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Exaggerated post exercise hypotension following concentric but not eccentric resistance exercise: Implications for metabolism

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Abstract
Post exercise hypotension (PEH) is primarily attributed to post-exercise vasodilation via central and peripheral mechanisms. However, the specific contribution of metabolic cost during exercise, independent of force production, is less clear. This study aimed to use isolated concentric and eccentric exercise to examine the role of metabolic activity in eliciting PEH, independent of total work. Twelve participants (6 male) completed upper and lower body concentric (CONC), eccentric (ECC), and traditional (TRAD) exercise sessions matched for work (3 × 10 in TRAD and 3 × 20 in CONC and ECC; all at 65% 1RM). Blood pressure was collected at baseline and every 15 min after exercise for 120 min. Brachial blood flow and vascular conductance were also assessed at baseline, immediately after exercise, and every 30 min after exercise. V̇O₂ was lower during ECC compared to CONC and TRAD (−2.7 mL/Kg/min ± 0.4 and −2.2 mL/Kg/min ± 0.4, respectively, p < 0.001). CONC augmented the PEH response (Peak ΔMAP −3.3 mmHg ± 0.9 [mean ± SE], p = 0.006) through 75 min of recovery and ECC elicited a post-exercise hypertensive response through 120 min of recovery (Peak ΔMAP +4.5 mmHg ± 0.8, p < 0.001). CONC and TRAD elicited greater increases in brachial blood flow post exercise than ECC (Peak Δ brachial flow +190.4 mL/min ± 32.3, +202.3 mL/min ± 39.2, and 69.6 mL/min ± 19.8, respectively, p ≤ 0.005), while conductance increased immediately post exercise in all conditions and then decreased throughout recovery following ECC (−32.9 mL/min/mmHg ± 9.3, p = 0.005). These data suggest that more metabolically demanding concentric exercise augments PEH compared to work-matched eccentric exercise.

Keywords: Vasodilation, exercise, eccentric, metabolism

Highlights
- The contribution of metabolic activity on post exercise hypotension (PEH), independent of force production, is unclear. This study used concentric, eccentric, and combined (concentric+eccentric) resistance exercise to partition these factors.
- Concentric-only resistance exercise augmented PEH in a group healthy adults, while work-matched eccentric-only exercise elicited a period of post exercise hypertension. The percent change in blood pressure post exercise was also negatively correlated to cumulative oxygen consumption.
- Our data indicate that metabolic cost and force production have competing influences on post exercise blood pressure regulation.

Introduction
Post exercise hypotension (PEH), characterised by a transient decrease in blood pressure following a single bout of exercise, has been reported to last between 1 and 24 h following resistance, aerobic, and combined exercise (Angadi, Bhammar, & Gaesser, 2015; Brito Ade, de Oliveira, Brasiliero-Santos Mdo, & Santos Ada, 2014; Cavalcante et al., 2015). Evidence suggests that aerobic exercise potentiates the duration of PEH compared to resistance exercise (Keese, Farinatti, Pescatello, & Monteiro, 2011), and higher intensity exercise potentiates the magnitude of PEH compared to lower intensities (Carvalho, Pires, Junqueira, Freitas, & Marchi-Alves, 2015; de Freitas Brito et al., 2015; Eicher, Maresh, Tsongalis, Thompson, & Pescatello, 2010). However, these results do not delineate between factors related to total work and metabolic cost. This is important to note, because
the reported intensity-related differences are abated when exercise is normalised to total work performed (Jones, George, Edwards, & Atkinson, 2007).

While the presence of PEH following exercise is well documented, its specific mechanisms are less clear. It is generally accepted that PEH is primarily influenced by post exercise vasodilation (Franco et al., 2013; New et al., 2013). This vasodilation increases vascular conductance in the previously active muscle and in the non-active muscle and visceral organs (Endo, Shimada, Miura, & Fukuba, 2012). Some suggested mechanisms include the Kinin-Kallikrein pathway, the nitric-oxide (NO) pathway, and histamine release (Lee et al., 2009; Moraes et al., 2007; Motta et al., 2010). In addition, muscle afferent mediated baroreflex resetting, sympathovagal balance, and a reduction in cardiac output may also contribute to PEH (Cote, Bredin, Phillips, Koehle, & Warburton, 2015; Floras & Wesche, 1992). These factors are not all mutually exclusive, and are likely all contributing factors. Furthermore, these factors are not all discriminatory between force production (and ultimately total work) and metabolic demand. For example, the NO pathway could be mechanically stimulated during force generation (Clifford, Kluess, Hamann, Buckwalter, & Jasperse, 2006), or by accumulation of metabolic by-products associated with force generation (Umbrello et al., 2014). Likewise, group III muscle afferents are activated by mechanical distortion during force production, while group IV afferents are activated due to metabolite accumulation (Kaufman, Iwamoto, Longhurst, & Mitchell, 1982; Kaufman, Longhurst, Rybicki, Wallach, & Mitchell, 1983). Therefore, understanding the independent contributions of metabolic activity and force generation on PEH may provide insight into its mechanisms.

One method of partitioning metabolic demand from force generation is through isolation of eccentric and concentric muscle contractions. Early research by Abbott, Bigland, & Ritchie identified a significantly greater metabolic demand during positive (concentric) compared to negative (eccentric) work (Abbott, Bigland, & Ritchie, 1952); a finding that has since been corroborated by a large body of evidence (Beaven, Willis, Cook, & Holmberg, 2014; Elmer, Marshall, McGinnis, Van Haitsma, & LaStayo, 2013). Therefore, the purpose of this study was to use isolated eccentric and concentric exercise to partition the contributions of metabolic activity (elevated in concentric exercise) and factors related to force production (consistent between exercises) on PEH. We also aimed to compare blood flow, vascular conductance, and pulse wave velocity (PWV) between these exercise modalities to help explain any differences. We hypothesised that concentric exercise would elicit a higher metabolic demand during work-matched exercise, which would potentiate the PEH response. We also expected to observe elevations in blood flow and conductance, and a reduction in pulse wave velocity (PWV) during recovery from concentric compared to eccentric and traditional (control) exercise. Results from this study may help to explain the mechanisms contributing to PEH, which have implications for exercise prescription in individuals suffering from poor blood pressure regulation.

Methods

Participants

Twelve subjects (6 males and 6 females, 21 ± 2 years old, 61.8 ± 5.8 Kg, 1.67 ± 0.03 m) participated in this study, and all provided written informed consent. Subjects were apparently healthy, free of metabolic and cardiovascular disease, had no history of high blood pressure, were not on any medications known to affect blood pressure, and had at least 3 months of strength training experience. Data from all female subjects were collected during the luteal phase of the menstrual cycle.

Study protocol

Ethical approval for the protocol used in this study was granted by the institutional review board at the study site (Log# 15-559). Participation included 4 total visits (1 pre-screening visit and 3 experimental sessions). The first visit began with the consenting process, followed by completion of a health history questionnaire, and a 1 repetition max (1RM) assessment on guided weight stack machines for the following 6 exercises: chest press (CP), leg extension (LE), wide-grip lateral pull down (LP), leg curl (LC), biceps curl (BC), and triceps extension (TE).

Visits 2–4 followed the same experimental protocol except for the exercise condition, and were performed at the same time of day for each subject. Subjects arrived at the vascular function lab 3 h post-prandial; and having abstained from caffeine for 8 h, alcohol for 24 h, and significant physical activity for 24 h. Visits 2, 3 and 4 were separated by an average of 14 days, and subjects were encouraged to continue their existing exercise programme during that time frame (provided they still adhered to the 24-hour abstention from significant physical activity). Upon entering the lab, subjects laid supine on a gurney while a 3-lead ECG collected heart rate. After a 10-minute rest, brachial blood flow, brachial conductance, femoral blood flow, femoral conductance, and upper and lower limb pulse wave velocities (PWVs) were all collected via Doppler ultrasound (GE Logiq 7, GE Healthcare, Milwaukee, WI).
using a M12L linear array probe at sampling frequencies of 14 MHz (ultrasound) and 5 MHz (Doppler) and an insonation angle of ≤60°. One-minute clips were collected proximal to the brachial and femoral bifurcation for blood flow analysis. Thirty-second clips were also collected at the carotid, radial, and posterior tibial arteries for pulse wave velocity (PWV) analysis, which is commonly used as an index of arterial stiffness (Kong et al., 2017; McGreevy, Barry, Bennett, & Williams, 2013) with higher velocity indicating a stiffer vessel. The collection locations for each of these sites were marked with indelible ink and imaged side-by-side to the original image to assure consistency. Also, once marked with ink, the distances between the assessment sites at the carotid and radial arteries, carotid and femoral arteries, and carotid and ankle arteries were measured and used for PWV calculation. The order of assessments was consistent throughout all data collection cycles (carotid, brachial, radial, femoral, and ankle). After blood flow and PWV were assessed, blood pressure was collected twice with one minute between collections. If there was a 5 mmHg difference in SBP or DBP between the two collections, blood pressure was collected a third time. The average of these assessments was calculated and recorded. All blood pressures were collected manually using a sphygmomanometer, and were collected by the same investigator.

After the baseline assessment, subjects were taken to the strength laboratory where they performed a brief 3-minute warm-up on an upper and lower body ergometer (Schwinn Airdyne). The warm-up was succeeded by one of three different exercise protocols. These included a concentric-only (CONC), eccentric-only (ECC), or traditional exercise (TRAD) protocol for the same 6 exercises for which they performed the 1RM on visit 1. Repetition rate was controlled at 3.5 s with a metronome, and resistance was set to 65% of the 1RM. VO₂ was analysed continuously throughout each exercise session with face mask and metabolic cart (ParvoMedics, Sandy, UT), and is reported as the average increase above baseline for each session. Prior to data collection, a proper seal with the facemask was verified. During the CONC and ECC sessions, a 3:1 block-and-tackle pulley system was used to isolate the desired contraction (depicted in Figure 1). Specifically, the top of the pulley system was secured to the rafters above the weight stack for each machine and the base of the pulley supported the weight stack prescribed for each subject. This allowed the subject to perform only the concentric phase of each exercise during the CONC session while the investigator used the pulley system to perform the eccentric phase and vice versa. Therefore, subjects actively performed the desired contraction (i.e. concentric), and were passively moved through the opposing contraction (i.e. eccentric). All of the sessions were matched for total work (calculated as the absolute value of force x displacement). Thus, the number or reps performed during TRAD (3 x 10) was half that performed during ECC and CONC (3 x 20) since TRAD included both eccentric and concentric phases of the exercise. Furthermore, the CONC protocol, which was deemed most difficult during pilot testing, was performed 1st (2nd visit). The order of the ECC and TRAD sessions were counterbalanced. This allowed the investigators to adjust the repetitions performed in the ECC and TRAD sessions to match the number of repetitions successfully completed during the CONC session (group average of 305 ± 45 reps) thereby matching mechanical work across all three conditions (group averages of 305 ± 45 and 153 ± 21 for ECC and TRAD, respectively). Lastly, each set was separated by a 90s rest.

Following the final set of exercise subjects immediately returned to the vascular lab (all within 5 min of the end of exercise) where they laid down on the

![Figure 1. A depiction of the pulley system used to isolate eccentric and concentric contractions. As illustrated, the pulley system could be used to lift and lower the weight stack without the assistance of the participant.](image-url)
gurney and blood flow, PWV, and blood pressure were immediately collected. Blood flow, HR, and PWV were then measured every 30 min, and blood pressure every 15 min throughout a 2-hour recovery period.

Data computation
Blood flow (mL/min) was calculated as: mean velocity × π × (diameter/2)^2 × 60. Brachial and femoral conductance were calculated as blood flow/MAP. PWV was calculated in two steps. First, the time interval between the peak of the R-wave and the initial inflection of the subsequent pulse wave (ms) was measured for each location (carotid, brachial, femoral, and ankle). Similar to the foot-to-foot method, the upper-body PWV was calculated by subtracting the time delay between the r-wave and subsequent pulse-wave at the carotid from the time delay between the r-wave and subsequent pulse-wave at the radial artery. PWV velocity is reported as an absolute value (m/s), and normalised to MAP ([m/s]/mmHg).

Statistical analysis
Statistical software IBM SPSS version 14 was utilised for all data analysis. Initially, any significant main effect of sex, or interactions between sex, condition, and time on MAP, SBP, and DBP were explored with a two-way repeated measures analysis of variance (ANOVA). No significant main effects or interactions were observed, therefore, the study sample is presented as a single cohort. A one-way repeated measures ANOVA was used to test for any significant main effects of condition (3) for average VO₂ during exercise. A time (6) by condition (3) repeated measures ANOVA was used to test for any significant interactions, or main effects of time or condition for blood flow and conductance in the brachial and femoral arteries as well as upper and lower limb PWV. A time (10) by condition (3) repeated measures ANOVA was used to test for any significant interactions or main effects of time or condition for SBP, DBP, HR, and MAP. Any significant interactions or main effects of time or condition were further explored with post-hoc analyses. To confirm any relationship between oxygen consumption and PEH, a Pearson’s correlation coefficient is reported for the relationship between the PEH index (percent decrease in MAP relative to baseline) and total liters of oxygen consumed throughout the exercise session. Significance was accepted at α = 0.05 and all data are presented as Mean ± standard error.

Results
Oxygen consumption
First, baseline VO₂ was not significantly different between conditions (4.5 mL/Kg/min ± 0.2, 4.0 mL/Kg/min ± 0.3, 3.9 mL/Kg/min ± 0.1 for CONC, TRAD, and ECC, respectively, p = 0.1). The change in VO₂ was significantly lower in ECC (6.67 ± 1.25 mL/kg/min) compared to CONC (9.99 ± 1.61 mL/kg/min) and TRAD (9.26 ± 1.83 mL/kg/min, F<sub>2,22</sub> = 34.012; Figure 2A). No differences were observed between CONC and TRAD during the exercise session. When the total volume of oxygen consumed (L/Kg) was compared between conditions, results indicated a stepwise increase in ECC, TRAD, and CONC, respectively (P<0.05 for all comparisons, Figure 2B). This confirms that this protocol effectively partitioned metabolic activity from total work.

Blood pressure and heart rate
MAP significantly decreased from 15 through 75 min following CONC (F<sub>18,108</sub> = 9.13, p < 0.001; Figure 3B). In contrast, PEH was absent following TRAD...
and MAP was significantly elevated throughout the entire 2-hour recovery period following ECC ($p \leq 0.02$ for all comparisons). PEH index was calculated as the average of each subject’s individual peak percent decrease in MAP compared to baseline, and decreased in a stepwise manner from ECC, TRAD, and CONC, respectively (all $p < 0.03$; Figure 4A). Results from a Pearson’s correlation analysis indicated that cumulative oxygen consumption ($L/Kg/session$) was negatively correlated to the PEH index ($r = -0.640$, $p < 0.001$; Figure 4B).

SBP significantly decreased between 15 and 105 min of recovery after CONC, and increased at all time points post ECC ($F_{18,198} = 3.82$, $p \leq 0.04$ for all comparisons; Figure 3C). No changes were observed in SBP following TRAD. DBP was significantly lower at 75 min following CONC, but was elevated at all time points following ECC ($F_{18,198} = 2.08$, $p \leq 0.04$ for all comparisons; Figure 3D). HR increased by $19 \pm 9$ bpm immediately after CONC, and remained elevated by at least $5$ bpm through recovery. However, HR was only significantly elevated by $15 \pm 1$ bpm immediately following TRAD, and by $7 \pm 11$ bpm at the 30-minute mark. HR was also only elevated by $5 \pm 6$ bpm immediately following ECC ($F_{10,110} = 3.27$, $p \leq 0.05$ for all comparisons; Figure 3A).

Blood flow and vascular conductance

Brachial blood flow significantly increased immediately post-exercise in CONC and TRAD, and remained elevated through 60 and 30 min of recovery, respectively ($F_{10,110} = 9.13$, $p < 0.001$; Figure 5A). Following ECC, brachial blood flow significantly increased immediately post exercise, and then dropped below baseline by at least $-20.2$ mL/min from 60 to 120 min of recovery ($p \leq 0.05$ for all comparisons; Figure 5A). Brachial conductance significantly increased by immediately following CONC and ECC, but then significantly decreased below baseline by at least $0.25$ mL/min/mmHg from 60 to 120 min of recovery following ECC while remaining elevated throughout recovery following CONC ($F_{10,110} = 3.59$, $p < 0.001$; Figure 5B). Brachial conductance also significantly increased immediately post-exercise in TRAD, and remained elevated through 30 min of recovery ($p \leq 0.01$ for all comparisons).

Femoral blood flow increased immediately following TRAD, and was greater after CONC compared to ECC immediately post exercise and at 60 min of recovery. Femoral blood flow was also significantly greater after TRAD compared to ECC immediately post exer-

Figure 3. Heart rate (a), mean arterial pressure (b), systolic blood pressure (c), and diastolic blood pressure (d) compared across time and between conditions. * indicates a statistically significant difference between CONC and TRAD, ! indicates a significant difference between ECC and TRAD, # indicates a statistically significant difference between CONC and ECC. Filled (black) symbol indicates a statistically significant difference from baseline. Data presented as mean ± SE and for all comparisons $p < 0.05$. 
cise and at 60 min of recovery ($F_{5,55} = 2.59$, $p \leq 0.05$ for all comparisons; Figure 5C). There was also a significant time by condition interaction for femoral conductance ($F_{10,110} = 4.48$, $p < 0.001$), which was mediated by a significant increase by $1.62 \pm 1.92$ mL/min/mmHg immediately following TRAD that was not observed in the other conditions ($p = 0.01$).

Pulse wave velocity

Upper limb PWV significantly decreased immediately following each condition, but remained lower by at least $0.7$ m/s throughout recovery in CONC ($F_{10,110} = 2.18$, $p < 0.04$ for all comparisons; Figure 5D). These results were consistent when normalised to MAP. No changes were observed for lower limb PWV or PWV normalised to MAP.

Discussion

The purpose of the present study was to compare the influences of metabolic demand and external work on post-exercise blood pressure regulation. Our data support our hypothesis, such that the more metabolically demanding concentric exercise elicited an augmented PEH response. In contrast, the eccentric
protocol, which included similar external work but a lower metabolic cost, elicited a period of elevated blood pressure post-exercise. Our data also indicate that the post-exercise hyperemic response was reduced in the less metabolically demanding ECC condition, as was vascular conductance. Thus, it appears that factors associated with increased metabolic activity significantly contribute to PEH, while factors related to force generation have opposing influences on post-exercise blood pressure regulation. These differences are potentially mediated by differences in post exercise vascular tone, indicated by differences in vascular conductance.

**Oxygen consumption**
In this study, \( \dot{V}O_2 \) was significantly elevated during CONC and TRAD exercise compared to ECC exercise (Figure 2A) and subjects consumed more total oxygen during the CONC session compared to both TRAD and ECC (Figure 2B). This verifies that the exercise protocol employed in this study was sufficient in partitioning metabolic demand from force production, and validates the comparisons between ECC and CONC. Although we expected CONC to result in the greatest \( \dot{V}O_2 \), there was no difference in \( \dot{V}O_2 \) between CONC and TRAD. One possible explanation for this is that the increase in \( \dot{V}O_2 \) above baseline during ECC is primarily attributed to stabiliser muscles and synergist activity. If this is true, then this would result in an overestimation of oxygen consumption during the ECC condition, meaning that there would be a reduced “additive” effect of eccentric contractions in TRAD compared to CONC. In other words, the less oxygen that is consumed during an eccentric contraction, the less of a difference should be expected between CON and TRAD. Also, with that in mind, it’s likely that the increase in the relative metabolic cost within the primary active muscle during each exercise was greater than our data indicate, as \( \dot{V}O_2 \) values measured at the mouth are also influenced by the \( \dot{V}O_2 \) from non-active tissue and stabilising muscles. Due to that, the percent change in metabolic cost may have been far greater within the active muscle.

**Blood pressure and HR**
The reported changes in SBP, DBP, and HR following CONC agree with previously published research (Duncan, Birch, & Oxford, 2014; Terblanche & Millen, 2012). The magnitude of the decrease in MAP and SBP (approximately 3.8% and 4.6%, respectively) also agrees with other reports in normotensive subjects (Angadi et al., 2015; Rezk, Marrache, Tinucci, Mion, & Forjaz, 2006), while larger decreases have been reported in hypertensive subjects (Brito Ade et al., 2014; de Freitas Brito et al., 2015). In contrast to CONC, we did not observe a substantial PEH response following TRAD. This is likely due to a lower cumulative oxygen cost during the TRAD session. Most notably, however, was the period of hypertension following ECC. To our knowledge, this is the first study to compare the PEH response between eccentric and concentric exercise, and therefore is the first to report this difference in post exercise blood pressure regulation. This relationship may best be illustrated by Figure 4B, which depicts a significant linear relationship between metabolic cost (liters of oxygen consumption per kilogram of mass) and PEH. However, it must be noted that despite the additional metabolic cost above baseline associated with ECC the PEH index is positive due to the hypertensive effect of the eccentric protocol. Thus the elevated metabolic cost, albeit smaller in magnitude, that should contribute to hypotension was offset by some other competing factors.

**Blood flow and conductance**
In general, brachial blood flow and conductance were elevated to a greater magnitude and duration following CONC compared to ECC (Figure 5A and B). Femoral blood flow was also greater following CONC exercise compared to ECC for the first hour of recovery (Figure 5C); however, these results should be interpreted cautiously as there were no significant changes from baseline in either condition. Ultimately, these data suggest that concentric and eccentric exercise have opposing influences on post-exercise blood flow and vascular conductance. This is supported by previous studies that have reported significant increases in active, and post-exercise, hyperemia with increasing exercise intensity (Atkinson et al., 2015; Nyberg, Berg, Helgerud, & Wang, 2017), and others that have reported impaired endothelial function and reduced local blood flow following eccentric exercise (Hosseinzadeh et al., 2015; Rakobowchuk et al., 2017).

**Pulse wave velocity**
Upper limb PWV decreased immediately post exercise in all 3 conditions, but remained lower throughout recovery following CONC (Figure 5D). This supports the role of vascular tone in the PEH response, as a more compliant vessel following concentric exercise would promote a reduction in blood pressure. Our data agree with previous
studies that have reported sustained decreases in arterial stiffness following concentric exercise (Perdomo et al., 2016), and prolonged elevations in arterial stiffness following eccentric exercise (Burr, Boulter, & Beck, 2015).

**Potential mechanisms**

The results from our study indicate that metabolic demand and force generation have opposing influences on post-exercise blood pressure regulation, blood flow regulation, and arterial stiffness. There may be a number of mechanisms that could mediate these differences. For instance, Lizardo, Silveira, Vassallo, and Oliveira (2008) reported a reduced PEH response following administration of the NO inhibitor N(G)-nitro-L-arginine methyl ester (L-NAME) in rats. However, the transient nature of NO mediated vasodilation limits its influence on sustained post-exercise vasodilation, suggesting that PEH is not completely dependent on NO production (Halliwill, Minson, & Joyner, 2000). Similarly, immune responses also vary between concentric and eccentric contractions. While the overall impact of immune responses on PEH is unclear, some research indicates that eccentric exercise results in decreased plasma STNFR1 and 2 concentrations (Arroyo et al., 2017), which has been positively correlated to blood pressure (Fernandez-Real et al., 2002). Inhibition of peripheral H1 and H2 receptors has also been shown to blunt the reduction in blood pressure following exercise, indicating that activation of peripheral histamine receptors is necessary for PEH (Lockwood, Wilkins, & Halliwill, 2005; McCord, Beasley, & Halliwill, 2006). Muscle tone is another factor that may have influenced the period of elevated blood pressure following ECC. Intramuscular pressure and muscle fibre swelling have been reported to increase in the days following intense muscular work (Crenshaw, Thornell, & Friden, 1994; Peeze Binkhorst, Slaaf, Kuipers, Tangelder, & Reneman, 1990). Thus with regards to ECC, an increase in muscle tone with only minimal metabolically induced vasodilation would likely result in increased blood pressure, pulse wave velocity, and reduced vascular conductance.

Baroreflex resetting is another mechanism that likely contributes to the augmentation of PEH following metabolically active concentric work. As exercise ceases, sympathetic withdraw and increased parasympathetic control reduce heart rate, muscle sympathetic nerve activity, and ultimately blood pressure. Additionally, GABAergic buffering of the baroreflex is diminished following the cessation of exercise due to a temporary internalisation of neurokinin-1 receptors (Chen, Bechtold, Tabor, & Bonham, 2009; Kajekar, Chen, Mutoh, & Bonham, 2002). The internalisation of neurokinin-1 receptors is suggested to be mediated by substance P release via group III and IV muscle afferent feedback, which would likely be greater during concentric exercise compared to eccentric exercise due to differences in metabolite accumulation. Therefore, GABAergic buffering of the baroreflex may be less affected following eccentric exercise compared to concentric exercise, which would result in more sympathoinhibition following concentric exercise. For a more in depth review on this topic, see Halliwill, Buck, Lacewell, and Romero (2013). Future research may consider exploring the influence of muscle afferent mediated resetting of the baroreflex on PEH between positive and negative work.

**Application**

The results from this study have implications for exercise prescription, especially in populations that suffer from poor blood pressure regulation. Based on our data, individuals with hypertension, or who may be susceptible to hypertension, may benefit from primarily concentric exercise (i.e. cycling, rowing, etc.). During resistance training, these individuals may also benefit from minimising eccentric work and maximising concentric work. This could be done by extending the duration of concentric contractions and shortening the duration of eccentric contractions, or by performing exercises that exclude eccentric components entirely (such as pulling a rope attached to a weighted sled, using a stair-stepper, or rowing). In contrast, these results also suggest that individuals who suffer from post-exercise hypotension, syncope, or orthostatic intolerance may benefit from primarily eccentric exercise. This could be performed by maximising the duration of eccentric contractions compared to concentric contractions, walking at a downhill grade, or with specialised equipment that isolates eccentric contractions. Of course, this would be primarily for the strength-related benefits. Ultimately, eccentric and concentric exercise may have contrasting effects on post-exercise blood pressure, and this should be considered when prescribing exercise for health benefits.

**Limitations**

As with any study, this project had certain limitations to its study design. One limitation is that we could not concurrently control for volume of worked performed and the overall length of the exercise.
session. We chose to control for total work performed due to its influence on the PEH response, as reported by Jones et al. (2007). Thus, since the TRAD session included half of the repetitions performed in the other two sessions, the TRAD session was shorter. Similarly, we did not account for the excess post-exercise oxygen consumption period (due to laboratory constraints), which would very likely have augmented the differences in total oxygen consumption between CONC and TRAD. We were also unable to collect and analyse for any blood markers, such as histamine or circulating catecholamine. This information may have provided valuable mechanistic insight; future studies should consider including these variables. Lastly, the order of our exercises (specifically, lower body exercises being performed early and the last two exercises being arm exercises) may have reduced any significant interactions that may have otherwise been observed in the lower body. This may have resulted in us missing any significant interaction that may have otherwise been observed with femoral blood flow. Our goal was to elicit a robust PEH response, and therefore we used a full-body resistance exercise protocol. In the future, it may be beneficial to use only lower body exercise to determine if the same responses observed in the upper body also occur in the lower body.

Conclusion

Data from this study indicate that metabolic demand and force generation have opposing influences on post-exercise blood pressure regulation. Specifically, our data indicate that a more metabolically demanding exercise elicits and augmented PEH response; while a less metabolically demanding exercise of the same total work elicits a period of elevated blood pressure for at least 2 h post exercise.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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