs Squat, Cycle-ergometer vs Bench, Cycle-ergometer vs Biceps, Treadmill vs Arm-ergometer, Treadmill vs Squat, Treadmill vs Bench, and Treadmill vs Biceps.

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT FIGURE 3 and TABLE 4 ABOUT HERE \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

Visual analysis of the Re plot using mean and error plot indicates that all exercise modalities from low to high intensity resulted in turbulent flow (Re>2000) (Figure 4).

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*INSERT FIGURE 4 ABOUT HERE \*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

# Discussion

The purpose of this study was to determine the effects of different exercise modalities at three different exercise intensities on endothelial shear stress (ESS) and blood flow patterns (Reynold’s number (Re)) at the carotid artery. Our primary hypothesis indicated that running on a treadmill at high intensity produces greater ESS and turbulent blood flow (Re) than any of the other exercise modalities and intensities. This hypothesis was supported by the data provided. In addition, we also explored the blood flow patterns of each exercise modality in where it was found that all exercise modalities at each of the intensities presented turbulent flow.

Aerobic training has been known to improve endothelial function, cardiovascular measures, and improve cardiovascular risk factors due to its constant blood flow and large muscular recruitment (Hornig et al., 1996; Kobayashi et al., 2003). We reported no sex differences at any of the exercise modalities at any of the intensities studies. Our results are consistent with previous investigations from our laboratory and we have not found differences in hemodynamic responses at the brachial artery by sex during cycle-ergometry at low, moderate, and high intensities (Gurovich et al., 2021). In addition, we previously reported similar values on ESS of the carotid artery during cycle-ergometry at high-intensity (82.9±25.2 dynes/cm2) (Gurovich et al., 2021), however, it is to notice that treadmill running exercise from this investigation yielded on average 8.6% greater ESS (84.7±9.77 dynes/cm2) when compared to cycle-ergometer (77.5±20.3 dynes/cm2) from this investigation, however, these were not statistically significant.

*Limitations*

The present study is not exempt from limitations. Our study was limited to the sample size. Our between-subjects comparison analyzes could have been compromised by the low sample size (males=7, females=7). Furthermore, our overall sample size was 14 participants, however, this was enough to show differences in responses through the standardized mean difference as denoted by the effect size. Moreover, each of the pairwise comparisons (exercise modality by intensity) yielded a possible 42 comparisons. Thus, in order to avoid the increased chance of committing type 1 (false positive) and type 2 (false negative) errors, we utilized a Holm-Bonferroni correction; the correction utilized presents a more conservative alternative to the fisher’s LSD correction which has been shown to produce type 1 error and more liberal to the Bonferroni correction which has also been shown to produce type 2 error (Eichstaedt et al., 2013). Moreover, our study was cross-sectional, and only acute interaction of exercise modality and intensity and ESS or Re can be inferred. Thus, the differences between exercise modalities and intensities on ESS or Re at short and long-term exercise remains unknown.

The inferences derived from this investigation can only be extrapolated to a similar population (health young male and female participants), and the effects of different exercise modalities and intensities on ESS and Re for clinical populations (i.e. CV problems) remains unknown. Moreover, it is unknown if other alternative exercise modalities such as plyometrics (jumping), boxing, agility training, balance, Taichi, Yoga, etc. would affect (short or long term) endothelial shear stress and function, and as such, researchers should investigate these.

# Conclusion

Blood flow patterns during exercise in the carotid artery show that flow is mainly turbulent, independent of the exercise modality and intensity and that ESS is dependent on exercise intensity regardless of the exercise modality. In addition, activities engaging larger and more muscle groups, like running or biking, at a high intensity yield the greatest ESS. Thus, clinicians should take into consideration exercise-induced blood flow patterns at the carotid artery during the different exercise intensities and modalities.

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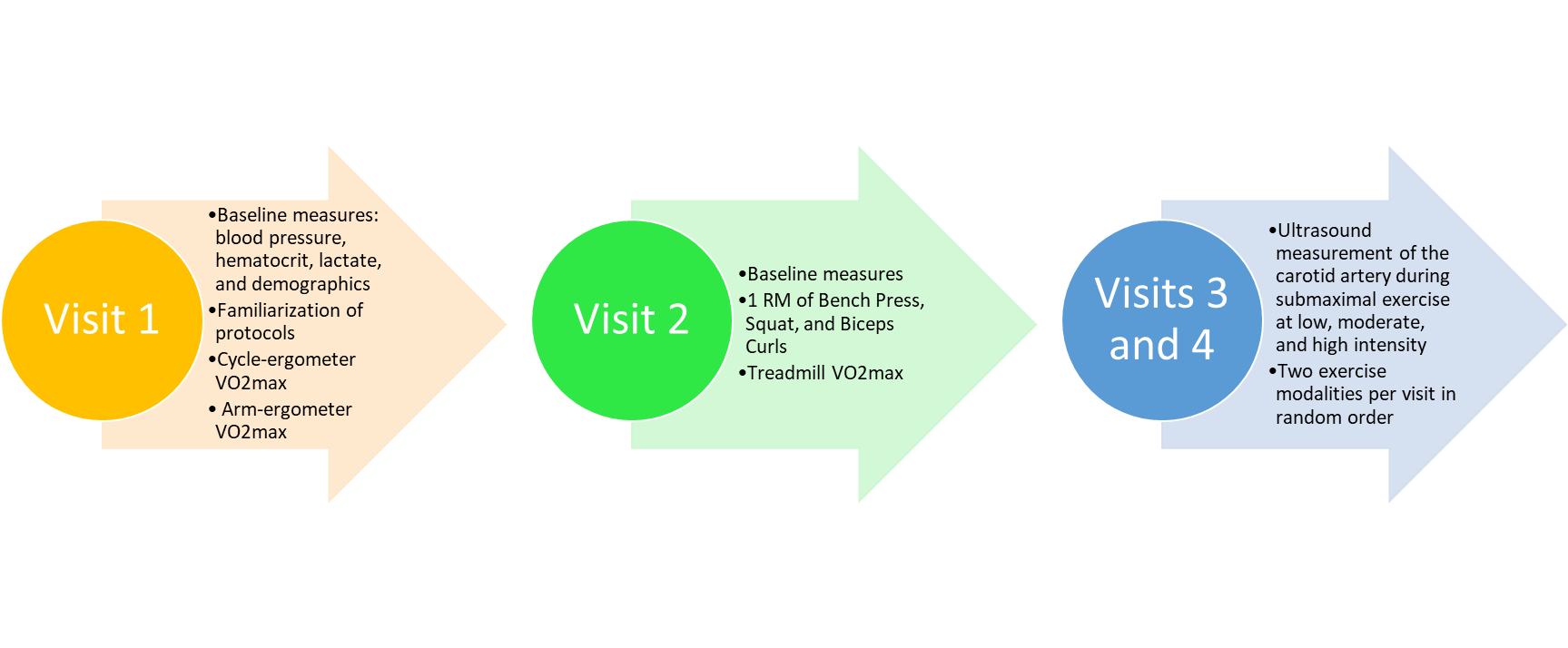


Figure 1. Study design; randomization of exercise modalities was performed during ultrasound testing (visits 3 and 4); two exercise modalities were performed per visit, i.e., cycle-ergometer followed by arm-ergometer on visit 3 and resistance exercise followed by treadmill running on visit 4.

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Description automatically generatedFigure 2. Typical ultrasound testing setup with neck probe holder utilized during all exercise testing.

Chart, diagram, schematic, box and whisker chart

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Figure 3. Boxplot of Endothelial Shear Stress (ESS) by exercise modality and intensity with comparisons between instruments at each intensity. \* Indicates p value < 0.05, \*\* < 0.01, \*\*\* < 0.001, and \*\*\*\* < 0.0001.

Chart, box and whisker chart

Description automatically generated

Figure 4. Boxplot of Endothelial Shear Stress (ESS) by exercise modality and intensity with comparisons between instruments at each intensity. \*indicates p value < 0.05, \*\* indicates p values < 0.01, and \*\*\* indicates p values < 0.001.

Chart

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Figure 4. A plot of mean and 95% CI of Reynolds number (Re) by exercise modality and intensity with a turbulent flow threshold number of 2,000 (red dash line).

Table 1. Demographic and descriptive data of the participants.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | All | Males | Females | t | p |
|  | Mean±SD | Mean±SD | Mean±SD |  |  |
| Age (yrs.) | 23.00±2.86 | 24.00±3.56 | 22.00±1.63 | 1.35 | 0.21 |
| Height (m) | 1.66±0.09 | 1.73±0.05 | 1.60±0.08 | 3.48 | <0.00 |
| Weight (kg) | 69.18±11.03 | 73.94±7.60 | 64.41±12.37 | 1.73 | 0.11 |
| BMI (kg/m2) | 24.97±3.45 | 24.73±2.19 | 25.21±4.57 | 0.25 | 0.80 |
| SBP | 113.29±8.91 | 117.00±9.07 | 109.57±7.59 | 1.66 | 0.12 |
| DBP | 74.07±6.83 | 75.14±7.49 | 73.00±6.51 | 0.57 | 0.57 |
| Treadmill VO2(ml/kg/min) | 43.26±9.99 | 50.6±5.21 | 35.91±7.95 | 4.08 | <0.00 |
| Cycle-ergometer VO2(ml/kg/min) | 32.00±9.18 | 34.59±10.16 | 29.41±7.99 | 1.05 | 0.31 |
| Arm-ergometer VO2(ml/kg/min) | 28.74±9.47 | 32.34±10.43 | 25.13±7.43 | 1.49 | 0.16 |
| 1RM-Squat (kg) | 83.34±36.84 | 101.83±43.04 | 64.86±17.08 | 2.11 | 0.06 |
| 1RM-Bench (kg) | 55.78±24.97 | 76.86±16.18 | 34.70±7.26 | 6.28 | <0.00 |
| 1RM- Biceps (kg) | 33.73±20.28 | 47.02±21.36 | 20.43±4.73 | 3.21 | 0.01 |

Table 2. Endothelial Shear Stress (ESS) by exercise intensity and Group (All and by Sex).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Rest | | | Low Intensity | | | Moderate Intensity | | | High Intensity | | |
| Modality | Group | Mean±SD | Modality | Group | Mean±SD | Modality | Group | Mean±SD | Modality | Group | Mean±SD |
| Baseline | All | 23.8±4.83 | Arm-ergometer | All | 39.4±10.72 | Arm-ergometer | All | 47.8±12.1 | Arm-ergometer | All | 57.8±20.73 |
| Baseline | M | 26.5±3.88 | Arm-ergometer | M | 37.4±12.57 | Arm-ergometer | M | 44.8±13.76 | Arm-ergometer | M | 55.3±26.04 |
| Baseline | F | 21±4.23 | Arm-ergometer | F | 41.5±9.01 | Arm-ergometer | F | 50.8±10.34 | Arm-ergometer | F | 60.3±15.43 |
| Baseline two | All | 26.5±3.26 | Cycle-ergometer | All | 48±10.8 | Cycle-ergometer | All | 62.6±19.43 | Cycle-ergometer | All | 77.5±20.3 |
| Baseline two | M | 27±2.38 | Cycle-ergometer | M | 49±11.69 | Cycle-ergometer | M | 62.6±22.28 | Cycle-ergometer | M | 71.7±23.64 |
| Baseline two | F | 26.1±4.11 | Cycle-ergometer | F | 47.1±10.69 | Cycle-ergometer | F | 62.5±17.93 | Cycle-ergometer | F | 83.2±15.99 |
|  |  |  | Treadmill | All | 47.5±13.06 | Treadmill | All | 67.3±17.89 | Treadmill | All | 84.7±9.77 |
|  |  |  | Treadmill | M | 50.5±17.78 | Treadmill | M | 73.5±21.34 | Treadmill | M | 88±10.69 |
|  |  |  | Treadmill | F | 44.4±5.67 | Treadmill | F | 61.2±12.23 | Treadmill | F | 81.4±8.21 |
|  |  |  | Bench | All | 34.8±12.98 | Bench | All | 42.1±12.02 | Bench | All | 45.6±13.73 |
|  |  |  | Bench | M | 40.1±15.5 | Bench | M | 45.7±13.71 | Bench | M | 48.7±16.34 |
|  |  |  | Bench | F | 29.6±7.79 | Bench | F | 38.6±9.79 | Bench | F | 42.5±10.93 |
|  |  |  | Biceps | All | 37.3±13.26 | Biceps | All | 41.3±12.76 | Biceps | All | 50.7±14.71 |
|  |  |  | Biceps | M | 44.9±13.67 | Biceps | M | 48.7±12.08 | Biceps | M | 59.1±11.29 |
|  |  |  | Biceps | F | 29.7±7.68 | Biceps | F | 34±9.04 | Biceps | F | 42.3±13.28 |
|  |  |  | Squat | All | 44.1±14.39 | Squat | All | 48.8±16.44 | Squat | All | 56.8±13.57 |
|  |  |  | Squat | M | 48.9±16.74 | Squat | M | 57.2±12.73 | Squat | M | 64.5±12.09 |
|  |  |  | Squat | F | 39.2±10.64 | Squat | F | 40.4±16.09 | Squat | F | 49.2±10.73 |

M=Males, F=Females.

Table 3. Pairwise comparisons by exercise intensity for Endothelial Shear Stress (ESS) and Reynolds number (Re).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Intensity | Modality 1 | Modality 2 | t | p.adj | Hedges g | Effect |
| *Endothelial Shear Stress Antegrade Flow (ESS)* | | | | | | |
| Low | Cycle-ergometer | Bench | 3.639 | 0.042 | 0.915 | Large |
| Low | Squat | Bench | 3.950 | 0.025 | 0.994 | Large |
| Moderate | Cycle-ergometer | Bench | 3.739 | 0.022 | 0.940 | Large |
| Moderate | Cycle-ergometer | Biceps | 3.847 | 0.022 | 0.968 | Large |
| Moderate | Treadmill | Arm-ergometer | 4.081 | 0.017 | -1.027 | Large |
| Moderate | Treadmill | Squat | 3.965 | 0.019 | 0.997 | Large |
| Moderate | Treadmill | Bench | 6.723 | 0.000 | 1.691 | Large |
| Moderate | Treadmill | Biceps | 5.742 | 0.001 | 1.444 | Large |
| Moderate | Squat | Biceps | 3.811 | 0.022 | 0.959 | Large |
| High | Cycle-ergometer | Squat | 3.382 | 0.044 | 0.851 | Large |
| High | Cycle-ergometer | Bench | 5.218 | 0.002 | 1.312 | Large |
| High | Cycle-ergometer | Biceps | 4.548 | 0.005 | 1.144 | Large |
| High | Treadmill | Arm-ergometer | 5.283 | 0.002 | -1.329 | Large |
| High | Treadmill | Squat | 7.487 | 0.000 | 1.883 | Large |
| High | Treadmill | Bench | 7.289 | 0.000 | 1.834 | Large |
| High | Treadmill | Biceps | 7.725 | 0.000 | 1.943 | Large |

Table 4. Within exercise modality by intensity pairwise comparisons for Endothelial Shear Stress (ESS).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Modality | Intensity 1 | Intensity 2 | t | p.adj | Hedges g | Effect |
| Cycle-ergometer | Low | Moderate | -4.93 | 0.00 | -1.24 | large |
| Cycle-ergometer | Low | High | -8.61 | 0.00 | -2.16 | large |
| Cycle-ergometer | Moderate | High | -7.14 | 0.00 | -1.80 | large |
| Arm-ergometer | Low | Moderate | -3.68 | 0.01 | -0.93 | large |
| Arm-ergometer | Low | High | -5.07 | 0.00 | -1.28 | large |
| Arm-ergometer | Moderate | High | -3.11 | 0.01 | -0.78 | moderate |
| Treadmill | Low | Moderate | -4.58 | 0.00 | -1.15 | large |
| Treadmill | Low | High | -8.18 | 0.00 | -2.06 | large |
| Treadmill | Moderate | High | -3.60 | 0.00 | -0.91 | large |
| Squat | Low | Moderate | -1.17 | 0.26 | -0.29 | small |
| Squat | Low | High | -3.79 | 0.00 | -0.95 | large |
| Squat | Moderate | High | -4.02 | 0.00 | -1.01 | large |
| Bench | Low | Moderate | -4.67 | 0.00 | -1.18 | large |
| Bench | Low | High | -2.08 | 0.12 | -0.52 | moderate |
| Bench | Moderate | High | -0.81 | 0.43 | -0.20 | small |
| Biceps | Low | Moderate | -2.19 | 0.05 | -0.55 | moderate |
| Biceps | Low | High | -5.81 | 0.00 | -1.46 | large |
| Biceps | Moderate | High | -5.24 | 0.00 | -1.32 | large |