WHOOP

THE ADVANTAGE OF CONTINUOUS PHYSIOLOGICAL MONITORING

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Introduction

The WHOOP monitoring platform continuously measures physiological strain and the body's response to that strain to provide personalized training recommendations based on an individual's response to various loads. The ability to action continuous data by applying it to dynamic training recommendations is a unique feature of the WHOOP system, and is primarily made possible by the proprietary "Day Strain" algorithm. Day Strain is a measure of user-normalized total cardiovascular load that jointly accounts for both obvious (example: from workouts) and non-obvious (example: from emotional stressors and activities of daily life) inputs. Day Strain therefore allows WHOOP to quantify the effects of down time, something not possible in cases of fitness tracking wearables designed to be removed after exercise.

The first section of this report provides a detailed explanation of the WHOOP Day Strain feature. The remainder of the report then demonstrates the significance of non-workout strain both by illustrating the magnitude of the cardiovascular load accrued outside the workout and by demonstrating the practical significance of this additional information by analysis of the predictive power of Day Strain as compared to the predictive power of workout Strain alone for key recovery metrics such as next-day resting heart rate and heart rate variability.

What is Day Strain?

The WHOOP system quantifies cardiovascular stress using the proprietary Strain metric. When calculating Strain, WHOOP individualizes cardiovascular exertion by processing heart rate data based on a user's learned resting heart rate and max heart rate; more time spent in the higher end of an individual's heart rate range will yield a higher Strain. Strain maps cardiovascular load taken on during a time period to a continuous value between 0 and 21. The Strain measure is also monotonically increasing, meaning it can only be increased throughout a given time period.

WHOOP breaks down its analysis of Strain into "Day Strain," calculated from bedtime to bedtime, and "Workout Strain," calculated during a user-defined time range. Workout Strains are included in the appropriate Day Strain, such that the Day Strain of a day which includes a workout will always be greater than or equal to the Workout Strain from the contained workout.

Strain Outside Workouts

One of the fundamental ideas of the WHOOP system is the notion that even when not officially "working out", the body may still be accumulating non-negligible Strain. To demonstrate this, data from 127 WHOOP users between November 1st, 2016 and January 10th, 2017 were ana-

lyzed. These users were highly compliant and recorded data for at least 40 full days. In total, there were 5,772 days of data, with at least one reported workout on 2,884 of them.
The distribution in **Figure 1** illustrates the contribution of "non-workout" Strain to Day Strain for the 2,884 days with reported workouts. Table 1 indicates the mean, median, and standard deviation of the distribution.

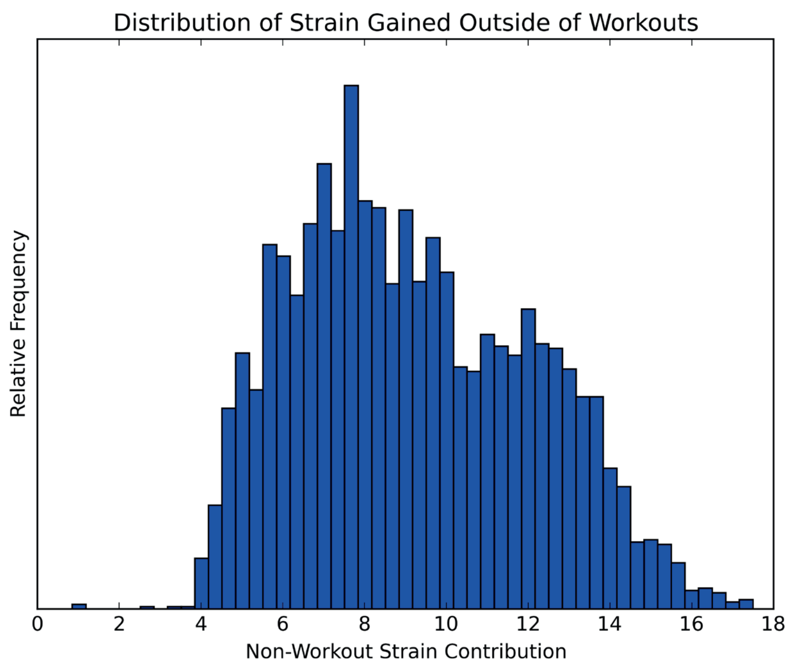

Figure 1, The distribution of non-workout Strain contributions for the 2,884 days with reported workouts between 11.1.2016 and 12.10.2017.

	Non-Workout Strain Contribution
Mean	9.3
Median	8.9
Standard Deviation	2.9

Table 1, The distribution of non-workout Strain contributions between 11.1.2016 and 12.10.2017.

Even though users may not perceive the rest of the day as significant, these results provide evidence that the body accrues meaningful Strain during the down times. For context, the average cycling workout from 30 to 60 minutes earns a 9.2 Strain, and the average weight-lifting workout from 30 to 60 minutes records a 6.7 Strain on the WHOOP system. In other words, the body still takes on non-negligible strain when performing everyday activities.

Since the Strain during the down times is spread over the course of many hours, one might hypothesize that this hidden physical activity, while present, is not practically significant (i.e. is not a determinant of one's physiological status the next day). The following sections demonstrate how not considering this extra Strain provides a very different picture of sleep quality and next-day Recovery.

Day Strain and Sleep Performance

WHOOP uses their proprietary Sleep Need metric to evaluate how much sleep a user needs to recover each night; this dynamic and personalized calculation is based on a learned physiological baseline, naps during the day, sleep debt accumulated over past nights, and Strain over the course of the day. WHOOP then calculates their proprietary Sleep Performance metric by dividing total sleep duration by Sleep Need, mapping the night's sleep to an integer between 0 and 100. Since Day Strain over the course of the day provides a more complete understanding of the body's physiological workload than just Workout Strain from the day, it is intuitive to think that it provides a more complete picture of Sleep Need. If only Workout Strain was used to calculate Sleep Need, a user would be reported as needing less sleep that night, and therefore a higher Sleep Performance upon waking the next morning. With a better understanding of Sleep Need from Day Strain, a more appropriate Sleep Performance can be calculated.

To demonstrate this, Sleep Need for the 2,884 sleeps analyzed in **Figure 1** was calculated using both Day Strain and "Total Workout Strain" from the day; Total Workout Strain was calculated by processing the heart rates from all reported workouts during each day into a single Strain value. If a user did not report working out, the day's Total Workout Strain was reported as 0. The next morning's Sleep Performance was then derived using both calculations of Sleep Need. Sleep Performance calculated using Day Strain was subtracted from Sleep Performance calculated using Total Workout Strain, and the distribution of these differences were illustrated in **Figure 2**.

We note that Sleep Performance was 100% for each instance where changing from Total Workout Strain to Day Strain had no effect on Sleep Performance, as these users slept considerably more than their Sleep Need on these nights.

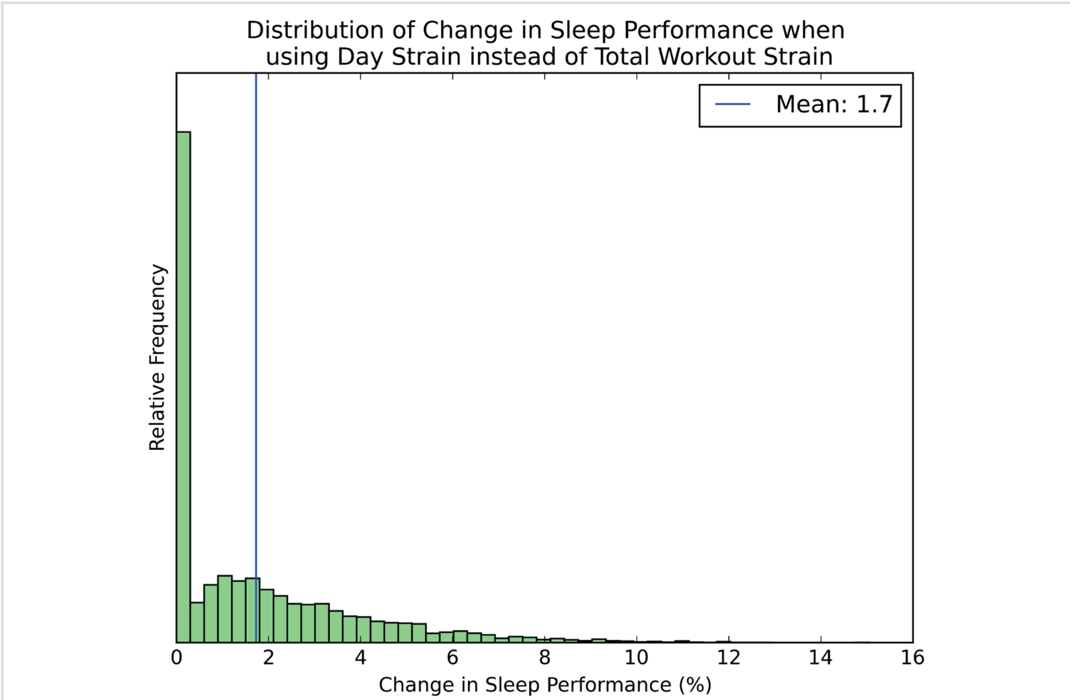

Figure 2, The distribution of change in Sleep Performance (%). The values above were determined by first calculating Sleep Performance based on the previous day's Total Workout Strain, and then subtracting the calculated Sleep Performance based on the previous day's Day Strain.

It is evident from **Figure 2** that Sleep Performance can be affected when considering entire Day Strain over just Total Workout Strain, as Day Strain incorporates a more complete picture of Strain accumulated over the entire day. For context, the average Sleep Need for these 2,884 sleeps was 8.7 hours and the average sleep duration was 7.7 hours, leading to an average Sleep Performance of 88.5%. With an average change in Sleep Performance of 1.7%, using Total Workout Strain instead of Day Strain leads to an expected Sleep Performance of 90.2%. This means that a user's average Sleep Need would be reported as 8.5 hours instead of 8.7 hours, corresponding to an expected difference in reported Sleep Need of 12 minutes.

The following section discusses how this incremental change in Sleep Performance from the additional information in Day Strain leads to better predictive power on next-day recovery metrics.

Day Strain as a Better Predictor of Recovery

Alongside Strain and Sleep Performance, the third essential component of the WHOOP system is the proprietary Recovery algorithm, which is used to provide nuanced and physiologically-relevant training recommendations. Heart rate variability (HRV), resting heart rate (RHR), and Sleep Performance are all inputs into the Recovery algorithm; it has been demonstrated that all three play very important roles in determining how physiologically ready one is to reap the benefits of training on a given day.[1]

The relationships between Total Workout Strain and next-day Recovery, HRV (measured by the root mean square of successive differences, or RMSSD), and RHR (measured in beats per minute) for the 2,884 days with at least one reported workout ("workout days") were analyzed in **Tables 2 and 3**. This was done by taking the upper 25% and lower 25% of Total Workout Strains from the "workout days" and seeing if days with very high Total Workout Strain tend to result in significantly different Recovery, HRV, and RHR the next morning than days with very low Total Workout Strain. Then, the relationships between Day Strain and next-day Recovery, HRV, and RHR for the 2,838 days without reported workouts ("non-workout days") were analyzed in **Tables 4 and 5**. This was done by taking the upper 25% and lower 25% of Day Strains from these "non-workout days" and seeing if days with very high Day Strain result in significantly different Recovery, HRV and RHR the next morning than days with very low Day Strain. T-Tests were used to determine whether there were statistically significant differences in both HRV and RHR between very low Strain days and very high Strain days. Because the distribution of Recovery was non-Gaussian, the Mann-Whitney U-Test was instead used to determine whether there was a statistically significant difference in Recovery between very low Strain days and very high Strain days.

Note that HRV and RHR were both normalized into z-scores over the previous week for each user. In other words, each day's HRV and RHR were transformed into how many standard deviations it lies from the previous week's average, and can therefore be loosely interpreted as whether the current HRV and RHR values were increasing or decreasing.

	High-Total Workout Strain Mean	Low-Total Workout Strain Mean	High-Total Workout Strain Median	Low-Total Workout Strain Median	P-Value
Next Day Recovery	59.4	60.2	60.0	62.0	p = 0.22

Table 2, Summary statistics and Mann-Whitney U-Test results for next-day Recovery for the lower and upper 25% of reported Total Workout Strain days. The Mann-Whitney U-Test was used because the distribution of Recovery was non-Gaussian.

[1] Allen et al., 2016

	High-Total Workout Strain Mean	Low-Total Workout Strain Mean	P-Value
Next-Day HRV (Z-Scores)	-0.04	0.00002	p = 0.55
Next-Day RHR (Z-Scores)	0.22	-0.04	p < 0.001

Table 3, Summary statistics and T-Test results for next-day HRV and RHR for the lower and upper 25% of reported Total Workout Strain days. Both variables were normalized into z-scores because each user has his own individual range of HRV and RHR levels.

	High-Day Strain Mean	Low-Day Strain Mean	High-Day Strain Median	Low-Day Strain Median	P-Value
Next Day Recovery	60.2	65.1	61.0	68.0	p < 0.001

Table 4, Summary statistics and Mann-Whitney U-Test results for next-day Recovery for the lower and upper 25% of Day Strain days. The Mann-Whitney U-Test was used because the distribution of Recovery was non-Gaussian.

	High-Day Strain Mean	Low-Day Strain Mean	P-Value
Next-Day HRV (Z-Scores)	-0.03	0.17	p = 0.003
Next-Day RHR (Z-Scores)	0.14	-0.26	p < 0.001

Table 5, Summary statistics and T-Test results for next-day HRV and RHR for the lower and upper 25% of Day Strain days. Both variables were normalized into z-scores because each user has his own individual range of HRV and RHR levels.

Together, **Tables 2-5** indicate that days with very high Day Strain lead to significantly lower next-day Recovery and HRV compared to days with very low Day Strain, while next-day Recovery and HRV do not differ significantly after days with very high and very low Total Workout Strain. While RHR is significantly higher after both very high Total Workout Strain and Day Strain days compared to after very low Total Workout Strain and Day Strain days, the gap between average RHR after very high Day Strain days and average RHR after very low Day Strain days is greater than the gap between average RHR after very high Total Workout Strain days and average RHR after very low Total Workout Strain days (0.4 vs. 0.26 standard deviations). This suggests that while both are predictive, Day Strain is still slightly better at predicting next-day RHR than Total Workout Strain.

Implications

This report illustrates how Day Strain provides more value than just Workout Strain when evaluating cardiovascular strain, as it leverages the strain taken on during periods beyond working out to provide a more complete assessment of how much sleep one needs to be properly recovered. It then reveals how Day Strain has a stronger relationship with next-day Recovery than Workout Strain.

The analysis demonstrates the benefit of the WHOOP system's continuous wear. When optimizing training and recovery, the evaluation of how much sleep one needs to recover properly is incomplete without being able to quantify how much strain the body takes on over the course of the entire day. In other words, Day Strain on the WHOOP system provides a complete picture of cardiovascular exertion by intelligently using data that non-continuous products do not provide.

References

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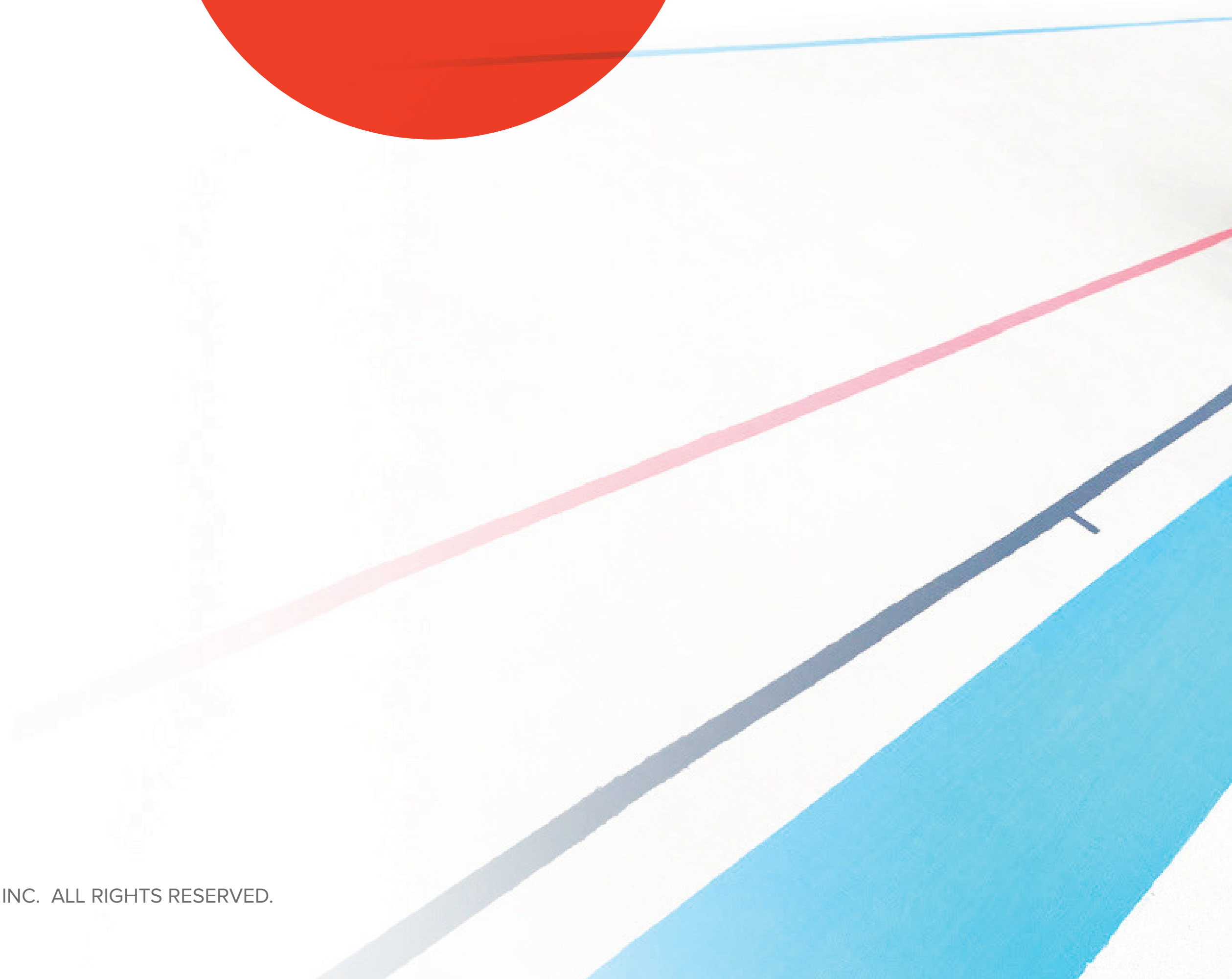

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