IEE 572 Design and Analysis of Engineering Experiments

Term Project Report

The Treadmill Experiment: Identifying Optimal Factor Levels for Achieving Target Heart Rate

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Recognition of and statement of problem

For cardiovascular health or general weight loss goals, the treadmill is likely the number one go-to gym equipment for most people. With all fitness goals, exercises should be tailored to achieve the desired results. The treadmill provides settings that you can adjust depending on your needs. For cardiovascular workouts and our experiment, an objective measurement that is easy to obtain is the person's achieved heart rate. According to the U.S. Department of Health and Human Services, a healthy adult should be partaking in a minimum of 75 minutes of vigorous exercise per week. Our objective is to determine the combination of factors that achieves 70%-80% of one's max heart rate over a span of 10 minutes for better and more dedicated use of one's time in the gym.

Choice of factors, levels and ranges

From our own personal experiences, we have listed below several factors which we believe contributes to a person's achieved heart rate and would like to investigate these factors in our experiment.

1. Treadmill Speed

When on a treadmill, the user has control over the pace at which the run is being performed. Because we are concerned with the practical application, we will be focused on moderate intensity levels. The two levels that we will be studying are:

   a. 3.5 MPH
   b. 5.0 MPH

2. Incline or Gradient

The Percent Grade is another treadmill feature that is typically utilized to vary the intensity of a run. The levels that we will utilize are as follows:

   a. 2% Incline
   b. 4% Incline

3. Exercise Attire

Some people like to increase the effectiveness of their workout through increasing perspiration levels. We want to know if increased body temperature contributes to increased heart rates, thus the following levels will be examined:

   a. Wearing a Jacket or Sweater
   b. Not wearing a Jacket or Sweater

4. Time of Day

When performing treadmill exercises, the time of day when these are performed is a factor that is often overlooked; we suspect that heart rate does vary depending on the time of day. We will be studying the following levels:

   a. Morning
   b. Evening

Factors		Levels	
		Low (-1)	High (+1)
X1	Speed (mph)	3.5	5
X2	Inclination (%)	2	4
X3	Clothing	Shirt & Shorts	Sweater & Sweatpants
X4	Time of Day	AM / Before work/class	PM / After work/class

Constant Factors:

1. Ambient Temperature

The ambient temperature may influence the body temperature; however, all experiments will be performed in a commercial gym that maintains the room temperature through air conditioning. The room temperature will be maintained at around 20 C.

2. Dietary Supplements

Some dietary supplements, such as caffeine, may alter the heart rate. For the sake of the experiment, there will be no additional dietary supplements that will be used.

Selection of the response variable

Different types of workouts require the heart rate of a person to be in a specific target zone. After initially increasing, a person's heart rate tends to stabilize and remains constant, given that no other factors change. We will be determining the optimal combination of factor levels that will yield the targeted heart rate. Heart rate zones are identified as percent ranges of a recommended maximum heart rate based on one's age. To improve aerobic fitness, moderate exercise, in the range of 70-80% of a person's maximum heart rate (MHR), is recommended. Our selected response variable will therefore be the percent of maximum heart rate achieved during each run. MHR will be approximated using the following formula:

$$MHR \approx 207 - (0.7 \times Age)$$

Response Measurement

The response will be measured using a wrist-mounted heart rate monitor such as a Fitbit shown below. The device will be used to continuously monitor the heart rate throughout the span of 10 minutes and averaged. The average heart rate through the 10 minute period, will then be calculated as a percent of the individual's MHR. The data gathered will be used to determine which combination of factors can keep one in the aerobic training zone (70%-80% MHR) for the longest duration of time.

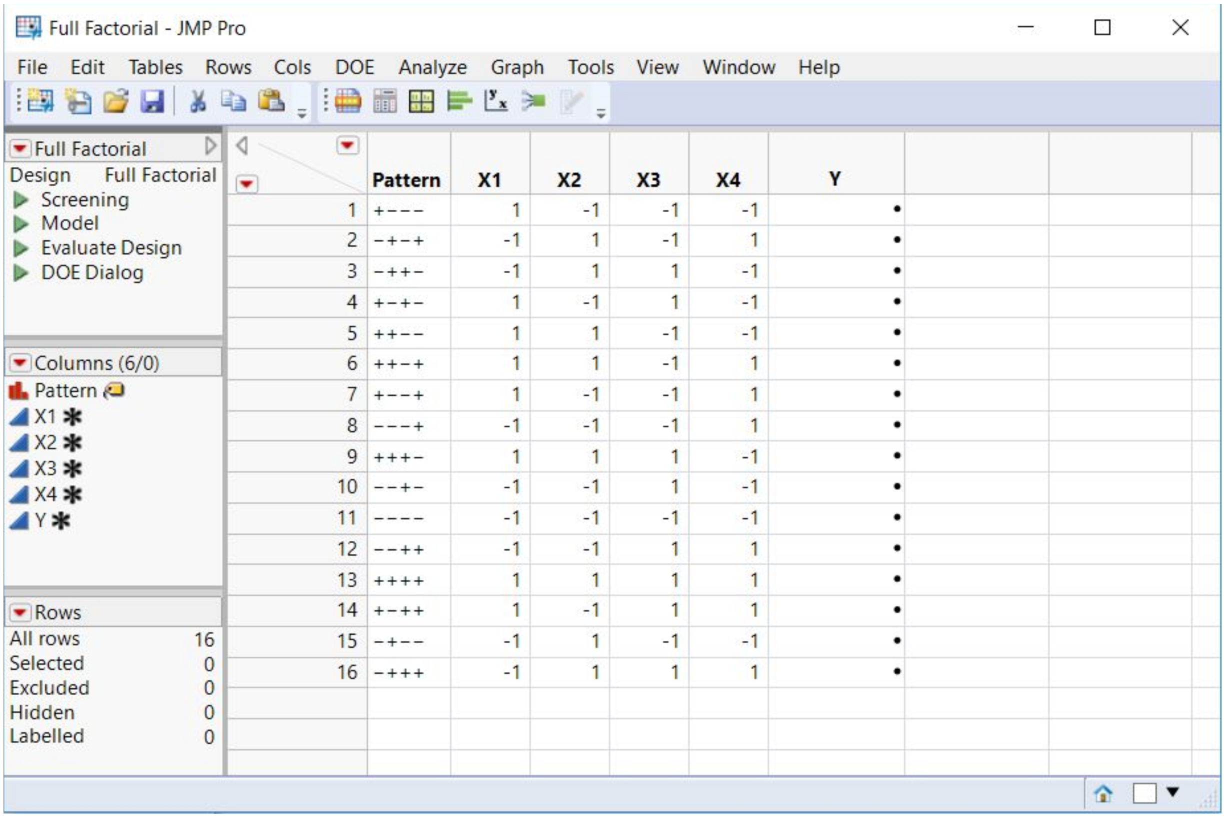
Fitbit Charge 3

Design of the Experiment

For this experiment 16 runs are required. One restriction we have set is to limit runs to one run per session to prevent the effects of factors such as fatigue, dehydration, or 'warming-up' from previous runs affecting any subsequent runs.

Runs are to be performed on weekdays, where an individual's schedule is routine. For our experiment, the individual performing the experiment works a standard 8 hour work day Monday through Friday. By performing all runs during the weekdays, the times of the runs will be collected at nearly the same time, and factors such as stress levels from a standard work day will be similar for all AM runs and all PM runs.

We used JMP to create a randomized run order design matrix. We used Screening function to generate the design matrix table. The table is generated using the full factorial design with 16 number of runs. This will enable us to completely analyze all the factor interactions.Our experiment will be run based on the following table.



	Pattern	X1	X2	X3	X4	Y
1	+−−−	1	-1	-1	-1	•
2	−+−+	-1	1	-1	1	•
3	−++−	-1	1	1	-1	•
4	+−+−	1	-1	1	-1	•
5	++−−	1	1	-1	-1	•
6	++−+	1	1	-1	1	•
7	+−−+	1	-1	-1	1	•
8	−−−+	-1	-1	-1	1	•
9	+++−	1	1	1	-1	•
10	−−+−	-1	-1	1	-1	•
11	−−−−	-1	-1	-1	-1	•
12	−−++	-1	-1	1	1	•
13	++++	1	1	1	1	•
14	+−++	1	-1	1	1	•
15	−+−−	-1	1	-1	-1	•
16	−+++	-1	1	1	1	•

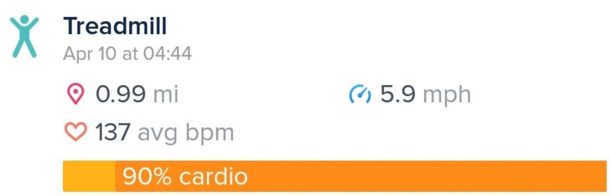
JMP generated randomized run order design matrix

Performing the Experiment

All 16 experiment runs were performed on one of five of the same model treadmill at the same gym, shown below. Prior to each run the experimenter spent approximately 5 minutes for static stretching which also provided some time for his heart rate to settle. The factor 'Time of Day' prescribed whether the run was performed in the morning prior to work or after the work day approximately 10-12 hours later. Work out attire was worn as prescribed by the randomized run order.

Before beginning the run, the prescribed speed and incline was selected on the treadmill and allowed to make all adjustments. Once the treadmill has reached the selected speed and incline, the 'Exercise' setting was selected on the experimenter's wrist-mounted fitness tracker, a Fitbit Charge 3, to allow for higher frequency of heart rate data collection, and the experimenter began his run. The duration of the run and heart rate data collection was 10 minutes and no adjustments to treadmill settings or clothing were made. After the completion of 10 minutes the 'Exercise' was stopped on the Fitbit to complete data collection and summarize the workout results, to include the Average Heart Rate used as our response variable for the experiment run. The completed design matrix table is shown below.

Treadmill settings screen (4% Incline and 5MPH shown)



Sample exercise result (standard order run 6 shown). Note that the average mph displayed is based on default stride length when using a treadmill where GPS-based pace cannot be used. Actual speed/pace was established by treadmill settings.

Run Number	Randomized Run Order	Factor				Label	Average Heart Rate (BPM)
		X1: Speed	X2: Inclination	X3: Clothing	X4: Time of Day		
1	11	-	-	-	-	(1)	96
2	1	+	-	-	-	a	134
3	15	-	+	-	-	b	108
4	5	+	+	-	-	ab	146
5	10	-	-	+	-	c	94
6	4	+	-	+	-	ac	137
7	3	-	+	+	-	bc	109
8	9	+	+	+	-	abc	155
9	8	-	-	-	+	d	94
10	7	+	-	-	+	ad	138
11	2	-	+	-	+	bd	108
12	6	+	+	-	+	abd	151
13	12	-	-	+	+	cd	107
14	14	+	-	+	+	acd	135
15	16	-	+	+	+	bcd	104
16	13	+	+	+	+	abcd	155

Completed Design Matrix Table

Statistical Analysis

After conducting the experiment, the observations were loaded in JMP. We used JMP to create the design matrix. The design matrix and the response data obtained from a single replicate are shown in ***Table 1***. The 16 runs were made in random order and later arranged in the standard design matrix.

	Pattern	Speed	Inclination	Clothing	Time of day	Average Heart Rate
1	−−−−	-1	-1	-1	-1	96
2	+−−−	1	-1	-1	-1	134
3	−+−−	-1	1	-1	-1	108
4	++−−	1	1	-1	-1	146
5	−−+−	-1	-1	1	-1	94
6	+−+−	1	-1	1	-1	137
7	−++−	-1	1	1	-1	109
8	+++−	1	1	1	-1	155
9	−−−+	-1	-1	-1	1	94
10	+−−+	1	-1	-1	1	138
11	−+−+	-1	1	-1	1	108
12	++−+	1	1	-1	1	151
13	−−++	-1	-1	1	1	107
14	+−++	1	-1	1	1	135
15	−+++	-1	1	1	1	104
16	++++	1	1	1	1	155

Table 1 - JMP Standard Order Design Matrix Table

The following procedure for conducting the full factorial and its statistical analysis was used:

1. Estimate factor effects and Form initial model
2. Perform statistical Testing
3. Refine Model
4. Analyze Residuals
5. Interpret Results

A full factorial experiment was conducted using all 4 factors and yielded the following results:

1. <u>Summary of fit and Analysis of Variance:</u>

The value of RSquare is 1. This is due to the 16 observations. The model has 15 degrees of freedom, leaving 0 degrees of freedom for error. The sum of squares for the model (7220.4375) is equal to the total sum of square of all effects and their interactions. ***Table 2*** and ***Table 3*** show the summary of fit and analysis of variance output from JMP.

Summary of Fit	
RSquare	1
RSquare Adj	.
Root Mean Square Error	.
Mean of Response	123.1875
Observations (or Sum Wgts)	16

Table 2 - Summary of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	15	7720.4375	514.696	.
Error	0	0.0000	.	Prob > F
C. Total	15	7720.4375		.

Table 3 - ANOVA Output

2. Effect Tests:

Table 4 displays the Effect tests output from JMP shows the degree of freedom for each main effect and their interactions and their sum of squares.

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Speed	1	1	6847.5625	.	.
Inclination	1	1	637.5625	.	.
Clothing	1	1	27.5625	.	.
Time of day	1	1	10.5625	.	.
Speed*Inclination	1	1	39.0625	.	.
Speed*Clothing	1	1	1.5625	.	.
Inclination*Clothing	1	1	0.0625	.	.
Speed*Time of day	1	1	0.0625	.	.
Inclination*Time of day	1	1	10.5625	.	.
Clothing*Time of day	1	1	0.0625	.	.
Speed*Inclination*Clothing	1	1	45.5625	.	.
Speed*Inclination*Time of day	1	1	22.5625	.	.
Speed*Clothing*Time of day	1	1	27.5625	.	.
Inclination*Clothing*Time of day	1	1	22.5625	.	.
Speed*Inclination*Clothing*Time of day	1	1	27.5625	.	.

Table 4 - Effect Tests

3. Sorted Parameter Estimates:

The sorted parameter estimates obtained from show the estimates of each parameter with pseudo t ratio and pseudo p values. From ***Table 5***, the pseudo p values for the factors Speed and Inclination can be observed to be less than 0.05, hinting that these are the only significant effects.

Sorted Parameter Estimates

Term	Estimate	Relative Std Error	Pseudo t-Ratio	Pseudo p-Value
Speed	20.6875	0.25	11.61	<.0001*
Inclination	6.3125	0.25	3.54	0.0165*
Speed*Inclination*Clothing	1.6875	0.25	0.95	0.3870
Speed*Inclination	1.5625	0.25	0.88	0.4205
Clothing	1.3125	0.25	0.74	0.4943
Speed*Clothing*Time of day	-1.3125	0.25	-0.74	0.4943
Speed*Inclination*Clothing*Time of day	1.3125	0.25	0.74	0.4943
Speed*Inclination*Time of day	1.1875	0.25	0.67	0.5345
Inclination*Clothing*Time of day	-1.1875	0.25	-0.67	0.5345
Time of day	0.8125	0.25	0.46	0.6674
Inclination*Time of day	-0.8125	0.25	-0.46	0.6674
Speed*Clothing	0.3125	0.25	0.18	0.8676
Inclination*Clothing	-0.0625	0.25	-0.04	0.9734
Speed*Time of day	0.0625	0.25	0.04	0.9734
Clothing*Time of day	-0.0625	0.25	-0.04	0.9734

No error degrees of freedom, so ordinary tests uncomputable.
Relative Std Error corresponds to residual standard error of 1.
Pseudo t-Ratio and p-Value calculated using Lenth PSE = 1.78125
and DFE=5

Table 5 - Sorted Parameter Estimates

4. <u>Effect Screening</u>:

The effect screening for the experiments shows that the parameter estimates have equal variances and are not correlated. This supports the basis of normality of the experiment. JMP uses Lenth's method to do effect screening of the experiment. The results are shown in ***Figure 1*** below.

Effect Screening

The parameter estimates have equal variances.
The parameter estimates are not correlated.

Lenth PSE

1.78125

Figure 1 - Lenth PSE

5. Normal Plots:

Normal and half normal plots help in visually identifying the significant effects. ***Figure 2*** and ***Figure 3*** were generated to depict the effects estimate. The Speed and Inclination effects are noted outliers, as they are distinctly out of the rest of the effects' path. It can be concluded that Speed and Inclination are the only significant effects.

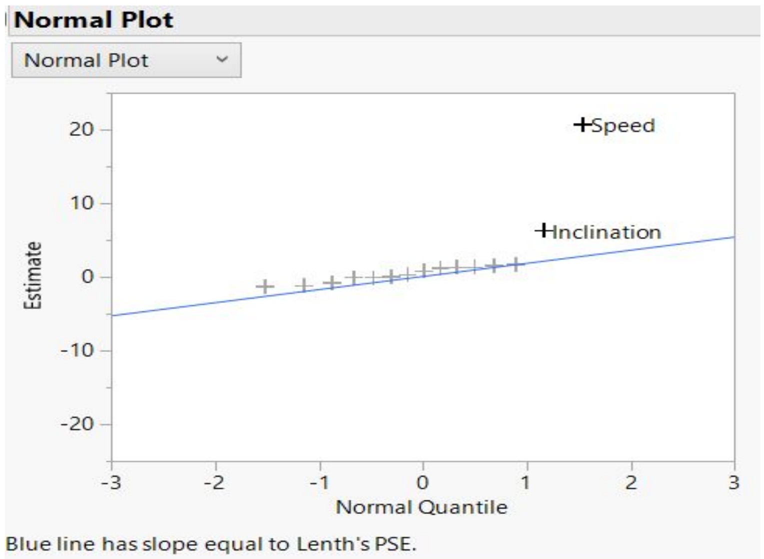


Figure 2 - Normal Plot

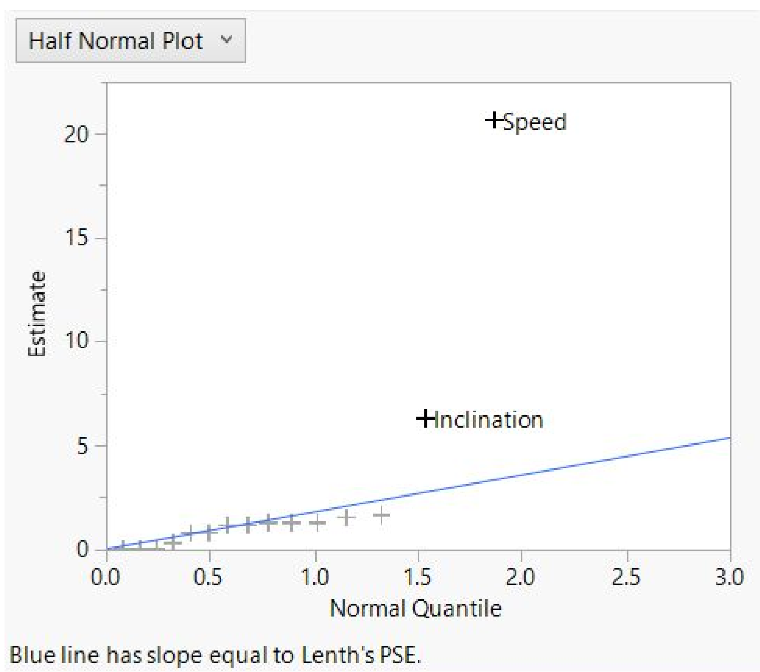


Figure 3 - Half Normal Plot

Fitted Model

As this is a single replicated factorial experiment with 4 factors, it cannot be said that there is no error present, as per the initial ANOVA output. As such, only factor effects that are significant will be used for an additional ANOVA analysis. All other less significant factors and their higher order interactions are assumed to have negligible effects.

For our experiment, the significant factors are deemed to be Speed and Inclination. The new experimental setup will be a full factorial experiment with 2 factors and 8 replicates.

JMP output for the fitted model:

1. Actual by predicted plot:

This plot shows that almost all observed average heart rate lies in the region predicted by the JMP after fitting the model. The RSq and PValue as observed from the plot in ***Figure 4*** are favorable.

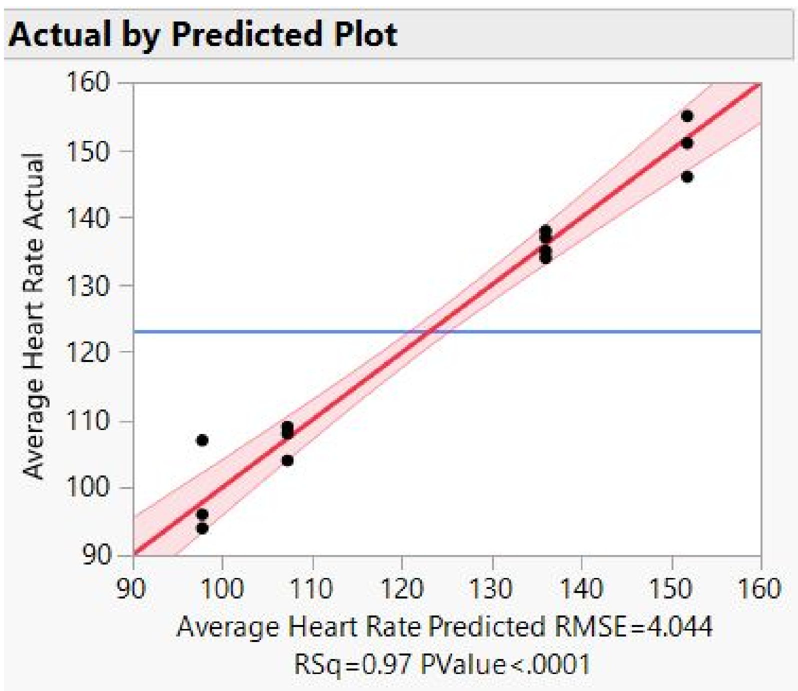


Figure 4 - Actual by Predicted Plot

2. Residual by Predicted Plot:

Almost all residuals lie close to the predicted line. The spread of the residual points can be used to say that the parameter estimates have equal variances. The residual by predicted plot is shown in ***Figure 5.***

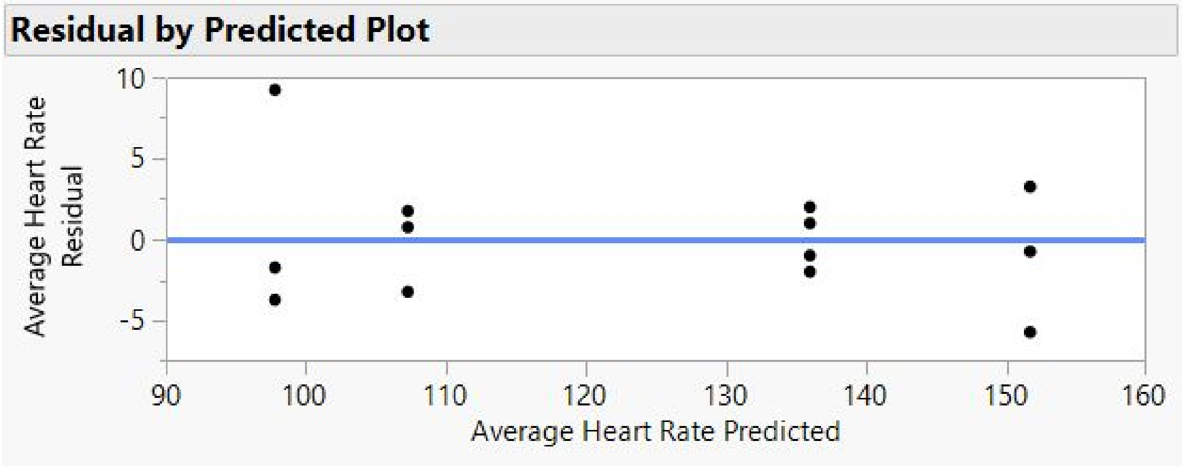


Figure 5 - Residual by Predicted Plot

3. <u>Summary of fit and analysis of variance</u>:

The value of RSquare in the new fitted model is 0.968226, making this a more adequate model for our design when compared to the original. The F value for model from ANOVA is 153.3592, further supporting the model's significance and adequacy.

Summary of Fit	
RSquare	0.97458
RSquare Adj	0.968226
Root Mean Square Error	4.044029
Mean of Response	123.1875
Observations (or Sum Wgts)	16

Table 6 - Fitted Model Summary of Fit

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	7524.1875	2508.06	153.3592
Error	12	196.2500	16.35	Prob > F
C. Total	15	7720.4375		<.0001*

Table 7 - Fitted Model ANOVA Output

4. <u>Parameter Estimated and sorted estimates</u>:

The Estimates for the parameters are shown in ***Figure 6***. The intercept, speed and inclination have large effect estimates. From the diagrams it can be concluded that the Speed and Inclination have significant effects whereas the interaction effect can be concluded to be insignificant.

Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	123.1875	1.011007	121.85	<.0001*
Speed	20.6875	1.011007	20.46	<.0001*
Inclination	6.3125	1.011007	6.24	<.0001*
Speed*Inclination	1.5625	1.011007	1.55	0.1482

Figure 6 - Parameter Estimates

Sorted Parameter Estimates				
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Speed	20.6875	1.011007	20.46	<.0001*
Inclination	6.3125	1.011007	6.24	<.0001*
Speed*Inclination	1.5625	1.011007	1.55	0.1482

Figure 7 - Main Effects Parameter Estimates

5. Effect Screening:

JMP uses Lenth's method to do effect screening. It can be verified and concluded that the parameter estimates have equal variances.

Effect Screening

The parameter estimates have equal variances.

The parameter estimates are not correlated.

Lenth PSE
9.46875

Figure 8 - Fitted Model Effect Screening

6. Normal Plots:

Normal and half normal plots are plotted to support the claim for the significant factors. As can be seen from half normal plot, the Speed and Inclination are significant effects whereas their interaction (Speed*Inclination) is not.

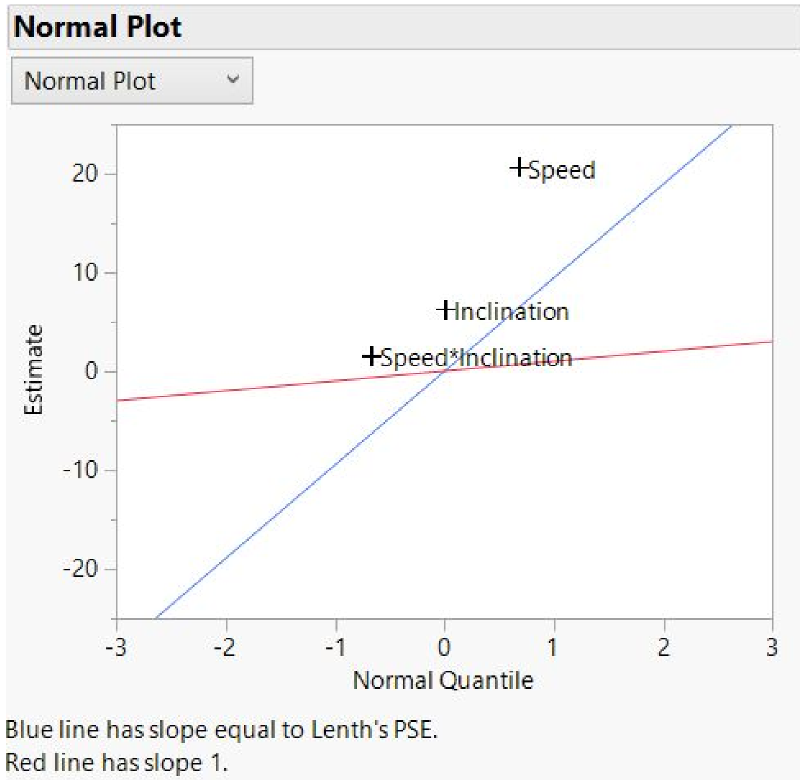


Figure 9 - Fitted Model Normal Plot

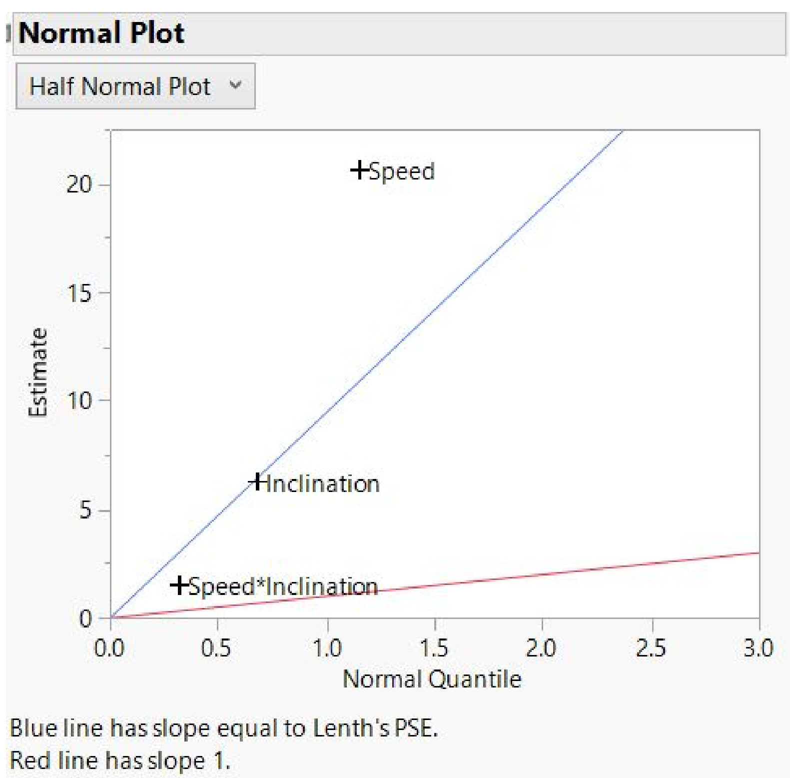


Figure 10 - Fitted Model Half Normal Plot

7. Prediction profiler:

It shows how the average heart range will change as the value of speed and inclination are changed. The +1 and -1 are the coded values for speed = 3.5mph and 5mph, respectively. Similarly for inclination 2% and 4% , the coded values are -1 and +1, respectively. The speed and inclination are considered as continuous variables. The average heart rate is affected aggressively by change in speed as compared to change in inclination.

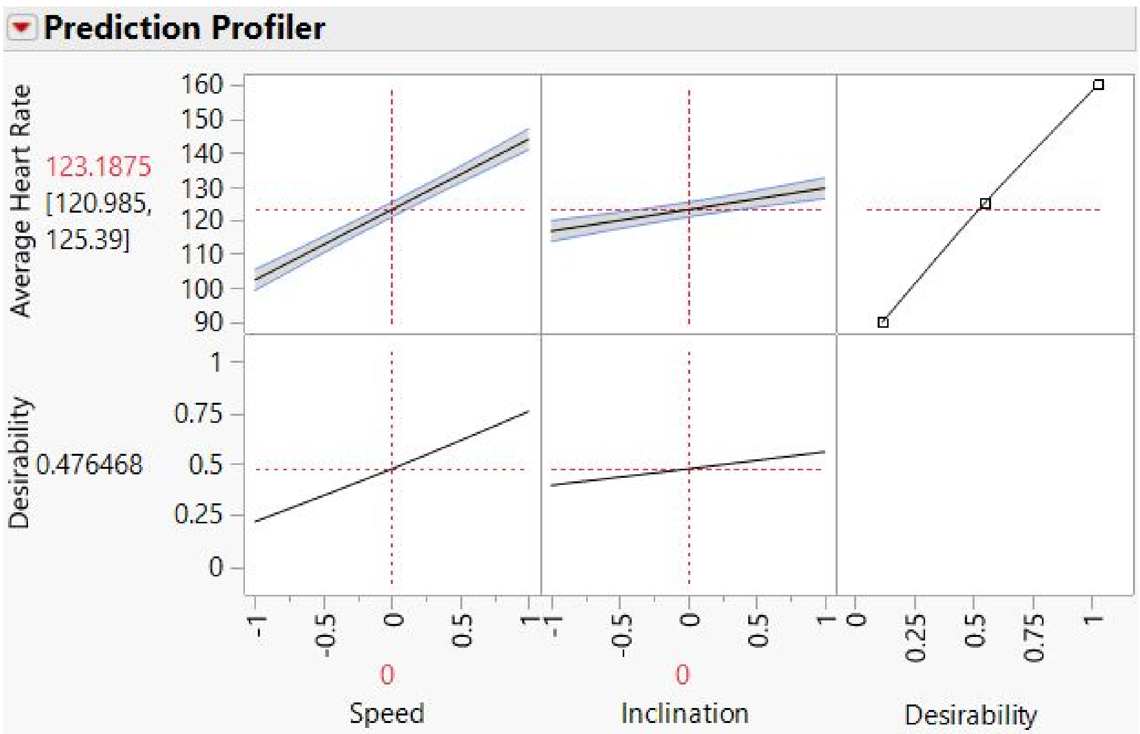


Figure 11 - Prediction Profiles

8. Interaction Profiles:

The interaction profiles help us to understand the effect of interaction between factors. As the lines plotted in the profiles are almost parallel, we can say that the interaction of speed and inclination has no significant effect. The change in speed or inclination has similar effects on average heart rate.

Figure 12 - Interaction Profiles

9. <u>Prediction Expression</u>:

As the fitted model is significant, the following regression expression can be used to predict the average heart rate. The values of speed and inclination are coded i.e between -1 and +1. (where Speed: -1 = 3.5 mph, +1 = 5 mph, and Inclination: -1 = 2%, +1 = 4%)

Prediction Expression

$$123.1875 + 20.6875 \bullet \text{Speed} + 6.3125 \bullet \text{Inclination} + \text{Speed} \bullet \left(\text{Inclination} \bullet 1.5625 \right)$$

Figure 13 - Regression Model

Conclusions

To accurately provide a recommendation, we must first calculate the target heart rate zone for our test subject. Our subject is 29 years of age, therefore the target heart rate is as follows:

$$MHR \approx 207 - (0.7 \times Age)$$
$$70\%\ MHR \approx 0.7 \times (207 - (0.7 \times 29)) = 130.70\ bpm$$
$$80\%\ MHR \approx 0.8 \times (207 - (0.7 \times 29)) = 149.36\ bpm$$

Using only Speed and Inclination, the analysis suggests when speed is at +1 and incline is at -1, the most optimal results are achieved. Using the computed regression equation, this combination of factors will yield a heart rate between 70%-80% MHR, as shown below:

$$HR = 123.1975 + 20.5875(1) + 6.3125(-1) + 1.5625(1)(-1)$$
$$HR = 136\ bpm$$

All other combination of factors will yield a heart rate that falls outside the target zone. The data analysis suggests that our test subject should only vary speed and inclination when attempting to exercise within the 70%-80% MHR zone. That is, the decision of what to wear and when to exercise should be based on convenience and comfort as they have a negligible effect on the response variable. If a recommendation is to be suggested for consistently reaching the targeted heart rate zone, our subject should set the treadmill to a 5mph speed and 2% incline with no regard to the time of day or exercise attire.

Recommendations for Further Experiments

Although a working combination was found for maximizing the results given the factor levels, there is still opportunity for optimization. Using the recommended factor level combination yields a 72.8% MHR. Since speed was found to have a larger effect than incline, an additional experiment could be performed would be a single factor ANOVA on the incline settings. This is because it was found that exercising with speed at the high level will generally yield a HR within the 70%-80% range. The experiment would be such that the response variable, heart rate, would be measured with speed held constant at the high level (5 mph). Each replicate would then be performed at incline settings between 2% and 4% (i.e. 3 replicates at 2.5%, 3.0%, and 3.5% inclines).

The experiment would find which incline would best be suited to be used in conjunction with a speed of 5mph to achieve a 75% MHR. Achieving 75% MHR will ensure that the test subject will likely stay in the 70%-80%MHR as there is ample room for any possible HR variance that occurs due to other external factors.

References:

Montgomery, Douglas C. *Design and Analysis of Experiments*. 9th ed., John Wiley & Sons, Inc., 2017.

https://www.heart.org/en/healthy-living/fitness/fitness-basics/target-heart-rates?s=q%3Dheart%2520rate%2520zones%26sort%3Drelevancy

https://www.hhs.gov/fitness/be-active/physical-activity-guidelines-for-americans/index.html

https://www.ncbi.nlm.nih.gov/m/pubmed/17468581/