Statistical Analysis and Results

# 1. Statistical Analysis

The present analysis was not pre-registered as we had no a priori hypotheses and thus was considered exploratory. Inferential statistics were treated as highly unstable local descriptions of the relations between model assumptions and data in order to acknowledge the inherent uncertainty in drawing generalised inferences from single and small samples (Amrhein, Trafimow, et al., 2019). For all analyses we opted to avoid dichotomising the existence of effects and therefore did not employ traditional null hypothesis significance testing on parameter estimates (Amrhein, Greenland, et al., 2019; McShane et al., 2019). Instead, we opted to take an estimation-based approach (Cumming, 2014). For all analyses model parameter estimates and their precision (i.e., 95% confidence intervals [CI]), along with conclusions based upon them, were interpreted continuously and probabilistically, considering data quality, plausibility of effect, and previous literature, all within the context of each model. We focused primarily on qualitative examination of our results based on visualization of the data and models for fixed effects. All analysis was performed in R (version 4.3.3, The R Foundation for Statistical Computing, 2022) and all data and code is presented in the supplementary materials (<https://osf.io/ugbtd/>).All data visualisations were made using ggplot2 (Wickham et al., 2022), ggeffects (Lüdecke, Aust, et al., 2024) and the patchwork (Pedersen, 2022) packages. The aim of our analysis was to explore to explore the effects of both low and high BFR conditions upon physiological and perceptual parameters during the warm-up, and on performance outcomes as a result of the warm-up. Linear mixed effects models were used with Restricted Maximal Likelihood estimation using the lme4 package (Bates et al., 2023). Given the variety of outcomes examined, the timing of their data collection (e.g., pre- to post-warm-up, during warm-up, or post-warm-up only), and the number of measurements taken (e.g., single measures or multiple measures) we describe all of the specific model structures, in addition to model checks and diagnostics using the performance package (Lüdecke, Makowski (@Dom\_Makowski), et al., 2024), in the online supplementary materials (download and view html file from: <https://osf.io/4jtzu>). Where possible we utilised maximal random effects structures for the data (i.e., as long as there were sufficient degrees of freedom, convergence could be achieved, and singularity was avoided).

# 2. Results

Full model summaries including all fixed effect parameter estimates, their confidence intervals, and p values, in addition to all random effect estimates and their correlations, are provided in the online supplementary materials (download and view html file from: <https://osf.io/3bdwt>). Here we focus on presenting the key results for the effects of condition, or condition:time interaction effects (i.e., where timepoint was pre- to post-warm-up or multiple measures where taken during warm-up such as heart rate each minute).

## 2.1 Effects of Warm-up on Physiological and Perceptual Outcomes

|  |
| --- |
| Figure 1: Individual participant and measurement level data (thin lines) with model predicted values and 95% confidence intervals (thick lines and bands OR points and error bars). Panel (A) shows the results for heart rate, panel (B) shows the results for blood lactate, and panel (C) shows the results for rating of perceived exertion. |

### 2.1.1 Heart Rate

Heart rate increased over time (i.e., each minute) in the control condition (slope = 1.31 [95% CI: 0.85, 1.78] beats.minute), low BFR condition (slope = 1.23 [95% CI: 0.69, 1.76] beats.minute) and the high BFR condition (slope = 0.79 [95% CI: 0.29, 1.29] beats.minute). However, despite heart rate appearing greater at the beginning of the warm-up for the high BFR condition it was similar between conditions by the end of the warm-up such that ([Table 1](#tbl-heartcontr) shows the between condition contrasts at three minute intervals). Heart rate results are seen in figure ([Figure 1](#fig-warmup) (A)).

Table 1: Between condition contrasts across time for heart rate.

| Condition 1 | Condition 2 | Contrast | Lower 95\% CI | Upper 95\% CI |
| --- | --- | --- | --- | --- |
| **Baseline** | | | | |
| Low BFR | High BFR | -7.86 | -16.63 | 0.92 |
| Control | High BFR | -9.64 | -17.10 | -2.17 |
| Control | Low BFR | -1.78 | -11.69 | 8.14 |
| **3 Minutes** | | | | |
| Low BFR | High BFR | -6.54 | -14.66 | 1.58 |
| Control | High BFR | -8.06 | -15.16 | -0.96 |
| Control | Low BFR | -1.52 | -10.72 | 7.68 |
| **6 Minutes** | | | | |
| Low BFR | High BFR | -5.22 | -12.99 | 2.55 |
| Control | High BFR | -6.48 | -13.81 | 0.85 |
| Control | Low BFR | -1.26 | -10.14 | 7.62 |
| **9 Minutes** | | | | |
| Low BFR | High BFR | -3.90 | -11.65 | 3.84 |
| Control | High BFR | -4.90 | -13.00 | 3.20 |
| Control | Low BFR | -1.00 | -10.00 | 8.00 |
| **12 Minutes** | | | | |
| Low BFR | High BFR | -2.58 | -10.65 | 5.48 |
| Control | High BFR | -3.32 | -12.60 | 5.96 |
| Control | Low BFR | -0.74 | -10.28 | 8.79 |
| **15 Minutes** | | | | |
| Low BFR | High BFR | -1.26 | -9.95 | 7.42 |
| Control | High BFR | -1.75 | -12.48 | 8.99 |
| Control | Low BFR | -0.48 | -10.91 | 9.94 |
| **18 Minutes** | | | | |
| Low BFR | High BFR | 0.06 | -9.49 | 9.61 |
| Control | High BFR | -0.17 | -12.54 | 12.20 |
| Control | Low BFR | -0.22 | -11.82 | 11.37 |
| Note: |  |  |  |  |
| CI = confidence interval; BFR = blood flow restriction |  |  |  |  |

### 2.1.2 Blood Lactate

Blood lactate was fit using log transformed values and thus values reported here are for the log transformations. Blood lactate results are seen in figure ([Figure 1](#fig-warmup) (B)) are however on the back transformed raw scale. Blood lactate increased from pre- to post-warm-up in the control condition (slope = 0.88 [95% CI: 0.69, 1.07] log(mmol.L)), low BFR condition (slope = 0.96 [95% CI: 0.77, 1.15] log(mmol.L)) and the high BFR condition (slope = 1.09 [95% CI: 0.89, 1.28] log(mmol.L)). However, there was no clear differences between conditions post-warm-up though a tendency for the high BFR condition to result in greater blood lactate levels ([Table 2](#tbl-lactatecontr) shows the between condition contrasts at both timepoints).

Table 2: Between condition contrasts at each timepoint for log blood lactate.

| Condition 1 | Condition 2 | Contrast | Lower 95\% CI | Upper 95\% CI |
| --- | --- | --- | --- | --- |
| **Pre-warm-up** | | | | |
| Low BFR | High BFR | -0.05 | -0.28 | 0.19 |
| Control | High BFR | 0.04 | -0.19 | 0.28 |
| Control | Low BFR | 0.09 | -0.14 | 0.33 |
| **Post-warm-up** | | | | |
| Low BFR | High BFR | -0.17 | -0.41 | 0.06 |
| Control | High BFR | -0.16 | -0.40 | 0.07 |
| Control | Low BFR | 0.01 | -0.23 | 0.24 |
| Note: |  |  |  |  |
| CI = confidence interval; BFR = blood flow restriction |  |  |  |  |

### 2.1.3 Rating of Perceived Exertion

Rating of perceived exertion under the control condition was 10.85 [95% CI: 10.08, 11.62] points, under the low BFR condition it was 11.85 [95% CI: 11.08, 12.62] points, and under the high BFR condition it was 14.4 [95% CI: 13.63, 15.17] points. Compared with the control condition the low BFR condition resulted in a 1 [95% CI: -0.21, 2.21] points greater rating of perceived exertion, and the high BFR condition resulted in a 3.55 [95% CI: 2.34, 4.76] points greater rating of perceived exertion. The contrast between the low BFR and high BFR conditions was 2.55 [95% CI: 1.34, 3.76] greater for the high BFR condition. Rating of perceived exertion results are seen in figure ([Figure 1](#fig-warmup) (B)).

## 2.2 Effects of Warm-up on Performance Outcomes

|  |
| --- |
| Figure 2: Individual participant and measurement level data (thin lines) with model predicted values and 95% confidence intervals (thick lines and bands OR points and error bars). Panel (A) shows the results for sit and reach, panel (B) shows the results for countermovement jump, panel (C) shows the results for sprint time, and panel (D) shows the results for isometric mid thigh pull. |

### 2.2.1 Sit and Reach

Sit and reach increased from pre- to post-warm-up in the control condition (slope = 3.02 [95% CI: 2.05, 3.99] cm), low BFR condition (slope = 4.1 [95% CI: 2.85, 5.35] cm) and the high BFR condition (slope = 3.72 [95% CI: 2.4, 5.03] cm). However, there was no clear differences between conditions post-warm-up ([Table 3](#tbl-sitreachcontr) shows the between condition contrasts at both timepoints). Sit and reach results are seen in figure ([Figure 2](#fig-perform) (A)).

Table 3: Between condition contrasts at each timepoint for sit and reach.

| Condition 1 | Condition 2 | Contrast | Lower 95\% CI | Upper 95\% CI |
| --- | --- | --- | --- | --- |
| **Pre-warm-up** | | | | |
| Low BFR | High BFR | 0.13 | -2.44 | 2.71 |
| Control | High BFR | -0.28 | -2.31 | 1.75 |
| Control | Low BFR | -0.42 | -2.48 | 1.65 |
| **Post-warm-up** | | | | |
| Low BFR | High BFR | 0.52 | -1.49 | 2.52 |
| Control | High BFR | -0.98 | -2.62 | 0.65 |
| Control | Low BFR | -1.50 | -3.10 | 0.10 |
| Note: |  |  |  |  |
| CI = confidence interval; BFR = blood flow restriction |  |  |  |  |

### 2.2.2 Countermovement Jump

Countermovement jump performance under the control condition was 30.54 [95% CI: 26.94, 34.15] points, under the low BFR condition it was 29.14 [95% CI: 25.67, 32.62] points, and under the high BFR condition it was 27.99 [95% CI: 24.5, 31.49] points. Compared with the control condition the low BFR condition resulted in a -1.4 [95% CI: -3.8, 1] cm lower countermovement jump height, and the high BFR condition resulted in a -2.55 [95% CI: -4.67, -0.43] cm lower countermovement jump height. The contrast between the low BFR and high BFR conditions was -1.15 [95% CI: -3.64, 1.34] greater for the high BFR condition. Countermovement jump results are seen in figure ([Figure 2](#fig-perform) (B)).

### 2.2.3 Sprints

The slope for distance in the sprints was essentially the same for all conditions suggesting no impact upon acceleration over 10 to 20 to 30 meters (0.14 [95% CI: 0.13, 0.14] seconds per meter). Differences between condition at the three distances were also minimal ([Table 4](#tbl-sprintcontr) shows the between condition contrasts at each distance) There was essentially no clear effect of either condition compared to the control condition for sprint time, nor any interaction with sprint distance. Sprint time results are seen in figure ([Figure 2](#fig-perform) (C)).

Table 4: Between condition contrasts over distance for sprint time.

| Condition 1 | Condition 2 | Contrast | Lower 95\% CI | Upper 95\% CI |
| --- | --- | --- | --- | --- |
| **10 meters** | | | | |
| Low BFR | High BFR | 0.01 | -0.06 | 0.07 |
| Control | High BFR | -0.01 | -0.08 | 0.05 |
| Control | Low BFR | -0.02 | -0.07 | 0.03 |
| **20 meters** | | | | |
| Low BFR | High BFR | 0.02 | -0.04 | 0.08 |
| Control | High BFR | -0.02 | -0.09 | 0.04 |
| Control | Low BFR | -0.04 | -0.09 | 0.00 |
| **30 meters** | | | | |
| Low BFR | High BFR | 0.03 | -0.03 | 0.10 |
| Control | High BFR | -0.03 | -0.10 | 0.03 |
| Control | Low BFR | -0.07 | -0.11 | -0.02 |
| Note: |  |  |  |  |
| CI = confidence interval; BFR = blood flow restriction |  |  |  |  |

### 2.2.4 Isometric Mid Thigh Pull

Isometric mid thigh pull performance under the control condition was 2269.8 [95% CI: 1966.2, 2573.4] N, under the low BFR condition it was 2272.97 [95% CI: 1949.46, 2596.47] N, and under the high BFR condition it was 2258.12 [95% CI: 1945.5, 2570.73] N. There were neglible differences between conditions. Compared with the control condition the low BFR condition resulted in a 3.17 [95% CI: -112.19, 118.52] N greater isometric mid thigh pull, and the high BFR condition resulted in a -11.68 [95% CI: -94.55, 71.18] N lower isometric mid thigh pull. The contrast between the low BFR and high BFR conditions was -14.85 [95% CI: -125.07, 95.37] greater for the high BFR condition. Isometric mid thigh pull results are seen in figure ([Figure 2](#fig-perform) (D)).

# 3. References

Amrhein, V., Greenland, S., & McShane, B. (2019). Scientists rise up against statistical significance. *Nature*, *567*(7748), 305–307. <https://doi.org/10.1038/d41586-019-00857-9>

Amrhein, V., Trafimow, D., & Greenland, S. (2019). Inferential Statistics as Descriptive Statistics: There Is No Replication Crisis if We Don’t Expect Replication. *The American Statistician*, *73*(sup1), 262–270. <https://doi.org/10.1080/00031305.2018.1543137>

Bates, D., Maechler, M., Bolker [aut, B., cre, Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., & simulate.formula), P. N. K. (shared. copyright on. (2023). *Lme4: Linear Mixed-Effects Models using ’Eigen’ and S4*.

Cumming, G. (2014). The New Statistics: Why and How. *Psychological Science*, *25*(1), 7–29. <https://doi.org/10.1177/0956797613504966>

Lüdecke, D., Aust, F., Crawley, S., Ben-Shachar, M. S., & Anderson, S. C. (2024). *Ggeffects: Create Tidy Data Frames of Marginal Effects for ’ggplot’ from Model Outputs*.

Lüdecke, D., Makowski (@Dom\_Makowski), D., Ben-Shachar (@mattansb), M. S., Patil (@patilindrajeets), I., Waggoner, P., Wiernik (@bmwiernik), B. M., Thériault (@rempsyc), R., Arel-Bundock, V., Jullum, M., gjo11, & Bacher, E. (2024). *Performance: Assessment of Regression Models Performance*.

McShane, B. B., Gal, D., Gelman, A., Robert, C., & Tackett, J. L. (2019). Abandon Statistical Significance. *The American Statistician*, *73*(sup1), 235–245. <https://doi.org/10.1080/00031305.2018.1527253>

Pedersen, T. L. (2022). *Patchwork: The Composer of Plots*.

Wickham, H., Chang, W., Henry, L., Pedersen, T. L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D., & RStudio. (2022). *Ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics*.