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Effects of External Counterpulsation on Performance and Recovery After Exertion

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Abstract: External counterpulsation (ECP) is a safe and effective non-pharmacological therapy for the treatment of refractory angina pectoris and coronary artery disease. Emerging evidence suggests that a single ECP session may be beneficial for exercise performance and markers of recovery; however, findings have been mixed. Furthermore, it is unknown how multiple sessions of ECP influence performance and short-term recovery after repeated, daily exercise. Fifty-seven healthy adults (27 male, 30 female, 38.9 ± 11.6 years) completed three consecutive daily study visits consisting of a weighted lower-body exercise circuit and a 10k cycling time trial. Measures of recovery included balance and jump (height and explosiveness) performance, which were assessed before the exercise circuit (PRE) and following the cycling time trial (POST). Participants randomly assigned to the treatment condition received 30 minutes of ECP therapy each day, while control participants received 30 minutes of sham treatment. Repeated measures ANOVA was used to examine within and between group differences on measures of recovery and cycling time trial performance. Participants that received ECP treatment each day after strenuous exercise for three days showed improved cycling time (p = .006) and balance performance (p < .001), whereas control participants demonstrated decreased jump explosiveness performance (p = .014). Results of this study provide preliminary evidence that ECP therapy may be beneficial for use in exercise recovery and performance in healthy adult populations.

Keywords: ECP, EECP, Exercise, Recovery, Fatigue, Vasodilation, Sequential Compression

1. Introduction

External counterpulsation (ECP) is a safe and effective non-pharmacological therapy for the treatment of refractory angina pectoris and coronary artery disease (CAD) [1, 2]. ECP is generally prescribed to treat patients who are not suitable candidates for stents or other similarly invasive treatments. During treatment, which is conducted with the patient lying supine, heart rhythm is recorded by electrocardiogram while pneumatic cuffs secured around the patient's calves, thighs, and hips inflate sequentially, distal to proximal, during diastole, increasing diastolic pressure and blood flow. At the onset of systole, pressure is released from all cuffs simultaneously, resulting in reduced systolic pressure (Figure 1) [3]. This sequence produces an acute therapeutic effect by increasing tissue blood flow, promoting venous return, increasing cardiac output, and reducing the heart's workload [4]. The Food and Drug Administration (FDA) estimates that 18,000 to 20,000 heart patients per year are treated with ECP with an extremely low risk of adverse events [5]. Improved outcomes for cardiac patients include decreased mortality and hospital readmission [6], reduced symptoms [7], and increased quality of life [8].

The likely mechanisms for improved outcomes in cardiac patients, including improved vascular endothelial function, reduction of vascular inflammation, increased central venous return, and improved cardiovascular [9-11], have also been

demonstrated in other clinical populations. Individuals with abnormal glucose tolerance had increased vascular endothelial growth factor (VEGF) concentrations (75% increase) and improved capillary density [12]. Sardina and colleagues reported that treatment with ECP therapy resulted in increased nitric oxide production and overall improved glycemic control in patients with type II diabetes mellitus [13]. Other researchers have reported ECP as an effective treatment for erectile dysfunction [14], inner ear disorder [15], restless leg syndrome [16], Alzheimer's disease [17], mild cognitive impairment [18], and cirrhosis of the liver [19].

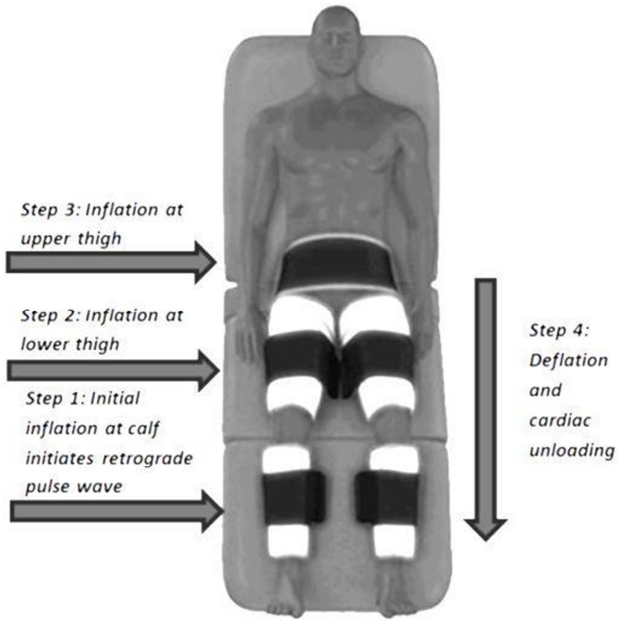

Figure 1. *Pressure sequence demonstrating the mechanism of ECP. Three pairs of pneumatic cuffs secured around the calves, thighs, and hips are sequentially inflated during diastole, distal to proximal, and simultaneously deflated at the onset of systole.*

There is also a growing body of literature suggesting that ECP may be beneficial among healthy populations. Hilz and colleagues found improved skin oxygenation and carbon dioxide clearance during ECP for young healthy individuals as well as older cardiac patients [9]. Ochoa and colleagues found sustained increases in VO2 during ECP treatments for both patients with coronary artery disease and healthy controls [20].

Multiple studies have also examined the effects of a single ECP session on post-exercise recovery among physically active individuals; however, findings are mixed [21-26]. One study found that exercise performance and hormonal indicators of stress improved, and inflammation markers were reduced following an ECP session between bouts of high-intensity exercise in elite rugby league players [21]. Another investigation examining the efficacy of ECP between bouts of exercise reported a positive influence on subsequent shuttle run test performance [22]. Although one study found that ECP following high-intensity exercise demonstrated a neutral effect on jump performance, it also reported potentially beneficial effects on biomarkers of recovery [23]. In two separate studies, Valenzuela and colleagues examined the effectiveness of a single ECP session on recovery following a high-intensity interval training (HIIT) cycling session [24] and a plyometric exercise bout [25]. Results of both studies revealed no differences between ECP and sham treatment on muscle soreness, jump performance, or creatine kinase (CK) levels. Similarly, Collins and colleagues found that ECP demonstrated no significant effect on counter-movement jumps, six-second sprint cycling, or cortisol in physically active males [26].

To our knowledge, no previous study has assessed the effect of multiple ECP sessions on exercise performance and recovery in healthy populations. This is important, considering that ECP treatment among diseased populations often involves multiple sessions over time (e.g., daily one-hour sessions for 35 days). As such, this study aimed to determine if daily, post-exercise ECP treatment impacts short-term recovery and subsequent exercise performance in healthy individuals. Specifically, it was hypothesized that participants who received ECP treatment would maintain performance on the cycling time trial and other outcome measures while the performance of participants in the control condition would decline across study days.

2. Materials and Method

2.1. Participants

This multicenter randomized control trial recruited fifty-seven healthy adults (27 males, 30 females, 38.9± 11.6 years, BMI 23.8 ± 2.9) from local athletic clubs in San Diego, California. The two centers included in the trial were a physical therapy clinic and a physical activity research center; both centers were used to conduct the entire study protocol, including ECP therapy. To qualify, participants had to be between ages 18 and 59, have regularly exercised at least twice a week for twenty minutes at a time, and have no contraindications to ECP therapy. Participants were randomized in blocks of 4 and stratified by sex to either an ECP treatment group or a control group. They refrained from non-study-related exercises or recovery activities during the three study days. All who completed the study were compensated with a $200 Amazon gift card. Written informed consent was obtained from all participants before enrollment and randomization. All enrolled participants completed the study except for one individual in the control group who experienced low tolerance to the study protocol. The study was approved by the University of California, San Diego Human Research Protections Program.

2.2. Experimental Design

Participation involved three consecutive days of in-person study visits. A familiarization visit preceded the first study visit by at least one day, but no more than one week. This familiarization visit included a thorough explanation of study exercises and the fitting of study equipment to the individual. Participants also answered questions about their age, sex, weekly exercise frequency, and how often they have ridden a

bicycle over the past 6 months. Cycling ability was self-assessed on a scale of 1 (beginner) to 5 (advanced).

Each study visit began with trained study personnel taking resting blood pressure and heart rate measurements. Participants self-reported their current soreness for 6 body areas (lower back, upper body, quadriceps, hamstring, calf, groin) using an 11-point scale, ranging from 0 (*no soreness*) to 10 (*extremely sore*). Using a 5-point scale (1 = "not at all," 2 = "a little bit," 3 = "somewhat," 4 = "quite a bit," and 5 = "very much"), participants also reported how fatigued they felt at the beginning of each study visit.

Participants were then fitted with a Polar® FT4 heart rate monitor (Polar, Kempele, Finland) and asked to warm up for 5 minutes by pedaling on a standard road bicycle fitted to a CompuTrainer® stationary trainer apparatus (RacerMate® CompuTrainer®, Seattle, WA). Next, participants completed the balance and jump tests before engaging in two repetitions of an exercise circuit, during which they wore a weighted vest containing 12% to 15% of their body weight, designed to induce lower-body muscle damage (cellular micro-fractures) and fatigue. The protocol for the exercise circuit is presented in Table 1. All participants were monitored during the exercise circuit for proper form and completion of all exercises until protocol-defined completion.

Upon completion of the exercise circuit, a 10-kilometer cycling time trial was completed using the CompuTrainer®. At each mile and upon completion of the cycling time trial, heart rate was recorded from the heart rate monitor. After the time trial, participants were instructed to continue pedaling for a cool-down period and then complete the balance and jump tests again.

Both groups completed identical protocols as described. The ECP treatment group then received 30 minutes of ECP therapy at progressively higher inflation pressure (Day 1 at least 181.0 mmHg, Day 2 at least 206.9 mmHg, and Day 3 at least 222.4 mmHg), while control group participants were fitted with the ECP leg cuffs but received no inflation while resting in a supine position for 30 minutes. The ECP machines used for this trial were the Renew® ECP NCP-4 and NCP-5. Both versions of the ECP machines have been deemed to be therapeutically equivalent by the FDA.

Table 1. *Exercise protocol.*

Exercise	Duration / Repetitions
Squats*	30 seconds
Walking lunges*	20 meters
Squat jumps*	30 seconds
Elevated calf raises*	30 seconds
Split squats*	30 seconds/leg
Single-leg deadlift†	10 repetitions/leg
Lateral jumps	1 circuit/leg
Wall sit	60 seconds
Rest between exercises	< 15 seconds
Rest between circuits	< 1 minute
Number of circuits	2

*Participants performed exercises while wearing a weighted vest containing 12-15% of their body weight.
†Participants held a 10-lb kettlebell while performing the exercise

2.2.1. Cycling Time Trial

A 10-kilometer cycling time trial was completed on all three study days using a standard road bicycle fitted to a CompuTrainer® stationary trainer apparatus. All participants completed the same programmed course (program 47, RacerMate®, 2014). The chosen course was of variable topography (i.e., rolling) which both increased the difficulty and included continuous changes to percent grade to make the course challenging for participants. The time trial was completed on all study days and participants were instructed to complete the course as quickly as possible.

2.2.2. Balance

Single-leg balance was assessed before participants completed the exercise circuit (PRE) and after the cycling time trial (POST). For each trial, the participant stood on one foot in the center of a computerized dynamic posturography plate with their opposite foot raised six inches and arms at their sides. Participants were allowed two 10-second practice attempts before completing two 20-second trials on each leg.

The apparatus used for measuring balance was the Balance Tracking System (BTrackS™, Balance Tracking System Inc., San Diego, CA). The BTrackS™ Balance Plate is an FDA-registered force plate that uses four-sensor technology to measure static balance by calculating changes in the center of pressure (COP) and calculating postural sway [27]. More sway (indicative of movement to maintain balance) results in a higher score. Balance scores were computed by averaging the two 20-second trials for each leg.

2.2.3. Jump Height and Explosiveness

Two jump tests, one for height and one for explosive leg power, were conducted before participants completed the exercise circuit (PRE) and following the cycling time trial (POST). The jump tests were conducted using the Just Jump System (Probotics Inc., Huntsville, AL), which consists of a contact mat (27 in by 27 in) and a hand-held computer. Microswitches embedded in the contact mat measure the interval between participant liftoff from the mat and their landing (air-time). Using a basic kinematic equation, the computer calculates the vertical jump height from the air time and then displays the air-time (0.01 s) and height to the nearest half-inch for each jump [28].

Using the device specifications for the jump height test, participants completed four trials in which they jumped as high as possible with modest pauses (a few seconds) between each jump. These jumps resulted in the quantification of air-time and jump height. The four jumps were averaged for analysis.

For the jump explosiveness test, participants took four successive jumps with the goal of maximizing the height of each jump while minimizing time on the ground between jumps. This test quantified average ground time, average jump height, and a composite Power Factor value, derived by dividing air-time by ground time and used as a function of combined strength and quickness of the legs. The average was taken from two repetitions. Jump explosiveness was defined as time on the ground between 4 consecutive jumps with reduced time on the ground indicating more explosiveness.

2.3. Statistical Analyses

Statistical analyses were conducted using SPSS (v23). Outcomes were plotted and assessed for outliers while blinded to condition. Repeated Measures Mixed Model ANOVA was used to test within (study day) and between (study condition) participant differences, and potential interactive effects. Statistical significance was considered $p < .05$ for tests of interactions and main effects; Bonferroni correction was used for follow-up contrasts. All outcomes were tested to determine sphericity, homogeneity of variance, and normality of distribution.

The balance and jump tests were performed twice for each study day, both before and after the physical stressor routine and cycling time trial. Of interest were balance and jump performance outcomes before the physical stressor routine on Days 2 and 3 as compared to their baseline after the first physical stressor; this provides an indicator of recovery and readiness to perform after the prior day's stressor and subsequent treatment. As such, repeated measures mixed model ANOVA was specified to test within group differences from the jumping outcomes taken post-stressor and cycling time trial on Day 1 to pre-stressor on Day 2 and Day 3.

3. Results

3.1. Participant Demographics and Baseline Characteristics

Demographic and baseline characteristics are presented in Table 2. One-way ANOVA was used to determine possible differences in participant characteristics. Groups were similar in age and sex distribution. The ECP treatment group had a lower average diastolic blood pressure and BMI at baseline. The inclusion of subjective cycling ability was included to demonstrate homogeneity of the sample for cycling experience. Sex was not a significant covariate for any of the outcomes. Outcomes are presented in Table 3.

Table 2. *Demographic and baseline characteristics.*

	Control (n=28)	ECP (n=29)
Male/female	13/15	14/15
Age (years)	38.7 ± 12.5	39.0 ± 10.9
BMI (kg/m^2)*†	24.6 ± 3.1	23.0 ± 2.6
Resting heart rate (beats/min)	67 ± 11	64 ± 11
Systolic blood pressure (mmHG)	121 ± 14	115 ± 15
Diastolic blood pressure (mmHG)*	78 ± 8	72 ± 8
Exercise frequency		
Times/week	5.3 ± 2.0	5.9 ± 1.9
Aerobic (days/week)	3.4 ± 1.1	3.8 ± 0.7
Strength (days/week)†	2.3 ± 1.0	2.3 ± 1.0
Cycling ability†	3.2 ± 1.1	3.4 ± 1.1
Cycling frequency (past 6 months)†		
None	7.1%	14.3%
1-10 times	24.9%	10.7%
11-20 times	14.3%	7.1%
More than 20 times	53.6%	67.9%

Values shown as mean ± SD except for cycling frequency which is shown as a percent for each category
*Statistically significant difference, $p < .05$
†ECP Treatment n = 28

Table 3. *Performance outcome measures.*

Performance Outcome	Control (n=28)	ECP (n=29)
10k Time Trial Time (sec)		
Day 1	1492.71 ± 255.94	1533.62 ± 422.96
Day 2	1488.96 ± 287.03	1490.46 ± 334.76
Day 3	1475.54 ± 280.86	1441.23 ± 317.60
10k Time Trial HR*		
Day 1	151.02 ± 19.67	150.53 ± 16.97
Day 2	152.05 ± 21.04	148.26 ± 18.92
Day 3	151.01 ± 22.55	147.82 ± 16.99
Balance (cm)		
Day 1	76.70 ± 12.55	75.94 ± 12.77
Day 2	75.34 ± 10.74	67.57 ± 10.93
Day 3	71.89 ± 9.49	67.43 ± 9.66
Jump Explosiveness (sec)		
Day 1	0.39 ± 0.07	0.39 ± 0.07
Day 2	0.42 ± 0.09	0.37 ± 0.09
Day 3	0.42 ± 0.11	0.38 ± 0.11
Jump Height (cm)		
Day 1	35.03 ± 9.75	34.54 ± 8.03
Day 2	35.76 ± 9.96	35.10 ± 9.78
Day 3	35.10 ± 10.16	34.32 ± 9.47

Values are expressed as mean ± SD
*ECP Treatment n = 28.

3.2. Cycling Time Trial

Assumptions of sphericity and equality of variances were found to be met using Mauchly's test and Levene's test, respectively. Of the factors that differed between groups at baseline, only heart rate ($p = .030$) was a significant covariate and retained in the model. Results of the factorial ANOVA, after controlling for heart rate, revealed a significant interaction between study day and condition, $F(2, 51) = 3.69$, $p = .032$, indicating differing time trial performance by study condition. Bonferroni corrected follow-up contrasts revealed a significant decrease in cycling time trial times between Day 1 and 3 for the ECP condition, $p = .006$. There were no significant differences found for cycling time between any study days for the control condition. Main effects for both within-subjects and between-subjects were not significant (Figure 2).

3.3. Balance

Results of the factorial ANOVA revealed a significant interaction between study day and condition, $F(2, 50) = 3.45$, $p = .040$, indicating differing balance performance by condition over the study days. Bonferroni corrected follow-up contrasts revealed a significant decrease in sway (indicating improved balance) between post-stressor balance on study Day 1 and pre-stressor balance on Days 2 and 3 for the ECP condition, $p < .001$. Of the factors that differed between groups at baseline (heart rate, diastolic blood pressure, and BMI), none were significant in the model. There were no significant within-group differences found for balance for the control condition. Main effects for both within-subjects and between-subjects were not significant (Figure 3).

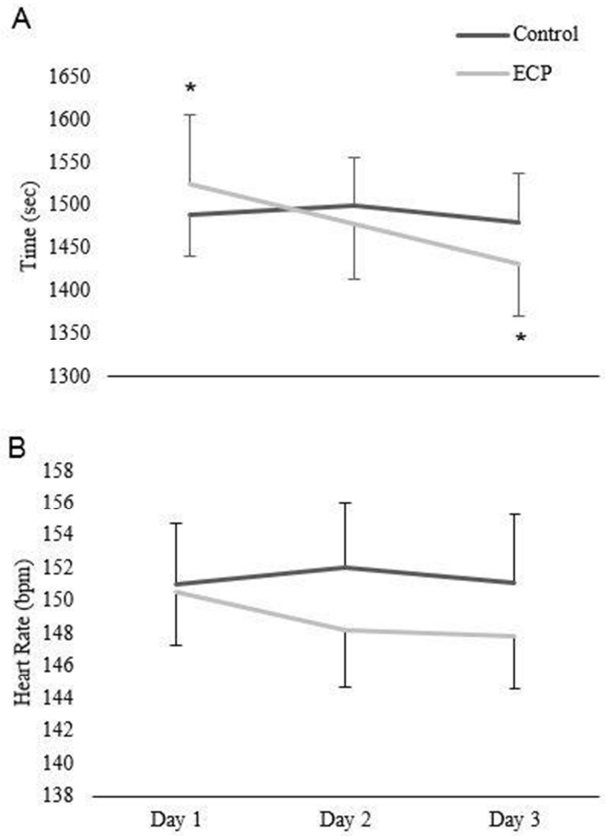

Figure 2. *Mean ± SD for (A) cycling time trial completion time, and (B) heart rate during the cycling time trial. *Significant decrease in time to complete cycling trial between Day 1 and Day 3, p = .002.*

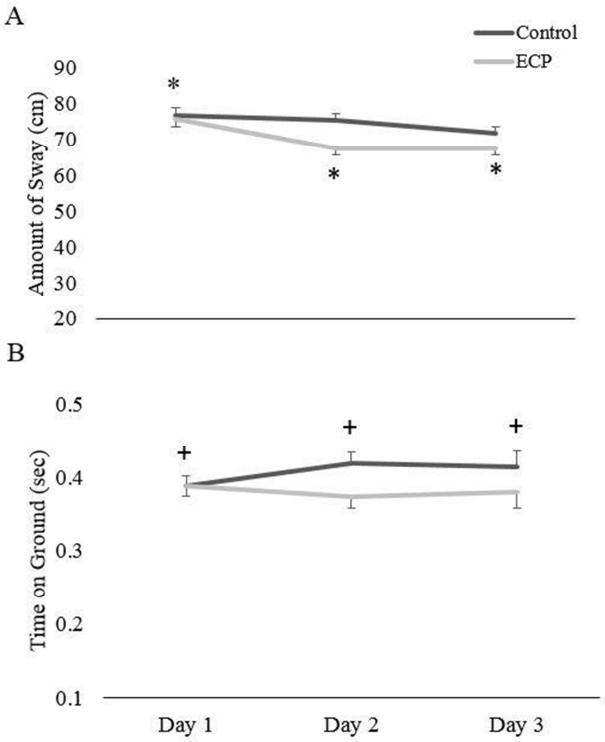

Figure 3. *Mean ± SD for (A) balance, and (B) jump explosiveness. *Significant decrease in sway from Day 1 to Day 2 and Day 3, p < .001. +Significant increase in time on ground from Day 1 to Day 2 to Day 3, p = .014.*

3.4. Jump Tests

Results of the factorial ANOVA revealed a significant interaction between study day and condition, $F(2, 51) = 3.61$, $p = .034$, indicating that performance on the jump explosiveness outcomes differed by condition over the study days. Bonferroni corrected follow-up contrasts revealed a significant increase in time on ground (indicating less explosiveness) between post-stressor tests on study Day 1 and pre-stressor tests on Days 2 and 3 for the control condition, $p = .014$. Of the factors that differed between groups at baseline (heart rate, diastolic blood pressure, and BMI), none were significant in the model. The ECP group had no significant difference in jump explosiveness across study days. There were no significant main effects or interactions for jump height.

4. Discussion

The current study found that three sessions of post-exercise ECP influenced the short-term recovery and subsequent performance of healthy individuals subjected to high-intensity exercise. It was hypothesized that performance for both the ECP and control conditions would likely decline after the stressor tasks, but that ECP treatment would mitigate this degradation across study days. Though this was seen for jump explosiveness, for other outcome measures, such as the cycling time trial and balance, there were significant improvements for the ECP group.

Participants in both groups demonstrated, on average, improved cycling times on Day 3 as compared to Day 1 despite the soreness and fatigue induced by the physical stressors as demonstrated by self-rated soreness and fatigue at the beginning of each study visit. Some of this could be attributed to a practice effect as participants became more accustomed to the nature of the time trial, shifting the cycling apparatus, and pacing themselves on the 10k course. However, the average cycling time for ECP participants significantly decreased each day while the control group had no significant changes across study days. It is also notable that, while not statistically significant, average heart rate during the cycling time trial decreased over the three study days despite improved cycling performance for the ECP group. In contrast, heart rate was stable for control participants across days (see Figure 2).

Although the results were mixed, there was some evidence for a limited impact of ECP on non-endurance outcomes, such as single-leg balance and jumping ability. Balance and jumping assessments were administered both before and after the physical stressor portion of the protocol (unlike the cycling time trial which was completed once per study day after the physical stressors). Balance and all measures of jumping ability were assessed from post-stressor on Day 1, when the maximum amount of performance degradation could be expected to have occurred, to pre-stressor on Days 2 and 3 to gauge recovery and readiness to perform after strenuous exertion the previous day. Although both groups

improved, the ECP group significantly decreased the amount of sway during one-legged balance from post-stressor Day 1 to pre-stressor measures on both Day 2 and 3 while the control group did not. The fine motor control movements of the lower leg required in order to maintain one-legged balance with minimal sway are greatly affected by events that create micro-tears in the musculature, such as those induced by the (eccentrically focused) physical stressors utilized in this study [29]. The increased blood flow and the resulting improvement in the delivery of oxygen and disposal of waste associated with ECP may have aided treatment participants in recovering fine control more rapidly compared to participants in the control group.

The jumping tests were designed to expose reductions in fast-twitch muscle power and reduced power/responsiveness due to fatigue from the physical stressors. For the explosiveness test (ability to spend less time on the ground, with relatively high jump height, over repeated quick jumps), control participants spent significantly more time on the ground relative to height (an indicator of less explosiveness) from post-stressor on Day 1 to pre-stressor on Days 2 and 3, while ECP participants maintained the same level of performance (no significant differences between days). Similar mechanisms as discussed with the balance tests may be at work in this scenario, although it is worth noting that the other measure of jumping ability was not significantly altered by ECP.

There are multiple mechanisms through which ECP benefits coronary heart disease patients that may translate to improved recovery and performance in healthy individuals. One of the most pronounced of these potential mechanisms is enhanced muscle and cardiac blood flow via vasodilation. ECP has been shown to impact coronary vasodilation and angiogenesis in heart patients and is thought to dilate existing arteries, including in the myocardium [2, 3]. This vasodilation may be a byproduct of increases in shear stress, which has been shown to be related to the creation and release of nitric oxide (a vasodilator) [30]. Nitric oxide supplementation has been shown to enhance running performance after single ingestion [31].

Another possible explanation of the performance differences between the control and ECP groups in the present study could be the formation of new blood vessels, or angiogenesis. In a study of induced myocardial infarction with dogs, it was found that after occlusion the ECP treatment group had significantly increased the capillary density in the myocardium compared to controls; up to 30% in the infarcted areas, and 10% in the non-infarcted areas [32]. This is especially relevant as a comparator to the present study as this effect was found after only two treatments taking place within a 5-hour period, providing some evidence of physiological impact after a very short time period. In a human study of individuals with abnormal glucose tolerance, Martin and colleagues found that after 7 weeks of ECP treatments, subjects demonstrated both increased VEGF concentrations (75% increase) and improved capillary density [12].

ECP may have impacted performance by means of increasing blood flow at the muscle level post-exercise, thereby increasing the availability of oxygen and the hormones and substrates important to recovery, and also facilitating the removal of deleterious metabolic byproducts. It is well documented that loaded exercises with a strong eccentric component, like those deployed for this study, produce an acute accumulation of metabolic by-products (namely lactate, hydrogen ions, and deprotonated phosphates) that interfere with actin-myosin interaction [33]. Ochoa and colleagues found that ECP increased resting VO2 levels during a single therapy session in both angina patients and healthy volunteers [20]. In this manner, ECP may be simulating “active” recovery, which is generally agreed to be advantageous to the recovery process when compared to “passive” recovery [34, 35]. Further evidence in support of this hypothesis is offered by Urano and colleagues who found increases in exercise tolerance in long-term ECP patients that may be related to the simulated low-level “exercise” (muscle contraction) induced by ECP treatment [36].

Additionally, ECP uses rapid sequential compression during the diastolic phase of circulation in order to achieve increased blood flow, differentiating it from compression boots and other compression-related therapies. However, the high-pressure sequential compression and massaging action of ECP may aid in recovery and readiness to perform as has been seen in multiple studies on compression therapy [37-39].

There are limitations to the study that should be noted. There is the potential for practice effect for some outcome measures, such as the one-legged balance and cycling time trial. Although participants for both conditions were introduced to all stressor and performance outcome routines during the familiarization visit, there was no opportunity to perform the routines under full trial conditions. A no-treatment baseline assessment visit that involved full effort for all potential stressors and outcome routines may have eliminated some variability during Day 1 of the study visits. Additionally, there were some differences between groups with regard to baseline fitness and BMI that may have been better controlled with a crossover design whereby both groups received both conditions. Furthermore, it was impossible to blind participants to experimental conditions, and therefore expectancy effects could not be controlled. Finally, due to the non-invasive nature of the study design, measurements of possible physiological mechanisms mentioned such as vasodilation, NO production, and increased perfusion were unable to be measured.

5. Conclusion

The results of this study provide preliminary evidence that ECP therapy may be beneficial for use in exercise recovery and performance in healthy adult populations. Further, it shows that benefits may be achieved with only three treatment sessions. Additional research is needed to better

understand the exact mechanisms by which this takes place, and what additional effects ECP may have on healthy populations.

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