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*Technical Note*

# Lower Limb Graduated Compression Garments Modulate Autonomic Nervous System and Improve Post-Training Recovery Measured via Heart Rate Variability

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ABSTRACT

***International Journal of Exercise Science 13(7): 1794-1806, 2020.*** Prior studies have examined the benefits of graduated compression garments (GCG) with regards to diverse exercise regimens; however, the relationship between GCG and the autonomic nervous system (ANS) has not been fully explored. The aim of this study was to examine Heart Rate Variability (HRV) trends—a proxy for ANS modulation—in response to donning GCG during a progressive overload training regimen designed to induce overtraining. Ten college-aged male novice runners were recruited for the 8-week crossover study. After three weeks of monitored free living, participants were randomized and blinded to an intervention group that donned a lower-body GCG during a two-week exercise regimen or a control group that donned a visually identical but non-compressive sham during identical training. No significant difference in HRV was calculated by the natural logarithm of the root mean square of successive RR-interval differences (lnRMSSD) between the 3-week free-living baseline and GCG intervention periods ($P = 0.3040$). The mean lnRMSSD was greater during the free-living phase and GCG intervention compared to the sham placebo ($P < 0.001$ and $<0.001$ respectively). With regard to the daily fluctuation of lnRMSSD, no significant differences were found between free-living and intervention ($P = 1.000$). Conversely, the intervention period demonstrated reduced daily fluctuation of lnRMSSD relative to the Sham placebo group ($P = 0.010$). These novel findings posit that post training use of a commercially available graduated compression garment in novice runners may be effective in counteracting some deleterious effects from overtraining while attenuating its effects on vagally-mediated HRV.

KEY WORDS: Overtraining, running, sympathetic and parasympathetic nervous system

## INTRODUCTION

Compression garments have been widely researched and clinically utilized to mitigate edema, deep vein thrombosis, and clotting for over a half of century (30). More recently, sportswear using lower limb graduated compression garments (GCG) have been posited to *(i)* promote positive venous hemodynamics and reduce venous pooling (5), *(ii)* enhance muscle oxygenation and proprioceptive awareness (2), *(iii)* reduce muscle oscillations and perceived fatigue (48), and *(iv)* accelerate the removal of metabolic waste including lactic acid (20, 44), thereby all contributing to the enhancement of performance and recovery metrics in individuals during sports and exercise (4). While these mechanisms are well established, there is a dearth of research exploring the relationship between lower limb GCG and its effect on the autonomic nervous system (ANS), which is known to play a pivotal role in recovery and stress-adaptation.

The ANS plays a dynamic role in the physiological response to exercise and regulates cardiovascular function via the parasympathetic nervous system (PNS) and sympathetic nervous system (SNS) (15). High SNS activity in response to training has been linked to lower fitness, increased perception of fatigue, and poor recovery in athletes (14). Furthermore, elevated cardiac vagal modulation has been demonstrated to have a strong association with aerobic fitness (18). Aerobically trained individuals have a decreased resting heart rate and more rapid heart rate recovery after exercise due to increased parasympathetic tone (7). ANS monitoring can therefore provide valuable insight into the adaptative response to endurance training.

Heart Rate Variability (HRV) measures act as a portal into characterizing the autonomic nervous system, and until recently, during recovery from exercise. It is a noninvasive, convenient, and reliable tool in which coach practitioners and athletes alike can track and leverage HRV data to monitor ANS modulation and balance (26, 49). A high HRV value is attributed to increased PNS drive while a low HRV value is attributed to increased SNS activity and ANS dysregulation (26). As a proxy measure for the restoration of cardiovascular homeostasis (47), HRV has been utilized to characterize sympathetic overdrive (14) and physical fatigue from exercise (40). Additionally, measurements taken immediately after supramaximal exercise (1) and longitudinally over three weeks of heavy training (40) have both demonstrated HRV attrition. These fluctuations reflect poor adaptations to training stress and together, they suggest that HRV is a promising application in guiding exercise prescription. In several cohorts of endurance athletes, marked benefits in recovery have been observed when training loads are adjusted based on HRV trends (32). Furthermore, high intensity training following periods of full ANS recovery (as demonstrated by positive HRV adaptations) has been shown to improve maximal running load and peak oxygen consumption (28). However, failure to reduce training load during overexertion has been shown to not only diminish HRV, but also reduce performance readiness in athletes (41). Together, these findings suggest that HRV is an adequate surrogate for measuring ANS restoration and physical recovery. Hence, the prospective impact of GCGs on HRV may act as a novel ergogenic aid that can be implemented to simultaneously improve post-exercise recovery and training performance optimization.

The purpose of this study was to determine if novice runners experienced augmented recovery by wearing lower limb GCG following a running program designed to induce overtraining. HRV was utilized as an index for recovery to compare the intervention with a sham control in a crossover study design. Our hypothesis is that donning GCG post-training may mitigate the deleterious effects of training stress as demonstrated by attenuated HRV responsiveness over time.

## METHODS

*Participants*

Ten college-aged males were recruited from the University of California, Los Angeles (UCLA) campus through word of mouth and social media. Demographic data is presented in Table 1. Inclusion criteria included individuals that were considered novice runners who engaged in minimal running during the past year (*i.e.*, less then 5 miles/monthly) and fell within ~30-50% of age-gender matched $VO_{2max}$. Exclusion criteria included the presence of any significant medical diagnoses, including musculoskeletal, cardiovascular, pulmonary, metabolic, or other disorders that would limit the ability to exercise or increase their cardiovascular risk of exercising. All participants provided written informed consent prior to enrollment. The study was performed in accordance with the ethical standards of the Helsinki Declaration and was approved by the UCLA Institutional Review Board. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (37).

**Table 1.** Demographics for novice male runners.

| Participant | Age (yr) | Height (cm) | Weight (kg) | BMI | $VO_{2max}$ (ml/kg/min) |
|---|---|---|---|---|---|
| 1 | 22 | 184 | 79.5 | 23.5 | 33.6 |
| 2 | 20 | 183 | 82.3 | 24.6 | 38.4 |
| 3 | 21 | 185 | 79.5 | 23.2 | 36.9 |
| 4 | 20 | 175 | 81.8 | 26.7 | 39.6 |
| 5 | 23 | 189 | 86.1 | 24.1 | 37.4 |
| 6 | 24 | 182 | 74.5 | 22.5 | 40.3 |
| 7 | 22 | 183 | 83.2 | 24.8 | 36.4 |
| 8 | 21 | 188 | 81.4 | 23.0 | 37.9 |
| 9 | 22 | 190 | 78.5 | 21.7 | 35.1 |
| 10 | 20 | 185 | 90.3 | 26.4 | 38.9 |
| Mean ± SD | 21.5 ± 1.4 | 184 ± 4 | 81.7 ± 4.3 | 24.0 ± 1.6 | 37.5 ± 2.0 |

*Protocol*

A randomized, placebo-controlled 8-week crossover study with concealed allocation and assessor blinding for two outcomes was conducted in the Exercise Physiology Research Laboratory at UCLA. Participants were randomly allocated to the order of training interventions by an investigator independent of the recruitment of participants using an online-generated random number program. Allocation was concealed with the use of consecutively numbered envelopes.

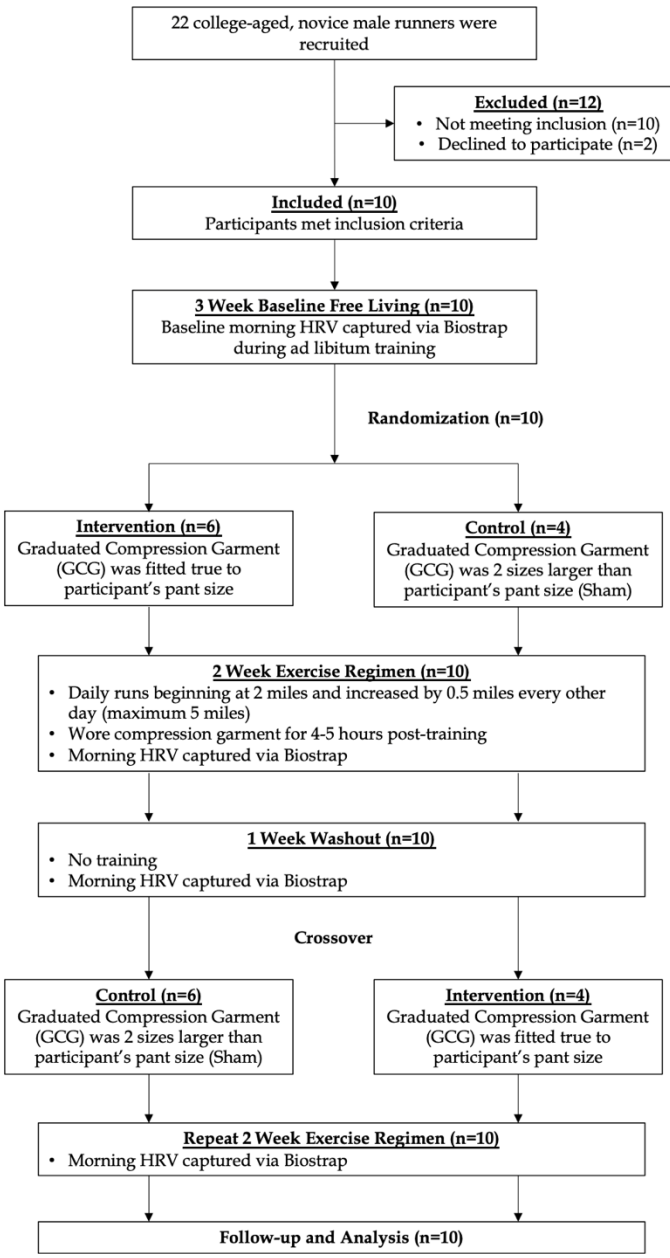


**Figure 1.** Consort Flow Diagram. Participants were randomized into an 8-week crossover-design study to determine if the GCG and Sham produced differential responses in mitigating the effects from the 2-week running program designed to induce overtraining. Recovery was characterized by HRV and compared to the participant's baseline, free-living values.

Figure 1 displays a consort flow diagram of the study. Upon recruitment, and to ensure inclusion criteria, a maximum oxygen uptake ($VO_{2max}$) was determined via gas exchange during an incremental, symptom-limited maximal treadmill exercise test using standard procedures. $VO_{2max}$ was measured breath-by-breath with a metabolic measurement system (Oxycon Pro CareFusion, Yorba Linda, CA, USA) using individually determined protocols that predict test completion within 8-12 minutes and standard procedures. Concurrently, heart rate was monitored with a 12-lead EKG interfaced to the metabolic measurement system. Trained and

experienced investigators conducted all testing in accordance with established guidelines for cardiopulmonary exercise testing (9, 43). $VO_{2max}$ was determined from the highest 15-second average and accepted as maximal in the presence of a plateau in $VO_2$ with increasing work rate. Participant height was determined using a precision stadiometer (Seca, Hanover, MD, USA) while body mass was measured on a calibrated digital BIA scale (InBody Biospace, Cerritos, CA, USA).

After enrollment participants were issued a wrist-worn physiological monitor (Biostrap®, Biostrap USA LLC, Los Angeles, California) that served to measure the primary outcome variable, lnRMSSD-HRV. Depending on randomization order, participants were given either *(i)* a lower limb graduated compression garment (GCG, Power Recovery Tight, 2XU® Pty. Ltd., Melbourne, Australia) or (ii) sham garment that was identical in appearance but two sizes larger, thereby negating its compressive properties. For the first 3-week free-living phase, participants engaged in ad-libitum exercise (except running) while daily morning HRV measures were captured. The values obtained established their baseline HRV and served as a reference for any changes sustained during either research arm. Subsequent to the 3-week baseline period, participants were randomized into the intervention (GCG) or control (SHAM) and instructed to follow a daily running regimen for two weeks. This program was designed to exhibit progressive overload and induce the effects of overtraining. Following this, participants underwent a 1-week washout with no training to negate overtraining effects and reestablish a baseline HRV. They then crossed-over into the alternate research arm to complete an identical progressive overload running regimen and measure morning HRV.

GCG and Sham Garments: For the intervention group, per manufactures instructions, the lower limb compression garment was fitted true to size to ensure a distal-proximal pressure gradient transitioning from 26 mmHg to 8 mmHg (from the ankle to gluteus region) with a standardized wearing time of 4-5 hours immediately post exercise (19). The sham group utilized two sizes larger than the aforementioned fitting, thereby negating its compressive properties. Participants were encouraged to wear the garments during their usual activities-of-daily-living.

HRV: Among the physiological metrics captured by the wrist-worn device and associated smartphone application, a recently validated photoplethysmography metric, lnRMSSD (*i.e.*, the natural log root mean square of successive R-R interval differences), was utilized to measure the vagally-mediated HRV response (23). Using a proprietary PPG processing software (Wavelet wristband, Wavelet Health, Mountain View, USA), the wrist-worn device captures a 60-second reading, producing HRV values with high signal quality (12). This method provided valuable insight into vagal tone, characterizing beat-to-beat variance within the heart with comparable accuracy relative to longer 5 and 10-minute measurements (13, 35). Due to its efficiency, the lnRMSSD indices used in this study offered a quick and reliable measurement that both researchers and participants were able to use with high compliance and minimal complication (10). Moreover, lnRMSSD was used because relative to the untransformed RMSSD measurement, the natural logarithm controls for outliers and simplifies analysis (35). This ultra-short (i.e. 60-seconds) HRV method has been shown in previous studies to successfully capture

inter-individual HRV fluctuations longitudinally (36) and accurately detect ANS changes in response to training effects (35).

Prior to HRV measures, participants were asked to abstain from food, caffeine, alcohol and smoking for 12 h before testing in order to control for confounding factors that could alter HRV. Immediately upon awakening in the morning, each participant was instructed to capture their HRV in an upright position with minimal bodily movements. It was encouraged that the measurements be performed prior to any other morning activity and conducted in a comfortable, temperature-controlled (22$^{o}$C) room with dimmed lighting and minimal noise or distraction. The participants captured their data using the wrist-worn wearable device by pressing a button on their smartphone app. The measurements were acquired in 60-seconds and the app automatically uploaded the data onto the manufacturer's secure cloud-based storage system where researchers could access and record the HRV data. Because the data was seamlessly shared between the participants and researchers, compliance was easily monitored and maintained throughout the study.

*Statistical Analysis*

Descriptive statistics are presented as mean ± standard deviation. Continuous variables were first assessed for normality via Shapiro-Wilk tests. Because the data were found to deviate significantly from normality, within-group comparisons were made with a Quade test followed by all-pairs tests. Feltz-Miller asymptotic tests for equality of coefficients of variation were performed. A Holm-Bonferroni correction to control the familywise error rate was applied. Statistical significance was determined based on $\alpha = 0.05$. Analysis was performed in Excel (Microsoft Corporation, Redmond, Washington) and R (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria). Based on a pre-hoc power analysis using previous literature of similar design (45), we calculated a required group sample size of 11 based off high-frequency power—which is an index of parasympathetic activity and correlates with RMSSD—to detect significant differences assuming $\alpha = 0.05$ and $\beta = 0.8$.

## RESULTS

All ten participants successfully completed the 8-week study with no missed sessions. Selected anthropometric measures and $VO_2$max were collected at enrollment. The natural logarithm of the root mean square of successive RR-interval differences (lnRMSSD) was obtained during the baseline 3-week free-living phase and throughout the 2-week SHAM placebo, 7-day (no training) washout, and 2-week GCG intervention (Table 2). No significant difference in mean lnRMSSD was detected between the 3-week free-living and GCG intervention periods ($P$ = 0.304), or the 7-day washout versus the intervention ($P$ = 0.356). However, the mean lnRMSSD was greater during the free-living and washout phases compared to the SHAM placebo ($P$ < 0.001 and P<0.003 respectively). The intervention was also greater compared to the placebo ($P$ < 0.001). In fact, the percent decrease in lnRMSSD was observed to be ~60% in the 2-week SHAM period while no substantial changes were observed in the GCG intervention (Figure 2). No significant differences were observed between the free-living and washout periods ($P$ = 0.069).

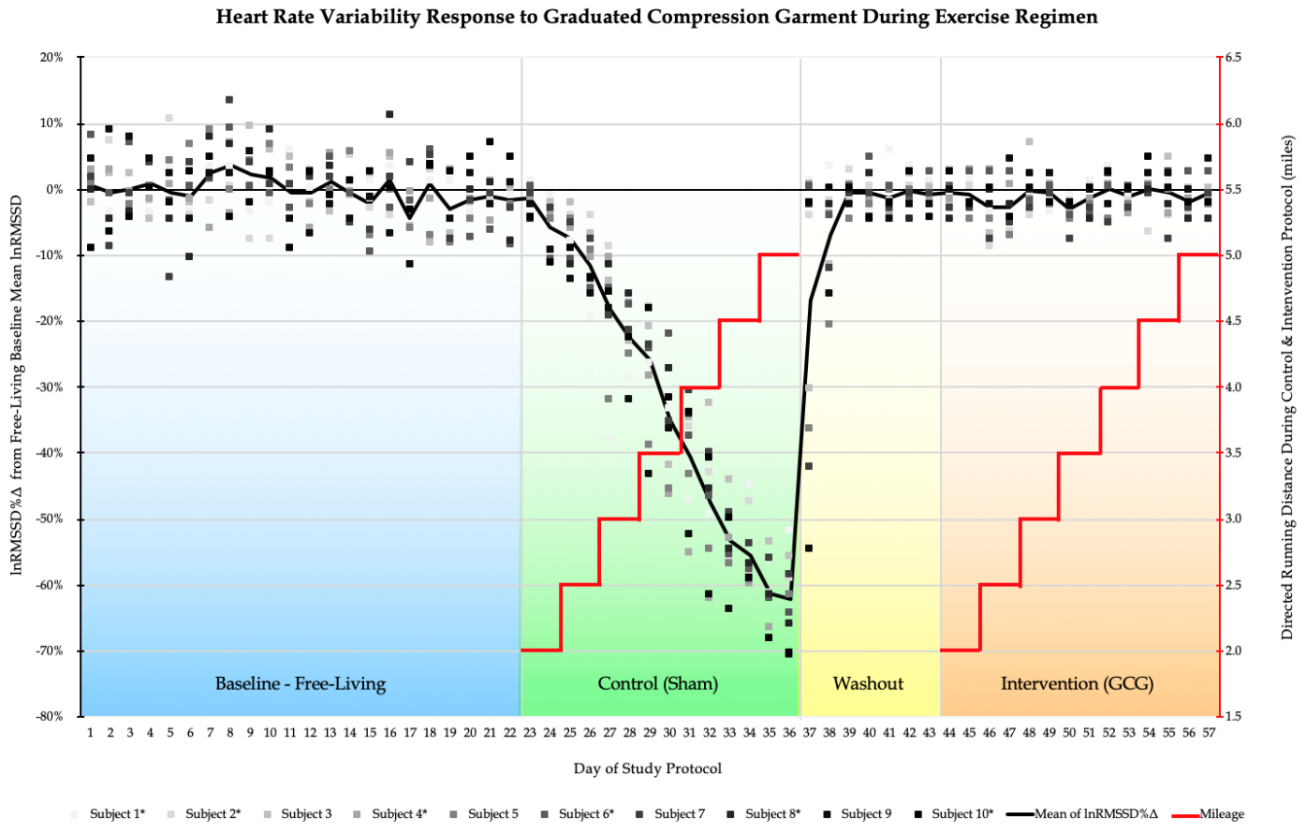


**Figure 2.** Heart rate variability response to graduated compression garment during exercise regimen. lnRMSSD%Δ equals the percent change in daily lnRMSSD relative to the mean HRV established during each participant's free-living baseline period. The Mean of lnRMSSD%Δ (black line) was calculated using the mean of all participants lnRMSSD%Δ for each day of the study. For consistency, the graph is designed so that all participants' data would be displayed in the order of free-living baseline, control, washout, and intervention. This did not cause an ordering effect due to the fact that all participants were randomized and served as their own controls. *Participants that were assigned to undergo the intervention (GCG) phase first (Days 37-43) and the control (SHAM) phase last (Days 44-57) due to randomization. Each day of the Intervention and Control portions of the protocol (Days 23-36; Days 44-57) participants were required to run a certain prescribed mileage (red line) starting with 2 miles up until 5 miles by the last day.

With regard to the daily fluctuation of lnRMSSD, no significant differences were found between baseline and intervention ($P$ = 1.000) or washout versus placebo ($P$ = 1.000). In contrast, the intervention period demonstrated significantly lesser daily fluctuation of lnRMSSD compared to both the washout ($P$ = 0.010) and placebo ($P$ = 0.010). The daily fluctuation of lnRMSSD for the free-living phase was also less than the washout ($P$ = 0.010) and placebo ($P$ = 0.010).

**Table 2:** Vagally-mediated HRV recovery metric (lnRMSSD) captured during each phase

| | Median lnRMSSD ± SD (ms) | | | |
|---|---|---|---|---|
| Participant | Baseline | Intervention (GCG) | Washout | Control (Sham) |
| 1 | 4.3 ± 0.1 | 4.3 ± 0.1 | 4.4 ± 0.1 | 2.9 ± 0.8 |
| 2 | 4.4 ± 0.2 | 4.3 ± 0.1 | 4.4 ± 0.1 | 3.1 ± 1.0 |
| 3 | 4.3 ± 0.2 | 4.3 ± 0.2 | 4.0 ± 0.5 | 3.1 ± 0.9 |
| 4 | 4.5 ± 0.1 | 4.4 ± 0.1 | 4.4 ± 0.1 | 2.9 ± 1.1 |
| 5 | 4.4 ± 0.2 | 4.3 ± 0.1 | 4.0 ± 0.6 | 2.8 ± 1.0 |
| 6 | 4.5 ± 0.2 | 4.5 ± 0.1 | 4.5 ± 0.1 | 3.1 ± 1.0 |
| 7 | 4.3 ± 0.2 | 4.2 ± 0.1 | 4.0 ± 0.7 | 3.1 ± 0.9 |
| 8 | 4.4 ± 0.3 | 4.3 ± 0.1 | 4.3 ± 0.1 | 3.1 ± 1.0 |
| 9 | 4.4 ± 0.2 | 4.4 ± 0.1 | 3.9 ± 0.8 | 2.7 ± 1.1 |
| 10 | 4.4 ± 0.2 | 4.4 ± 0.1 | 4.3 ± 0.1 | 3.0 ± 1.0 |
| Median | 4.4 | 4.3 | 4.3 | 3.1 |
| IQR | 0.1 | 0.1 | 0.4 | 0.2 |
| CV | 0.02 | 0.02 | 0.05 | 0.05 |

## DISCUSSION

This study sought to measure the effects that post training GCG use had on recovery, using daily HRV as a proxy for ANS modulation. These novel findings posit that post training use of a commercially available graduated compression garments in novice runners may play a role in counteracting some deleterious effects from overtraining (absent of adequate rest/recovery) while attenuating its effects on vagally-mediated HRV.

Following intense training (16), numerous studies have demonstrated a disproportionate stimulus in sympathetic drive with decreased HRV indices (e.g., lnRMSSD) during recovery (16, 39). The running protocol in this study was designed to provoke this ANS imbalance through a progressive overload training regimen absent of rest/recovery (1, 40, 50) leading to overtraining. Without the GCG, our sham control group had a significant reduction in lnRMSSD post-training; suggesting the running protocol was effective in accomplishing overtraining. On the other hand, participants wearing the GCG exhibited no significant differences in lnRMSSD post training relative to their established 3-week baseline (Figure 2). Although a paucity of research has explored the specific application of graduated compression garments on HRV, a few have qualified HRV as an adequate proxy measure for characterizing parasympathetic activity and cardiovascular resiliency (18, 47, 49). Findings show a rebound to greater HRV values is associated with sustained post-exercise recovery (8, 25, 39). Comparing lnRMSSD trends between each participant's GCG and sham phases suggest that the vagally-mediated ANS is better maintained while wearing the GCG during recovery.

It is known that athletes are able to maintain HRV homeostasis after exercise through acquired ANS adaptations from rigorous training (42). Our study participants were novice runners and lacked these adaptive changes but exhibited similar recovery patterns after wearing GCG. It is plausible that their enhanced recovery after donning the GCG is due to augmented cardiovascular mechanics through increased venous return, decreased venous pooling in the lower extremities, and reduced swelling and soreness (2). Considering Bernoulli's principle, the

gradual proximal decrease in pressure facilitates increased fluid velocity, thereby acting as a pressure gradient for venous return. The lower limb GCG in this study supplied a distal-proximal pressure gradient that gradually transitions from 26 mmHg to 8 mmHg (from the ankle to gluteus region). This increased venous return facilitates a greater cardiac preload, thus diminishing the need for ANS modulation on cardiac output during exercise and recovery (31). Instead of increasing heart rate via sympathetic innervation (17, 51), cardiac output is enhanced by a greater stroke volume though greater venous return via GCG. Because ANS balance and cardiovascular homeostasis contribute to HRV (26), the GCG's touted ability to improve hemodynamics and indirectly enhance cardiac output may explain the HRV responses in our results.

The wrist-worn device in this study used validated PPG technology to capture the RMSSD and provide reliable insight into vagal tone (46) without significant disruption from other physiological factors such as respiratory rate (38). Therefore, the trends observed in this study can be useful to the emerging population of athletes using wearable technology. The ability to easily measure HRV (RMSSD) and monitor recovery offers the potential to promote more efficient training with individualized programming. Conversely, recovery ignorance can contribute to maladaptation to training load and increased injury risk (41). Recovery is essential for athletes to combat the adverse health consequences of overtraining, that is, muscle atrophy, unhealthy sleep patterns, compromised immune system function, development of chronic joint inflammation, and even irritability or depression (33). Moreover, strenuous training volume may also induce a shift toward excessive SNS stimulation (22) and a subsequent decrease in HRV (34).

Fortunately, the detrimental effects of overexertion are preventable (29) and HRV monitoring may guide appropriate training program developments, thereby counteracting such events (32). HRV monitoring has been used to alter training regimens in order to promote optimal recovery prior to athletic competition (42) while HRV-guided cycling programs enhanced sports performance with a substantial increase in peak power output (24). Athletes wearing lower limb compression have also demonstrated decreased HR and improved performance during activity (6). Exercise prescriptions based on HRV trends have also improved $VO_{2max}$ and maximal workload (28). These regimens involved performing high-intensity training during periods of increased HRV, while resting during periods of reduced HRV (28). Individualized exercise prescriptions using HRV may also be useful for moderately trained to elite athletes (11, 21, 42). Many of these studies have seen success with HRV monitoring in trained athletes, though the feasibility of doing so in amateur athletes is lacking in the literature. However, we have demonstrated that HRV monitoring is feasible in novice runners and that they may also benefit from GCG as a means of improved recovery.

Although our sample size was relatively small, this study's use of a crossover design using sham garment controls visually identical to the interventional GCG aided in effective participant blinding while mitigating potential placebo effects. Furthermore, our use of the 3-week free-living baseline allowed us to establish an individualized, free-living HRV reference. That is, the participants proceeded with normal activities-of-daily-living with no restrictions, allowing us

to control for personal behaviors such as sleep patterns, caffeine intake, or other environmental, social, and psychological stressors that may affect each participant's physiological response and recovery during the study. Even so, we recognize that the scope of our findings is mainly focused on novice runners and should not be readily generalized to all athletes considering the differences in training load and physical fitness levels. While donning GCG post-exercise is suggestive of improved recovery and HRV, trainers and researchers should both continue exploring the applicability of GCG in sport performance and recovery. Ultimately, a study employing a larger and more diverse cohort of athletes may offer more generalizable evidence in this area of study.

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