SUPPLEMENTARY MATERIALS – S1

ESTIMATION OF HOW DO AFFECT MORPHOLOGICAL FEATURES OF A CAVE WHEN TRAVELING INSIDE IT

An attempt was made to test how the morphologies of the cave passages affected in the transit using different types of movement (crawling, walking or climbing). A cave was selected for this (Laminak cave in Berriatua, Northern Spain) (Fig. 1). To perform the tests, the participants wore neoprene socks and carried an electric lamp that simulated the light of a torch. First, measurements were made in horizontal galleries, but of variable size, to test walking and crawling movements. Also, two vertical passages were added, to test climbing movements.

At these sites, mini-circuits were drawn, with different measurement points. The traveled distance and the employed time for it (to calculate the travel rate) and the increase of the heart rate from a calm state (heart rate growth) were calculated. In the first tests (in horizontal galleries) was observed that the increase in heart rate was not a good index to calculate the costs (while the travel rate was), in the following measurements (in vertical zones of climbs and progression "by traversing") only employed time and distance (the travel rate) were measured.

All circuits were surveyed with a DistoX2 device, in addition to a tablet with Android system with Bluetooth™, and with TopoDroid® app, to obtain precise topographic plans.

MATERIAL FOR MEASURING

The employed tools were the following:

- **The electric torch**:

The selected lamp was a “*Zamflare®’s flame atmosphere lamp U19*”. This lamp has 96 LEDs, each LED flashes warm yellow, like a flame. It has a weight of 1000 g, more or less, and the flame has the following features, similar to those estimation of the prehistoric torches used in caves (Medina-Alcaide 2020) (Table 1):

Medium E (lux)	19
Medium I (cd)	2.91
Medium Radius (m.)	3.19
Medium L (cd/m2)	2.96

Table 1: light features of the electric torch.

- **Neoprene socs**

The neoprene socks used were from the brand *"Tribord®"*, *"Surf Olaian 100 3 MM. With Sole"*. This accessory tries to imitate walking barefoot but used to traffic, or the use of soft footwear (Ledoux 2018).

- **Heart rate belt**

This *"Kalenji® Dual Ant +"* heart rate belt is used to display the heart rate on the Android tablet. The data per second were extracted using the *"HR Monitor®"* application. As we measured the moment when the participants passed through a certain measurement point of the circuit, we know to which areas the various increases in beats per second are due.

MEASUREMENTS ZONES IN THE EXPERIMENTAL CAVE

Two types of spaces were selected in the Laminak cave (Fig. 1), two circuits for walking and crawling movements, and two for climbing movements, with different characteristics of height and width of the galleries, and different slopes.

To carry it out, two superimposed horizontal floors were selected (to measure crawling and walking movements), interconnected by a 7-meter vertical chimney (where climbing and traversing movements were measured). To these was added a small semi-vertical section located between the entrance gallery of the cave and the selected sectors. All areas are located in zones of total darkness.

Fig. 1: Topographic plan of the Laminak cave (*Ades Espeleologia Elkartea*), showing the measurement areas.

MEASUREMENTS IN THE HORIZONTAL PASSAGES:

- **UPPER CAVE-LEVEL**

It is a relatively narrow gallery of between 40 and 50 meters of total development. The gallery contains a variable morphology (with ceilings and walls that descend in height and width), and a changing slope, but generally comfortable and that avoids the necessary use of the hands to climb or move "by traversing" (exerting force of opposition to advance where the narrowness of the wall allows to advance horizontally or descend vertically) (Fig. 2). This ends in a crawlway zone, with a minimum height of 0.24 meters (Fig. 3). This ends in a crawlway zone, with a minimum height of 0.24 meters. In this gallery, different measurement points were arranged (A, B, C, D, E and Crawlway). The precise topography carried out using TopoDroid® with DistoX2, and calculated in VisualTopo®, allowed us to know the traveled distance (necessary to calculate the travel rate), the average heights or widths maintained along that section, or the slope (Tables 2 and 3). (All measurements are taken in meters -for distance, width or the height of the passages- or degrees -for slopes-)

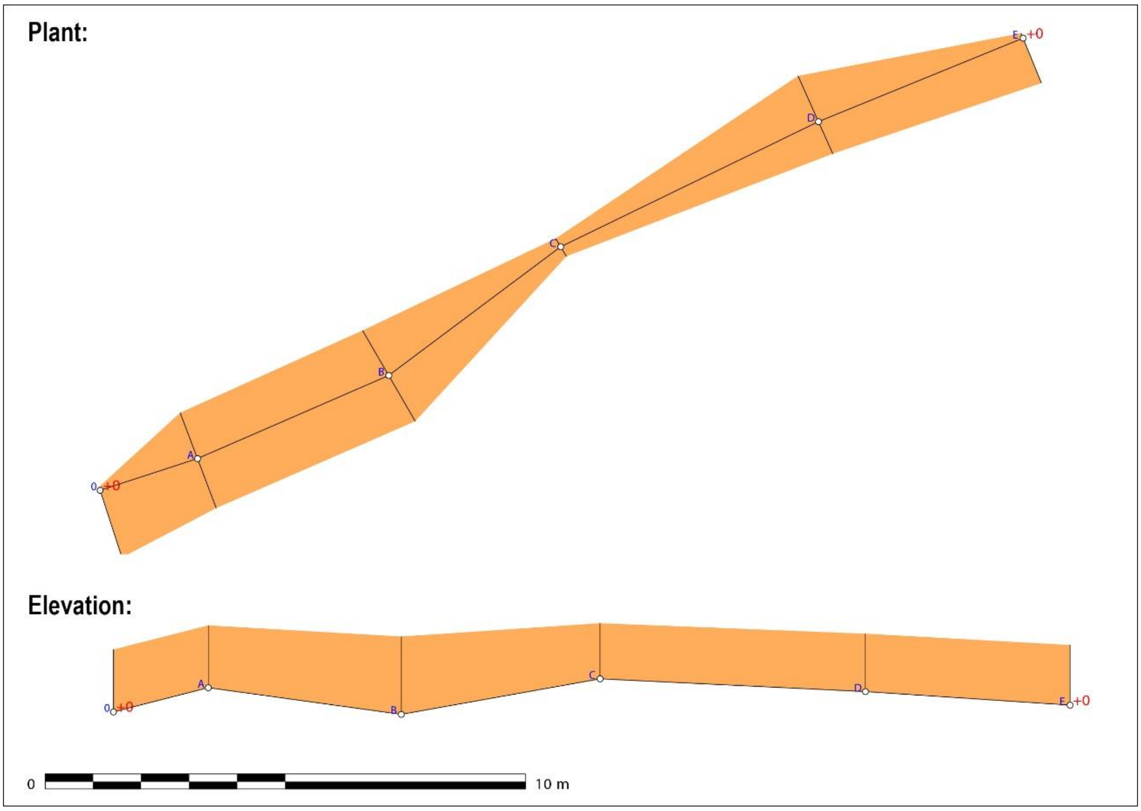


Fig. 2: Topographic plant and elevation of the measurement points (A, B, C, D and E).

From	To	Distance	Slope	Width(L)	Width(R)	Haut
0	A	2.20	14.30	1.02	1.10	1.40
A	B	4.38	-7.88	1.08	1.10	1.75
B	C	4.54	10.14	0.20	0.23	1.25
C	D	5.97	-2.74	1.04	0.73	1.30
D	E	4.61	-3.80	0.11	1.01	1.35

Table. 2: Topographic-survey data of the measurement points A, B, C, D and E.

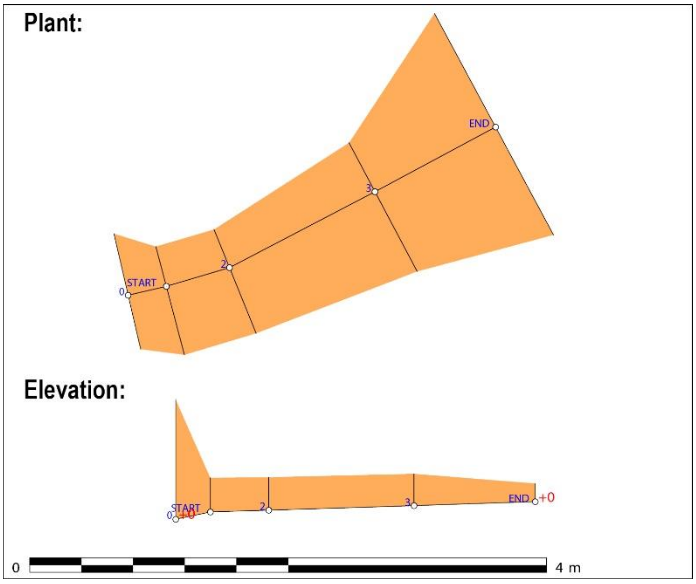


Fig. 3: Topographic plant and elevation of the measurement point Crawlway.

From	To	Distance	Slope	Width(L)	Width(R)	Haut
0	0	0.00	0.00	0.49	0.43	1.05
0	START	0.31	11.80	0.32	0.55	0.30
START	2	0.51	1.70	0.32	0.55	0.29
2	3	1.27	1.80	0.43	0.70	0.28
3	END	1.06	1.90	1.00	0.95	0.16

Table. 3: Topographic-survey data of the measurement point Crawlway.

- **LOWER CAVE-LEVEL**

Compared to the previous one, this gallery is large in size, which allows walking without worrying about narrowing the gallery due to the reduction of the ceiling height. However, there is a narrow point in its middle, which has led us to select the path from the end of the measured gallery to that narrow point (in the opposite direction to that of the gallery). We have signaled with START and END in the map the starting and the end points of this measurement point (Fig. 4) (Table 4).

Fig. 4: Topographic plant and elevation of the measurement point Lower Pass (from START to END points in the right part of the plan).

From	To	Distance	Slope	Width(L)	Width(R)	Haut
0	0	0.00	0.00	0.58	1.48	1.23
0	4	2.65	-13.90	0.39	0.43	2.18
4	3	8.04	-6.80	0.78	0.15	2.92
3	1	0.97	-2.20	0.75	0.49	2.03
1	2	12.79	-0.20	0.14	0.50	1.02
2	END	1.04	-1.40	0.91	0.56	3.21
END	a	12.39	0.00	1.52	0.96	1.7
START	a	20.13	1.10	1.20	0.73	1.45

Table. 4: Topographic-survey data of the measurement point Lower Pass (from START to END points in the last part of the surveyed passage.

MEASUREMENTS IN THE VERTICAL PASSAGES:

- **VERTICAL CHIMNEY BETWEEN BOTH HORIZONTAL CAVE LEVELS**

The chimney between both levels start with a first jump of 3 meters, but a 45º slope. We have taken this measure as a reference for the limit between climbing and walking or crawling movements (later confirmed by statistical regression). Subsequently, it descends 1.72 meters in an absolute verticality of 85.5º, to finish in a final ramp of 47º (Fig. 5). We have taken the measurement points in the first two sections, called V1 and V2 (Table 5).

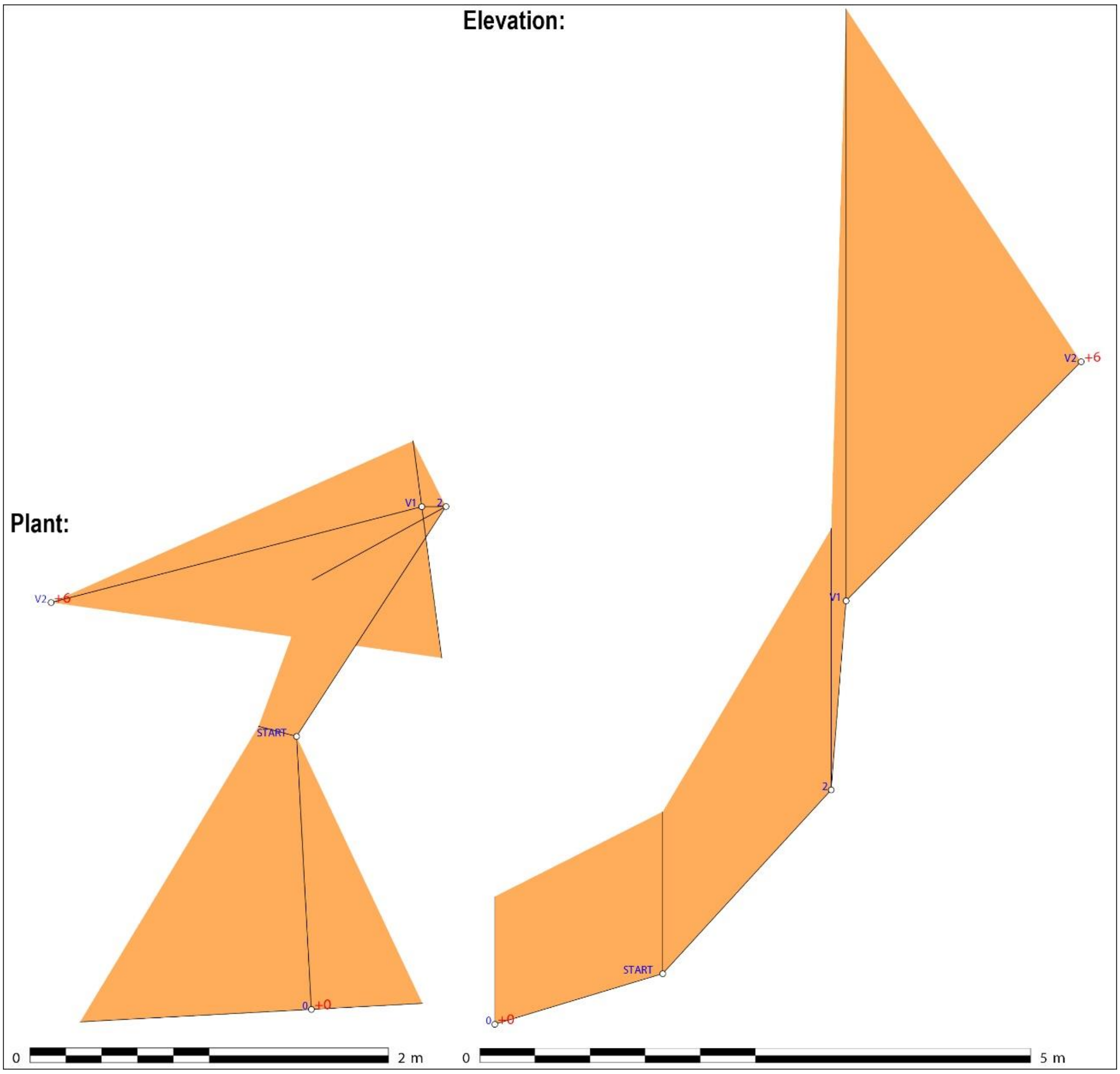


Fig. 5: Topographic plant and elevation of the measurement points V1 and V2.

From	To	Distance	Degd	Slope	Width(L)	Width(R)
0	0	0.00	0.00	0.00	1.29	0.62
0	START	1.59	356.90	16.80	0.22	0.00
START	2	2.26	33.00	47.50	0.85	0.00
2	V1	1.72	269.40	85.50	0.85	0.37
V2	V1	3.04	75.50	-45.01	0.44	0.00

Table. 5: Topographic-survey data of the measurement points V1 and V2.

- **SEMI-VERTICAL PASSAGE BETWEEN ENTRANCE GALLERY AND MEASUREMENT ZONES**

This semi-vertical hole starts with a very low-ceilinged tube-shaped passage. The verticality forces to exert pressure between walls to advance. This is where the only measurement point (V3) is located (Fig. 6) (Table 6).

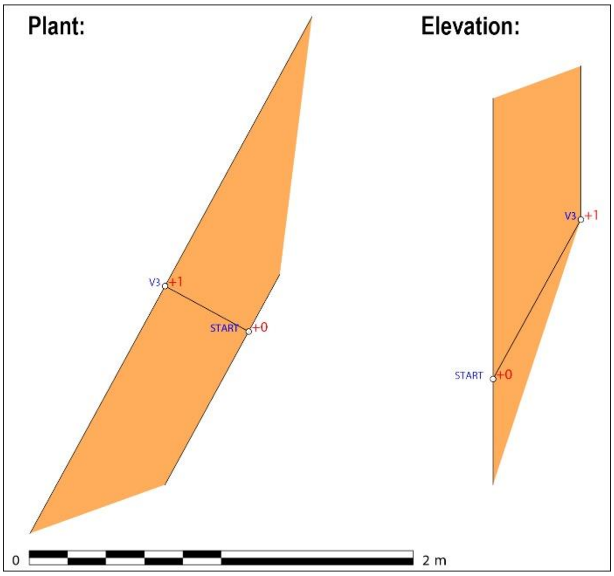


Fig. 6: Topographic plant and elevation of the measurement point V3.

From	To	Distance	Degd	Slope	Width(L)	Width(R)
START	START	0.00	0.00	0.00	0.91	0.34
START	V3	1.03	298.60	61.20	1.47	1.60

Table. 6: Topographic-survey data of the measurement point V3.

PHYSICAL PROBES

In these test circuits we placed volunteers with chronometers (we have used private mobile phones for it), in each measurement point, to know when the subject had passed. The studied subjects wear also a pectoral band with an incorporated pulsometer (a *Kalenji dual ANT*), measured with *Heart Rate Monitor* app in a tablet *Samsung Galaxy Tab A* de 8.0" with *Android 9* (only in the horizontal passages) (Table 7). With this, and the chronometers data, we know were tester has felt increases of heart pulses or decreases of traveling rates, and we have been able to compare these results with the curves of morphological features. The travelled distances in each measurement point (in meters), and the time needed by each volunteer to overcome each measurement area (in seconds) were taken into account to obtain the travel rate (in meters per second) (Tables 8, 9, 10 and 11). In all cases, an average value was taken to perform analysis.

The characteristics of the volunteers can be seen later, but they passed all the normality tests. Regarding the regression, it was observed that the variable "Heart.rate.growth" was not the most adequate to calculate the influence of the natural environment (the morphological characteristics of the cave) in the effort made to overcome them, so it was not taken into account when calculating movements by climbing.

On the other hand, the volunteers were given a maximum time of 5 minutes (300 seconds) to go through each obstacle. As some of the volunteers were not able to overcome the vertical obstacles, this maximum time (300 seconds) was used as a reference to estimate the average travel rate (in meters per second) and to perform the regressions (Table 11).

HEART RATE GROWTH

- **MEASUREMENT POINTS A, B, C, CRAWLWAY, D, E and LOWER PASSAGE**

Volunteer	A	B	C	Crawlway	D	E	Lower Pass
1	39	29	37	62	44	22	16
2	46	32	43	66	48	8	15
3	39	23	29	7	36	11	9
4	25	6	19	37	37	2	16
5	33	28	41	34	28	13	32
6	42	24	35	36	47	10	9
7	58	19	42	62	61	6	31
8	27	14	16	57	35	4	12
9	34	14	21	43	42	5	44
10	39	7	36	48	44	3	39
11	33	17	29	43	36	3	23
12	49	5	41	41	56	3	1
13	45	20	37	56	51	4	26
14	43	22	31	57	49	1	1
15	55	19	42	76	58	2	34
16	44	18	31	62	51	8	8
17	46	20	35	35	45	6	12
18	30	27	30	58	30	17	3
19	37	9	17	79	40	1	19
20	39	19	29	53	40	3	28
21	58	5	6	62	56	1	15
x̄	41	17.95	30.81	51.14	44.48	6.33	18.71

Table 7: Heart rate growth in each measurement point (only in passages by walking and crawling).

TRAVEL RATE

- **MEASUREMENT POINTS A and B**

Volunteer	Start time	Time (A)	Dist (A)	TR (A)	Time (B)	Time B-A	Dist (B)	TR (B)
1	15	3.9	2.22	0.57	9.09	5.19	4.38	0.84
2	15	5.06	2.22	0.44	14.94	9.88	4.38	0.44
3	20	4.52	2.22	0.49	12.03	7.51	4.38	0.58
4	110	5.11	2.22	0.43	15.1	9.99	4.38	0.44
5	35	4.3	2.22	0.52	11.94	7.64	4.38	0.57
6	40	9.71	2.22	0.23	21.09	11.38	4.38	0.38
7	20	4.85	2.22	0.46	7.82	2.97	4.38	1.47
8	20	4.74	2.22	0.47	8.82	4.08	4.38	1.07
9	20	4.64	2.22	0.48	10.54	5.9	4.38	0.74
10	10	5.33	2.22	0.42	11.75	6.42	4.38	0.68
11	10	4.73	2.22	0.47	9.1	4.37	4.38	1.00
12	30	5.58	2.22	0.40	13.31	7.73	4.38	0.57
13	20	5.33	2.22	0.42	15.21	9.88	4.38	0.44
14	48	3.01	2.22	0.74	12.9	9.89	4.38	0.44
15	29	5.49	2.22	0.40	14.01	8.52	4.38	0.51
16	130	3.47	2.22	0.64	11.89	8.42	4.38	0.52
17	104	6.25	2.22	0.36	14.29	8.04	4.38	0.54
18	40	6.15	2.22	0.36	12.87	6.72	4.38	0.65
19	30	2.59	2.22	0.86	6.81	4.22	4.38	1.04
20	30	6.19	2.22	0.36	17.25	11.06	4.38	0.40
21	50	2.82	2.22	0.79	8.69	5.87	4.38	0.75
x̄		4.94	2,22	0.49	12.35	7.41	4.38	0.67
Travel rate (1/ x̄)				2.04				1.49

Table 8: Travel rate in each measurement point (only in passages by walking and crawling).

- **MEASUREMENT POINTS C, D and E**

Vol.	Time (C)	Time C-B	Dist (C)	TR (C)	Time (D)	Time D-C	Dist (D)	TR (D)	Time (E)	Time E-D	Dist (E)	TR (E)
1	19.3	10.21	4.54	0.44	29.96	10.66	5.97	0.56	39.33	9.37	4.61	0.49
2	29.28	14.34	4.54	0.32	47.37	18.09	5.97	0.33	61.5	14.13	4.61	0.33
3	23.33	11.3	4.54	0.40	37.83	14.5	5.97	0.41	49	11.17	4.61	0.41
4	24.88	9.78	4.54	0.46	39.51	14.63	5.97	0.41	49.73	10.22	4.61	0.45
5	23.91	11.97	4.54	0.38	40.05	16.14	5.97	0.37	51.47	11.42	4.61	0.40
6	38.58	17.49	4.54	0.26	64	25.42	5.97	0.24	73	9	4.61	0.51

7	14.64	6.82	4.54	0.67	22.36	7.72	5.97	0.77	29.19	6.83	4.61	0.67
8	16.22	7.4	4.54	0.61	22.89	6.67	5.97	0.90	28.91	6.02	4.61	0.77
9	19.12	8.58	4.54	0.53	32.5	13.38	5.97	0.45	43.18	10.68	4.61	0.43
10	21.17	9.42	4.54	0.48	34.66	13.49	5.97	0.44	44.29	9.63	4.61	0.48
11	17.05	7.95	4.54	0.57	26.19	9.14	5.97	0.65	33.8	7.61	4.61	0.61
12	30.56	17.25	4.54	0.26	44.36	13.8	5.97	0.43	56.35	11.99	4.61	0.38
13	23.38	8.17	4.54	0.56	35.61	12.23	5.97	0.49	44.1	8.49	4.61	0.54
14	18.06	5.16	4.54	0.88	33.1	15.04	5.97	0.40	43.59	10.49	4.61	0.44
15	27.9	13.89	4.54	0.33	43.23	15.33	5.97	0.39	53.58	10.35	4.61	0.45
16	20.74	8.85	4.54	0.51	29.95	9.21	5.97	0.65	38.79	8.84	4.61	0.52
17	27.54	13.25	4.54	0.34	44.11	16.57	5.97	0.36	53.08	8.97	4.61	0.51
18	23.26	10.39	4.54	0.44	37.09	13.83	5.97	0.43	47.17	10.08	4.61	0.46
19	13.7	6.89	4.54	0.66	21.26	7.56	5.97	0.79	27.52	6.26	4.61	0.74
20	33.95	16.7	4.54	0.27	50.26	16.31	5.97	0.37	60	9.74	4.61	0.47
21	20.45	11.76	4.54	0.39	31.28	10.83	5.97	0.55	42.44	11.16	4.61	0.41
$\bar{x}$	23.19	10.84	4.54	0.47	36.55	13.36	5.97	0.49	46.19	9.64	4.61	0.50
Travel rate (1/ $\bar{x}$)				2.15				2.02				2.00

Table 9: Travel rate in each measurement point (only in passages by walking and crawling).

- **MEASUREMENT POINTS CRAWLAY and LOWER PASSAGE**

Volunteer	Time (Crawlway)	Dist (Crawlway)	TR (Crawlway)	Time (Lower Pass)	Dist (Lower Pass)	TR (Lower Pass)
1	37.3	3.15	0.08	25	36.56	1.46
2	53.54	3.15	0.06	29	36.56	1.26
3	39.65	3.15	0.08	32	36.56	1.14
4	39.3	3.15	0.08	33	36.56	1.11
5	40.04	3.15	0.08	23	36.56	1.59
6	39.4	3.15	0.08	38	36.56	0.96
7	39.53	3.15	0.08	23	36.56	1.59
8	34.45	3.15	0.09	30	36.56	1.22
9	29	3.15	0.11	31	36.56	1.18
10	31.04	3.15	0.10	31	36.56	1.18
11	30.08	3.15	0.10	29	36.56	1.26
12	53.54	3.15	0.06	33	36.56	1.11
13	42.73	3.15	0.07	33	36.56	1.11
14	57	3.15	0.06	28	36.56	1.31
15	44	3.15	0.07	29	36.56	1.26
16	31.37	3.15	0.10	31	36.56	1.18
17	38.63	3.15	0.08	32	36.56	1.14
18	32.47	3.15	0.10	33	36.56	1.11
19	38.34	3.15	0.08	30	36.56	1.22
20	55.04	3.15	0.06	26	36.56	1.41
21	34.04	3.15	0.09	35	36.56	1.05
$\bar{x}$	40.02	3.15	0.08	30.19	36.56	1.23
Travel rate (1/ $\bar{x}$)			12.28			0.81

Table 10: Travel rate in each measurement point (only in passages by walking and crawling).

- **MEASUREMENT POINTS IN V1, V2 and V3**

Volunteer	Time (V1)	Dist (V1)	TR (V1)	Time (V2)	Dist (V2)	TR (V2)	Time (V3)	Dist (V3)	TR (V3)
1	300	1.72	0.01	9.51	3.04	0.32	34.5	1.03	0.03
2	300	1.72	0.01	8	3.04	0.38	23.49	1.03	0.05
3	81	1.72	0.02	5	3.04	0.61	21.5	1.03	0.05
4	300	1.72	0.01	6.5	3.04	0.47	30.15	1.03	0.04
5	74	1.72	0.02	4	3.04	0.76	20.95	1.03	0.05
6	300	1.72	0.01	7.45	3.04	0.41	29.5	1.03	0.04
7	63	1.72	0.03	7	3.04	0.43	18.7	1.03	0.06
8	74	1.72	0.02	6.5	3.04	0.47	19.1	1.03	0.05
9	300	1.72	0.01	4.5	3.04	0.68	24.5	1.03	0.04
10	87	1.72	0.02	6.5	3.04	0.47	21.5	1.03	0.05
11	300	1.72	0.01	7.5	3.04	0.41	300	1.03	0.003
12	300	1.72	0.01	9.5	3.04	0.32	300	1.03	0.003
13	74	1.72	0.02	4.5	3.04	0.68	18	1.03	0.06
14	300	1.72	0.01	9.06	3.04	0.34	300	1.03	0.003
15	300	1.72	0.01	10	3.04	0.30	300	1.03	0.003
16	300	1.72	0.01	7.5	3.04	0.41	32.15	1.03	0.03
17	87	1.72	0.02	4	3.04	0.76	23.1	1.03	0.05

18	300	1.72	0.01	7.5	3.04	0.41	300	1.03	0.003
19	63	1.72	0.03	3.55	3.04	0.86	18.01	1.03	0.06
20	300	1.72	0.01	5	3.04	0.61	23.4	1.03	0.04
21	300	1.72	0.01	6.6	3.04	0.46	300	1.03	0.003
$\bar{x}$	214.43	1.72	0.01	6.65	3.04	0.50	102.79	1.03	0.03
Travel rate (1/ $\bar{x}$)			80.88			1.995			30.24

Table 11: Travel rate in each measurement point (only in passages by climbing).

STATYSTICAL ANALYSIS

We will proceed to analyse the data obtained from the experimentation. We have the features of the sample (ages, stature, weight), the values obtained in each observation point, and the average values obtained in each point. These data have been passed to a table (Table S1), and analysed in R statistical packet.

OPEN R, AND PREPARE PLUGINS

```
> library(openxlsx)
> library(nortest)
```

OPEN OUR MODEL

```
> sample<-read.xlsx("C:/Users/Table S1.xlsx",sheet=1)
> rownames<-sample[,1];sample[,1]<-NULL
> summary(sample)
```

Gender	Age	Stature	Weight
Length:21	Min. :23.00	Min. :1.55	Min. :45.00
Female: 11	1st Qu.:29.00	1st Qu.:1.63	1st Qu.:53.00
Male: 10	Median :34.00	Median :1.66	Median :60.00
	Mean :35.81	Mean :1.70	Mean :64.71
	3rd Qu.:41.00	3rd Qu.:1.81	3rd Qu.:75.00
	Max. :54.00	Max. :1.86	Max. :96.00

1)

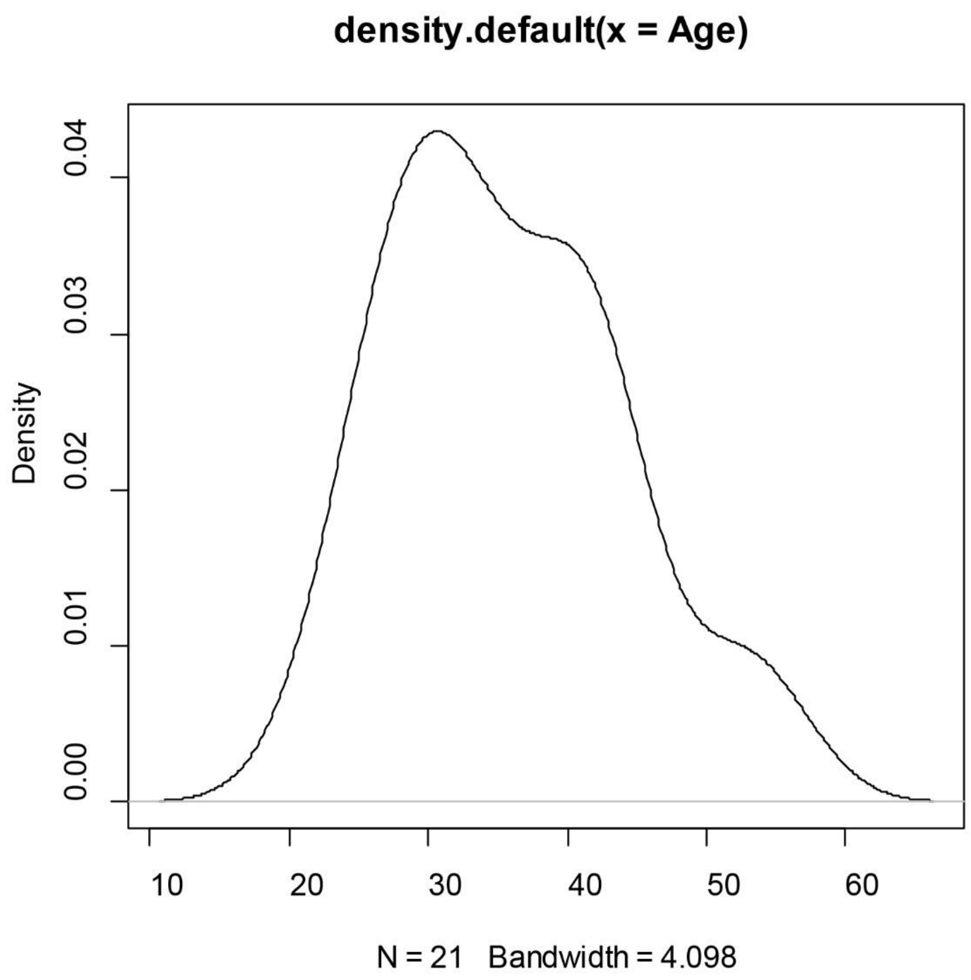
We are going to analyse the descriptive features of population, to test their normality.

NORMALITY TEST OF POPULATION'S DESCRIPTIVE FEATURES AND THE MEASUREMENTS

```
> Age<-sample[1:21,2]
> shapiro.test(Age)

        Shapiro-Wilk normality test

data:  Age
W = 0.94312, p-value = 0.2511
```

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The variable could become from a normally distributed population.

```
> plot(density(Age))
```



> Stature<-sample[1:21,3]

> shapiro.test(Stature)

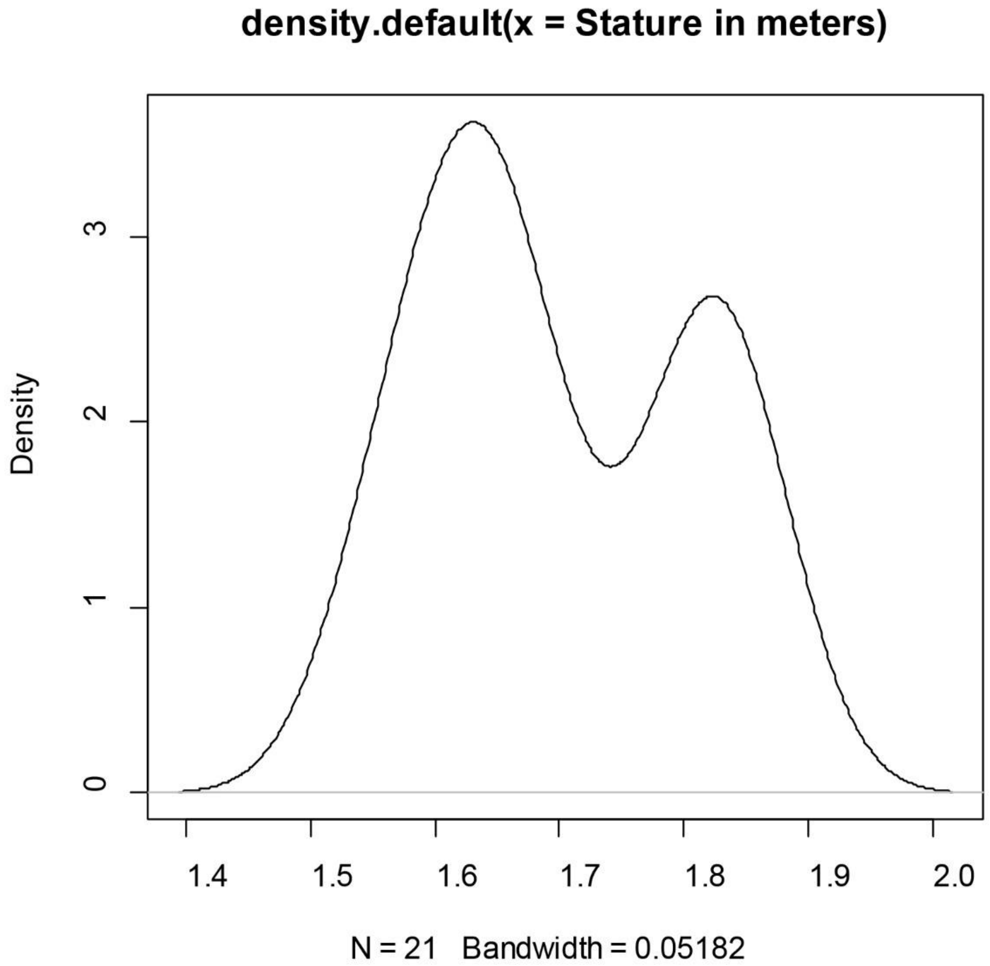
Shapiro-Wilk normality test

data: Stature

W = 0.88823, p-value = 0.02083

INTERPRETATION: with an alpha level of .05, the null hypothesis couldn't be accepted. The variable couldn't become from a normally distributed population. With an alpha level of .01, the null hypothesis could be accepted, so the variable could become from a normally distributed population. But in all case, the two peaks of the curve are formed by sexual dimorphism between males and females.

> plot(density(Stature))



> Weight<-sample[1:21,4]

> shapiro.test(Weight)

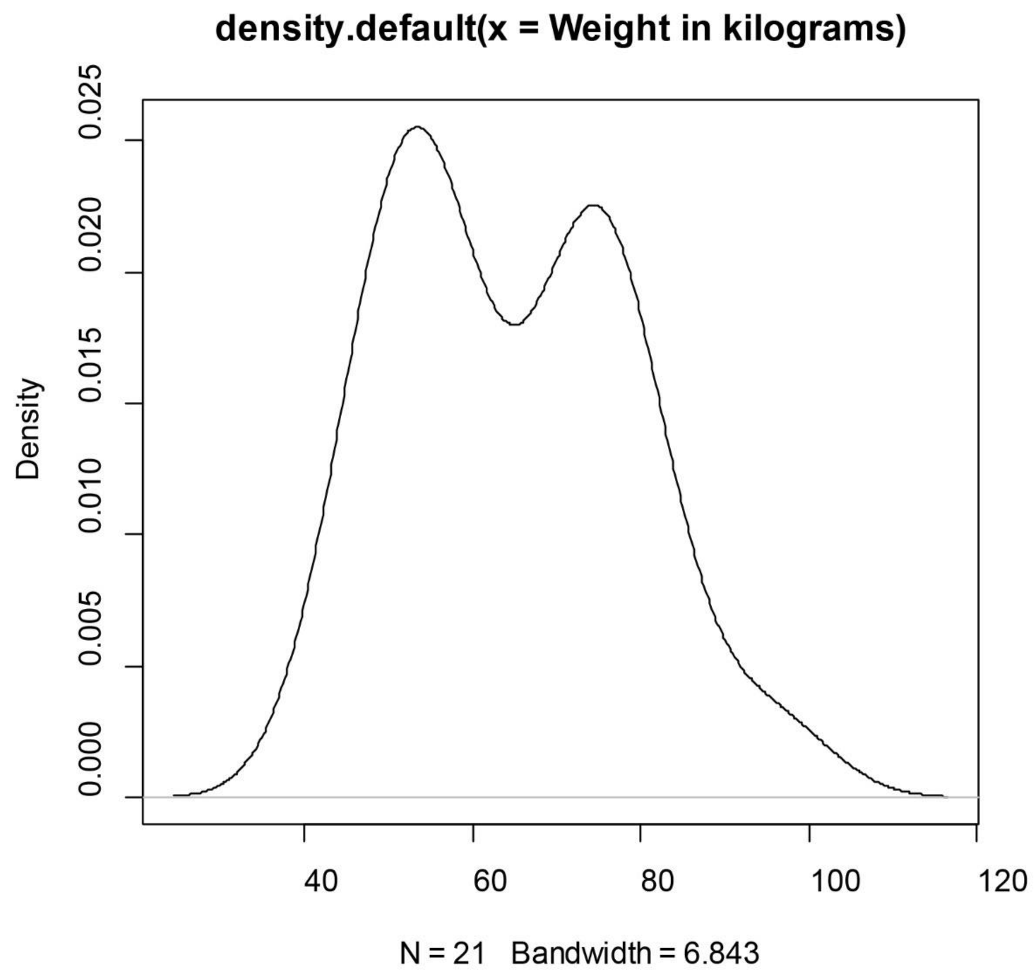
Shapiro-Wilk normality test

data: Weight

W = 0.92967, p-value = 0.1356

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The variable could become from a normally distributed population.

> plot(density(Weight))



TOTAL SAMPLE VARIABLES INTERPRETATION: the origin of all quantitative variables can be accepted as a normally distributed population, so selected data may be useful.

---

2)

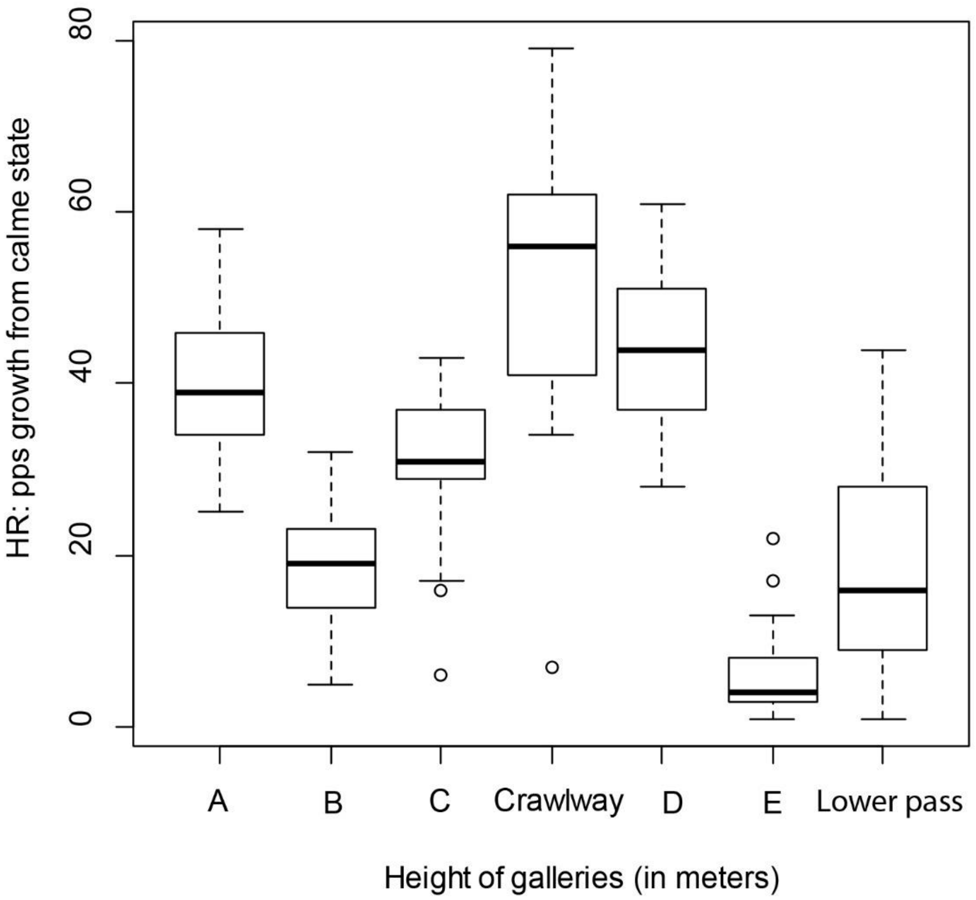
We are going to analyse measurements, to test their normality.

2.1)

Heart rate growth (we have measured the increase in pps from the calm state):

```
> HR<-read.xlsx("C:/Users/Table S1.xlsx",sheet=4)
> rownames<-HR[,1];HR[,1]<-NULL
> summary(HR)
      A            B               C               Crawlway          D
 Min.   :25    Min.   : 5.00   Min.   : 6.00   Min.   : 7.00   Min.   :28.00
 1st Qu.:34    1st Qu.:14.00   1st Qu.:29.00   1st Qu.:41.00   1st Qu.:37.00
 Median :39    Median :19.00   Median :31.00   Median :56.00   Median :44.00
```

```
 Mean   :41       Mean   :17.95   Mean   :30.81   Mean   :51.14   Mean   :44.48
 3rd Qu.:46       3rd Qu.:23.00   3rd Qu.:37.00   3rd Qu.:62.00   3rd Qu.:51.00
 Max.   :58       Max.   :32.00   Max.   :43.00   Max.   :79.00   Max.   :61.00
       E            Lower.Pass
 Min.   : 1.000   Min.   : 1.00
 1st Qu.: 3.000   1st Qu.: 9.00
 Median : 4.000   Median :16.00
 Mean   : 6.333   Mean   :18.71
 3rd Qu.: 8.000   3rd Qu.:28.00
 Max.   :22.000   Max.   :44.00
> boxplot(HR, ylab="HR: pps growth from calme state", xlab="Height of galleries")
```



NORMALITY TEST OF MEASUREMENTS in EACH measurement point

```
> A<-HR[1:21,1]
```

> shapiro.test(A)

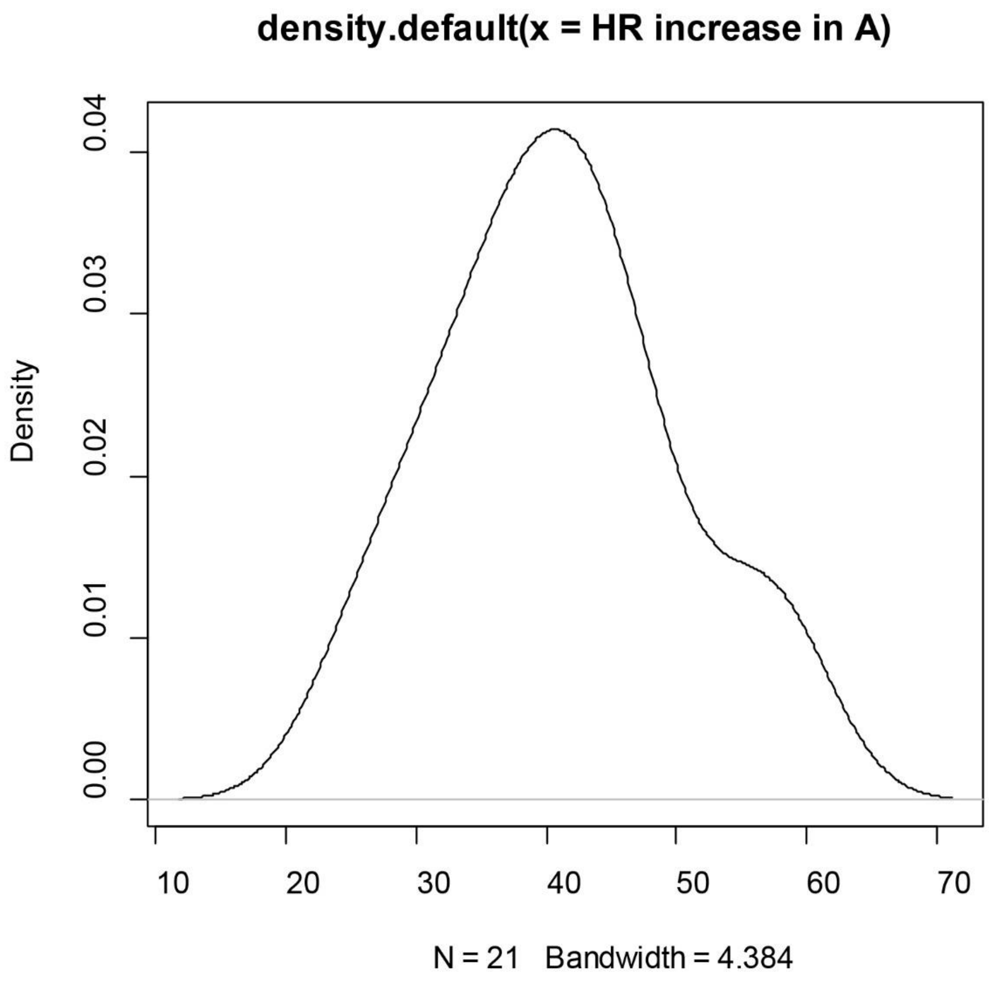
Shapiro-Wilk normality test

data: A

W = 0.96603, p-value = 0.6446

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(A))



> B<-HR[1:21,2]

> shapiro.test(B)

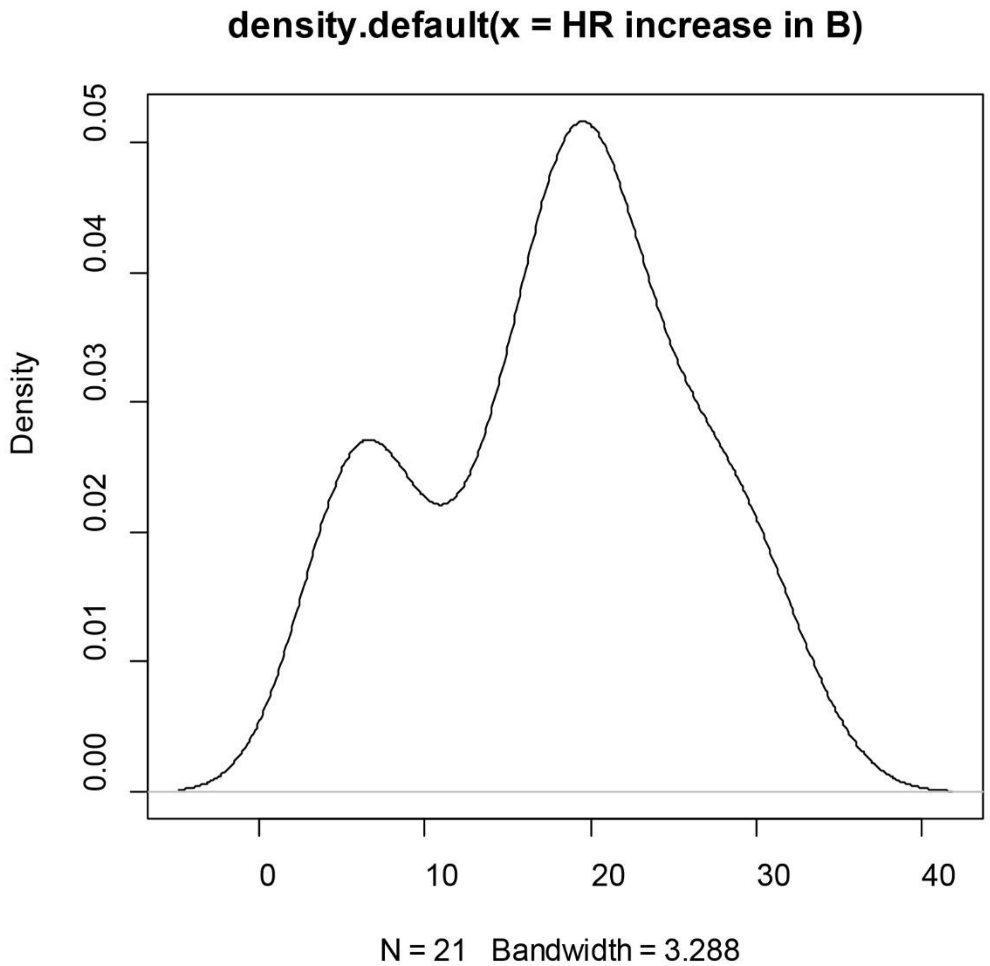
Shapiro-Wilk normality test

data: B

W = 0.94812, p-value = 0.3137

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(B))



> C<-HR[1:21,3]

> shapiro.test(C)

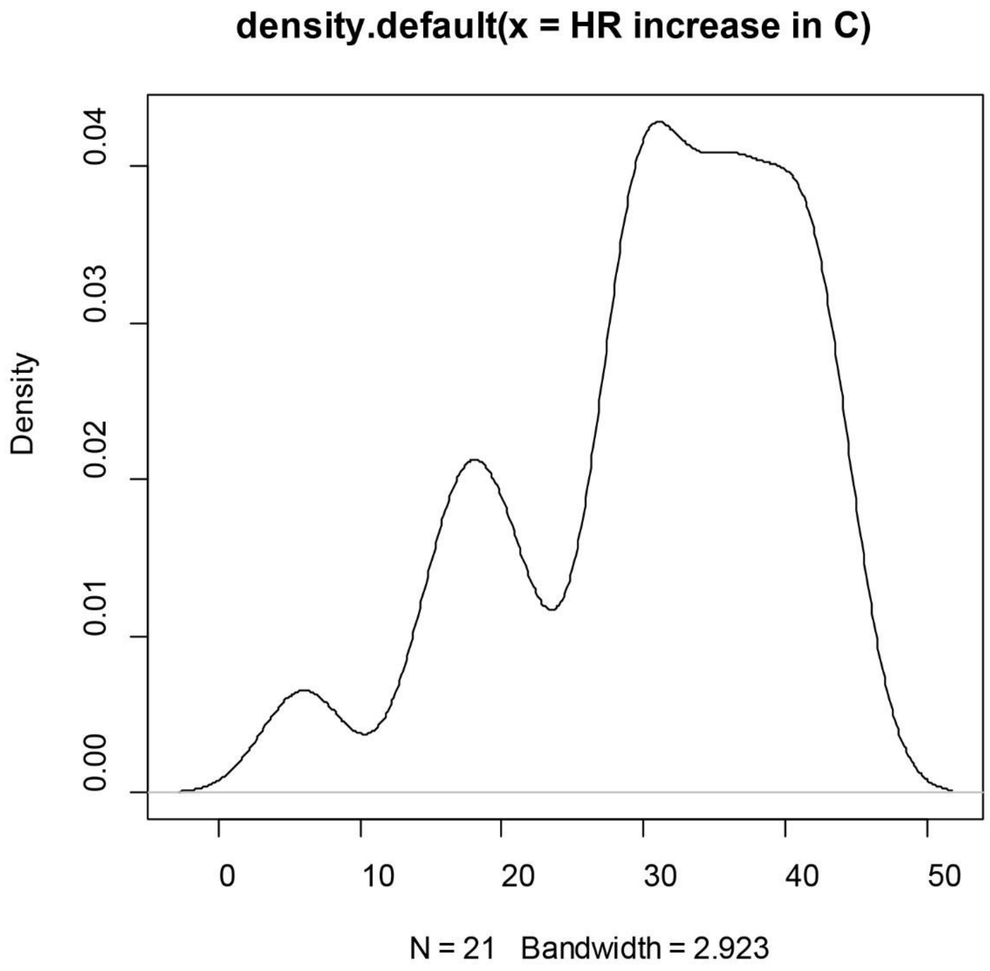
Shapiro-Wilk normality test

data: C

W = 0.91421, p-value = 0.06654

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(C))



> Crawlway<-HR[1:21,4]

> shapiro.test(Crawlway)

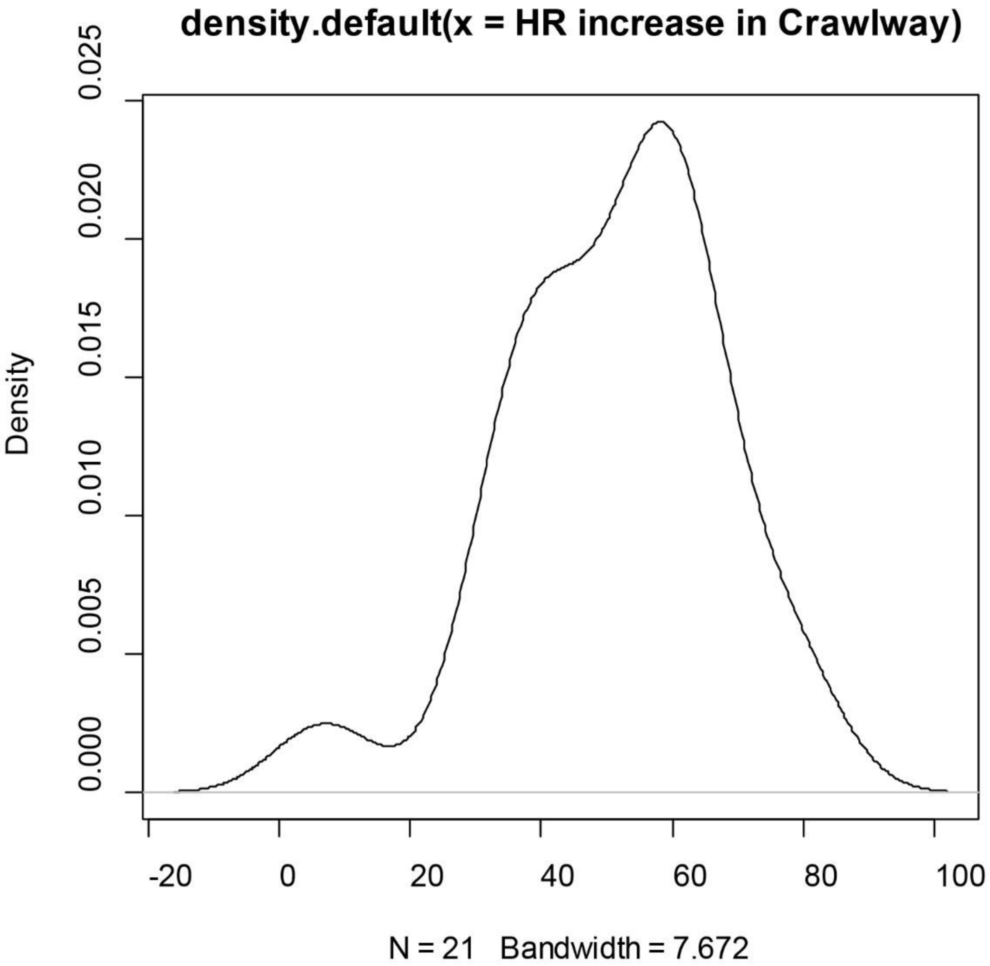
Shapiro-Wilk normality test

data: Crawlway

W = 0.94476, p-value = 0.2702

INTERPRETATION: with an alpha level of .05, the null hypothesis is rejected. The variable couldn't become from a normally distributed population.

> plot(density(Crawlway))



> D<-HR[1:21,5]

> shapiro.test(D)

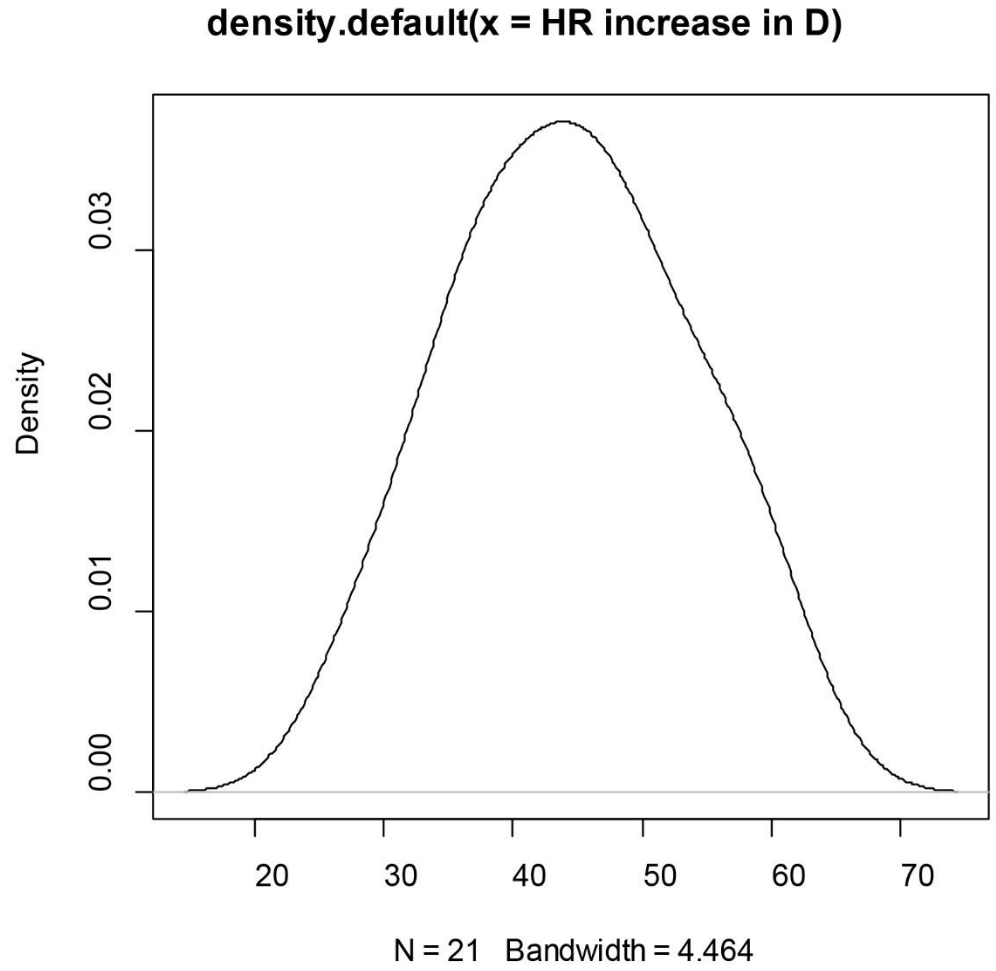
Shapiro-Wilk normality test

data: D

W = 0.97915, p-value = 0.9128

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

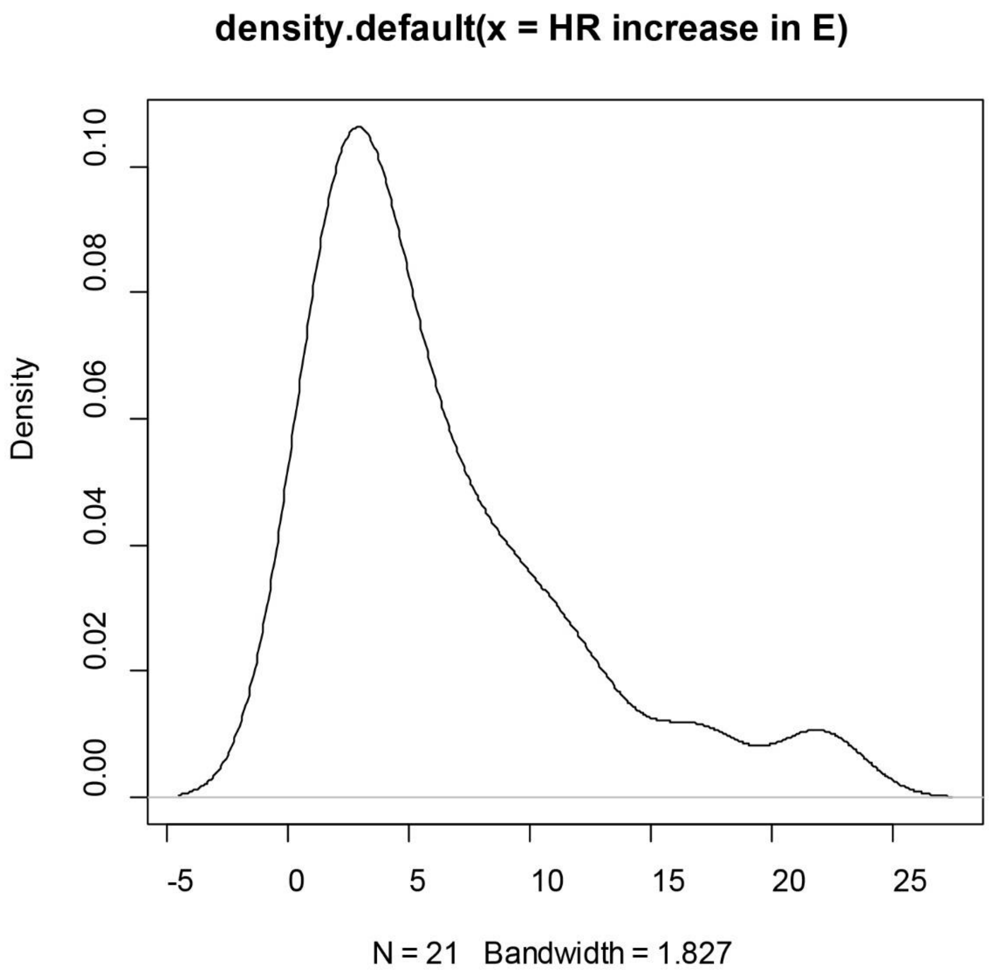
> plot(density(D))




```
> E<-HR[1:21,6]

> shapiro.test(E)

        Shapiro-Wilk normality test

data:  E

W = 0.84031, p-value = 0.002906
```

INTERPRETATION: with an alpha level of .05, the null hypothesis is rejected. The variable couldn't become from a normally distributed population.

```
> plot(density(E))
```



> Lower.Pass<-HR[1:21,7]

> shapiro.test(Lower.Pass)

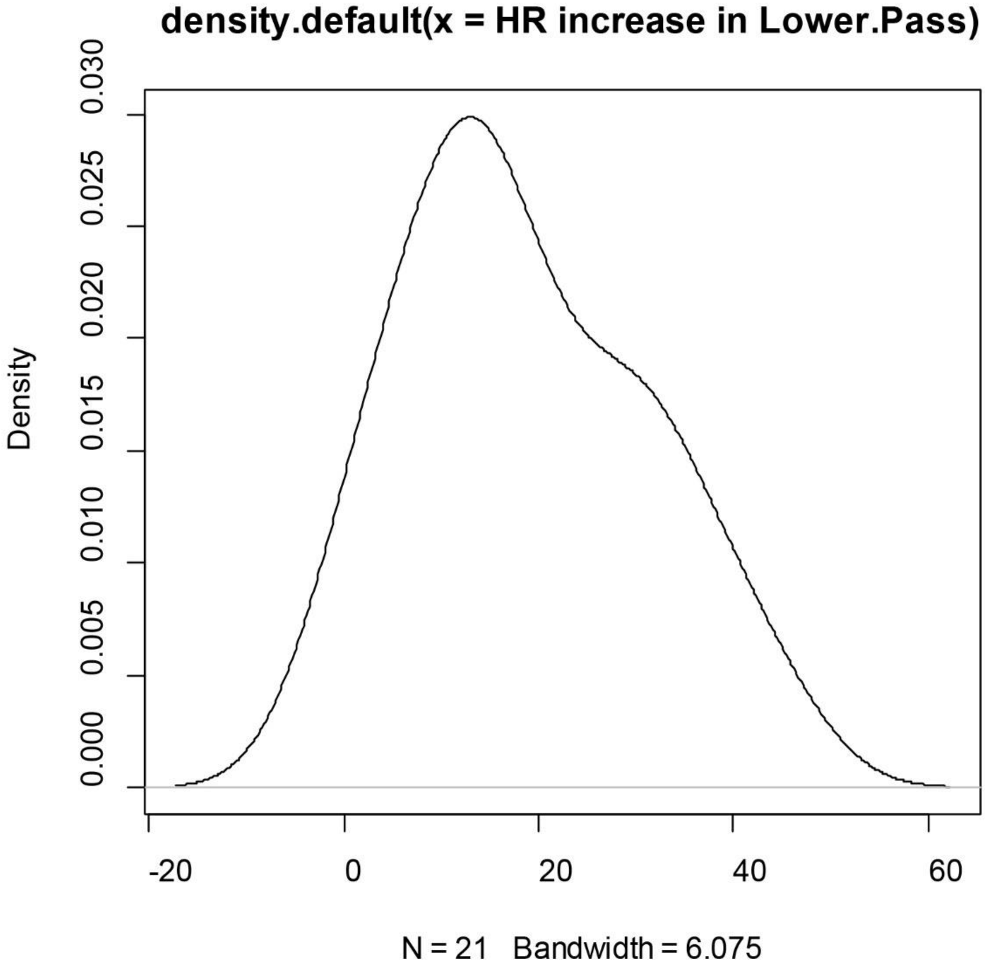
Shapiro-Wilk normality test

data: seventh

W = 0.95532, p-value = 0.4272

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(Lower.Pass))



HEART RATE INTERPRETATION: The measurements from E could be ruled out because it could not come from a normal population.

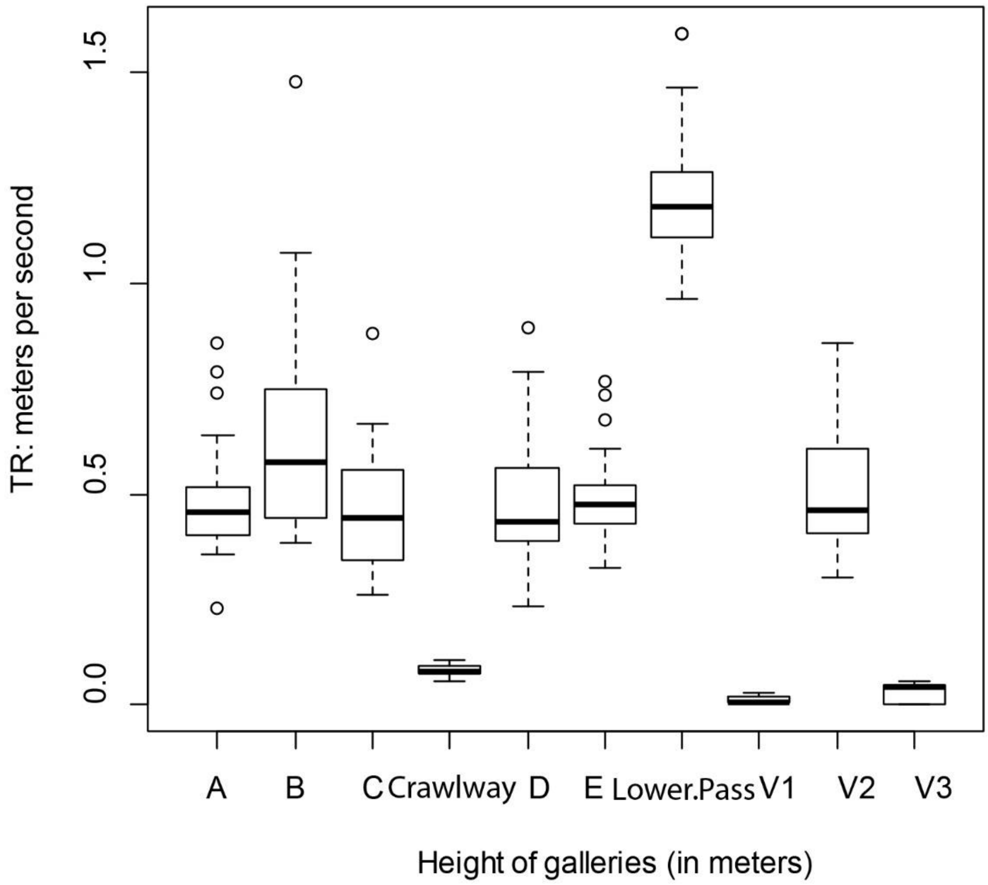
2.2)

Travel rate (measured in meters per second):

```
> TR<-read.xlsx("C:/Users/Table S1.xlsx",sheet=5)
> rownames<-TR[,1];TR[,1]<-NULL
> summary(TR)
```

A	B	C	Crawlway
Min. :0.2286	Min. :0.3849	Min. :0.2596	Min. :0.05526
1st Qu.:0.4044	1st Qu.:0.4433	1st Qu.:0.3426	1st Qu.:0.07372
Median :0.4577	Median :0.5733	Median :0.4447	Median :0.08015
Mean :0.4897	Mean :0.6717	Mean :0.4649	Mean :0.08180
3rd Qu.:0.5163	3rd Qu.:0.7462	3rd Qu.:0.5557	3rd Qu.:0.09254
Max. :0.8571	Max. :1.4747	Max. :0.8798	Max. :0.10862

```
       D                   E                   Lower.Pass          V1
 Min.   :0.2349     Min.   :0.3263     Min.   :0.9621     Min.   :0.005733
 1st Qu.:0.3894     1st Qu.:0.4316     1st Qu.:1.1079     1st Qu.:0.005733
 Median :0.4326     Median :0.4733     Median :1.1794     Median :0.005733
 Mean   :0.4942     Mean   :0.4992     Mean   :1.2302     Mean   :0.012364
 3rd Qu.:0.5600     3rd Qu.:0.5215     3rd Qu.:1.2607     3rd Qu.:0.021235
 Max.   :0.8951     Max.   :0.7658     Max.   :1.5896     Max.   :0.027302
       V2                  V3
 Min.   :0.3040     Min.   :0.003433
 1st Qu.:0.4053     1st Qu.:0.003433
 Median :0.4606     Median :0.042041
 Mean   :0.5012     Mean   :0.033070
 3rd Qu.:0.6080     3rd Qu.:0.047907
 Max.   :0.8563     Max.   :0.057222
> boxplot(TR, ylab="TR: meters per second", xlab="Height of galleries")
```



NORMALITY TEST OF MEASUREMENTS in EACH measurement point

> A<-TR[1:21,1]

> shapiro.test(A)

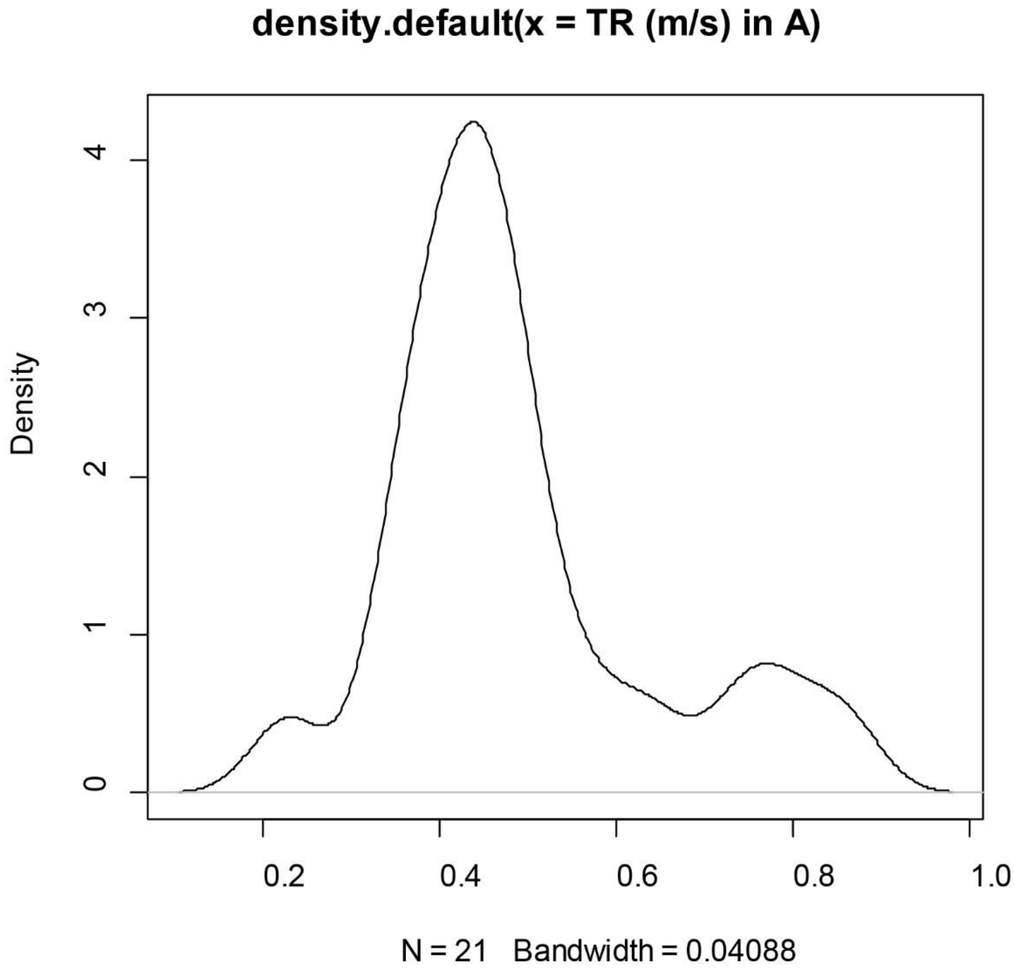
Shapiro-Wilk normality test

data: A

W = 0.89478, p-value = 0.02776

INTERPRETATION: with an alpha level of .01, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(A))



> B<-TR[1:21,2]

> shapiro.test(B)

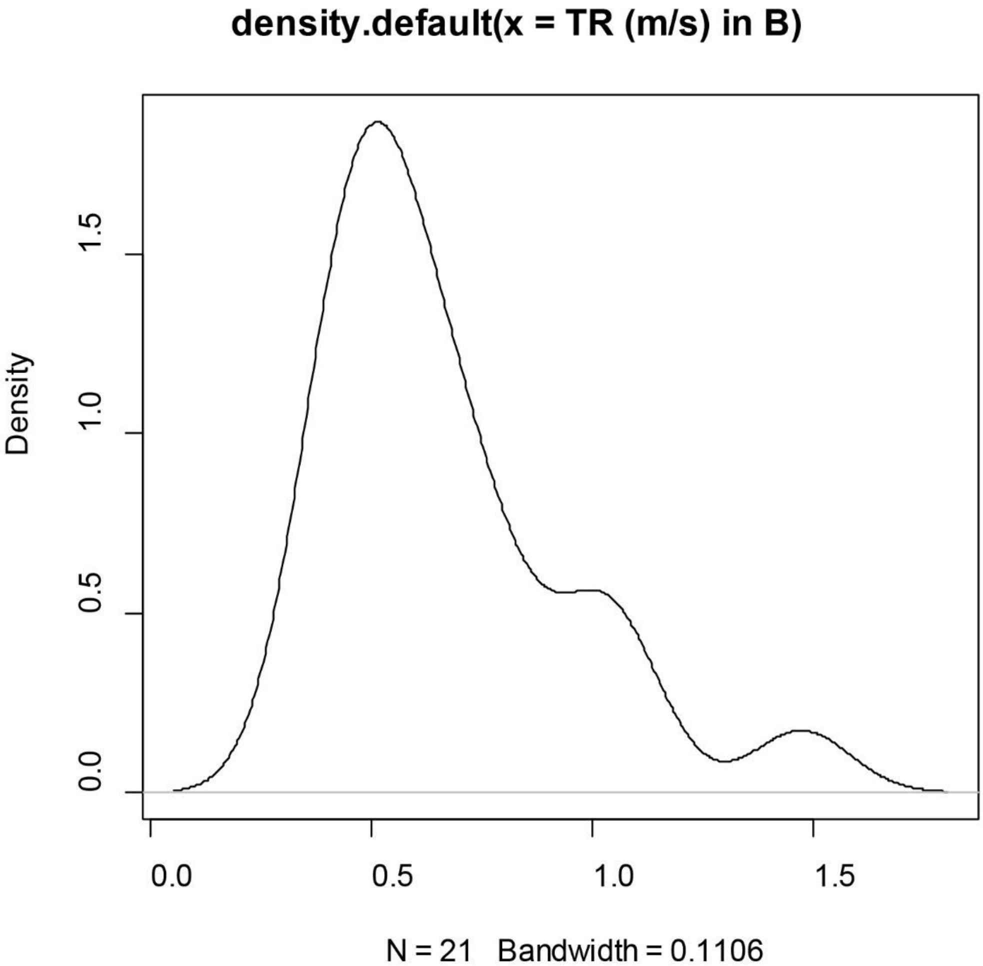
Shapiro-Wilk normality test

data: B

W = 0.85316, p-value = 0.004818

INTERPRETATION: with an alpha level of .05, the null hypothesis is rejected. The variable couldn't become from a normally distributed population.

> plot(density(B))



> C<-TR[1:21,3]

> shapiro.test(C)

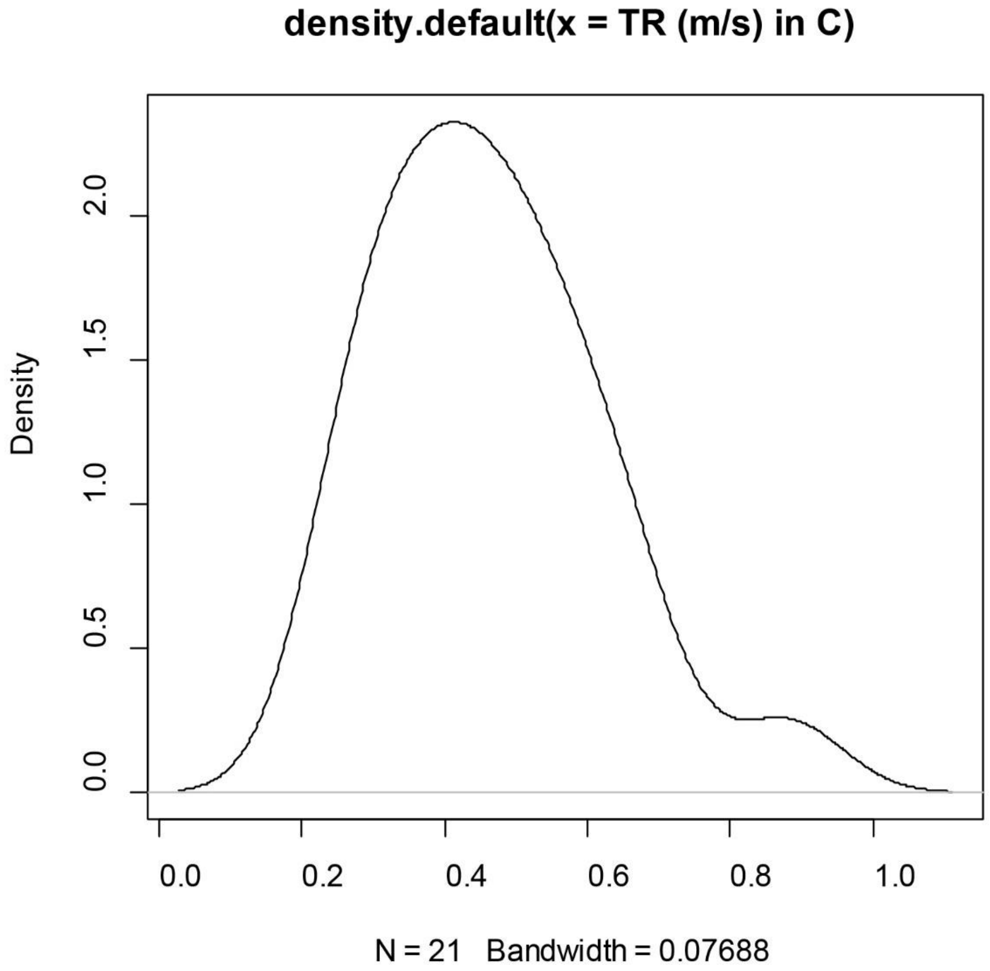
Shapiro-Wilk normality test

data: C

W = 0.94411, p-value = 0.2625

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(C))



> Crawlway<-TR[1:21,4]

> shapiro.test(Crawlway)

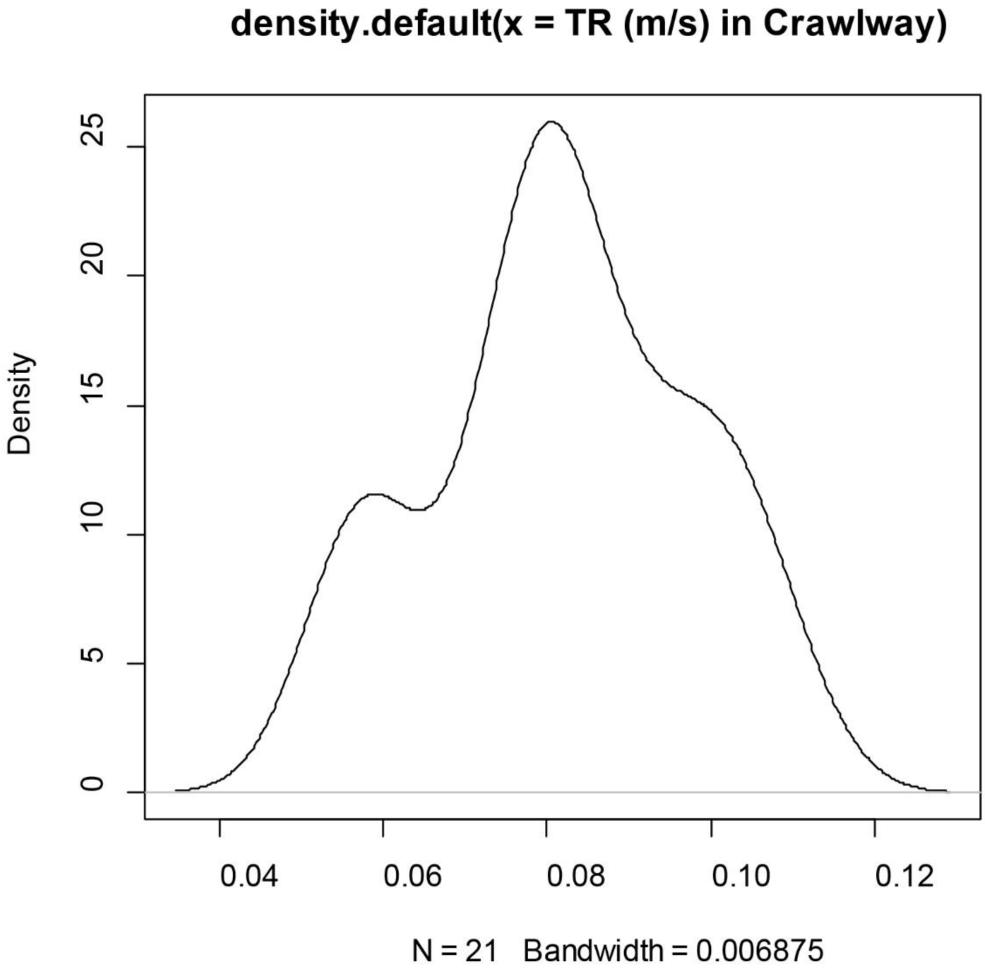
Shapiro-Wilk normality test

data: Crawlway

W = 0.94634, p-value = 0.29

INTERPRETATION: with an alpha level of .05, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(Crawlway))



> D<-TR[1:21,5]

> shapiro.test(D)

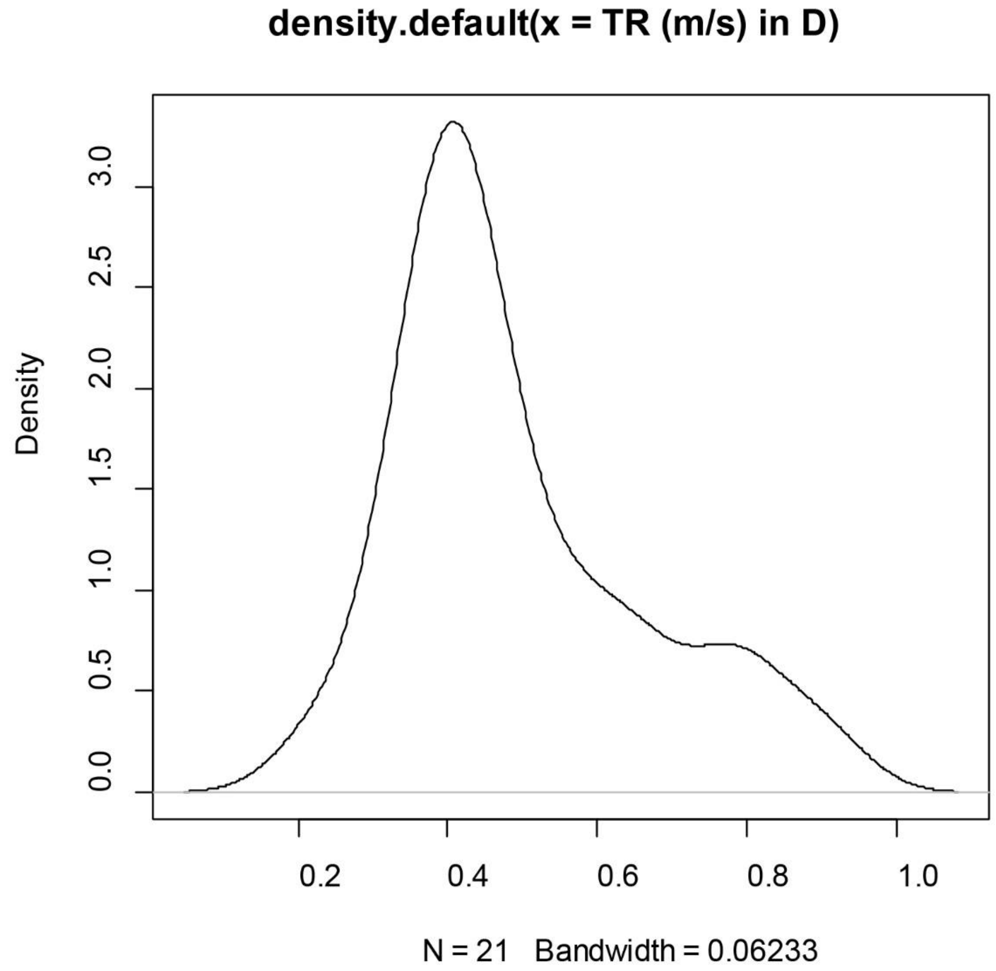
Shapiro-Wilk normality test

data: fifth

W = 0.89784, p-value = 0.03179

INTERPRETATION: with an alpha level of .01, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(D))



> E<-TR[1:21,6]

> shapiro.test(E)

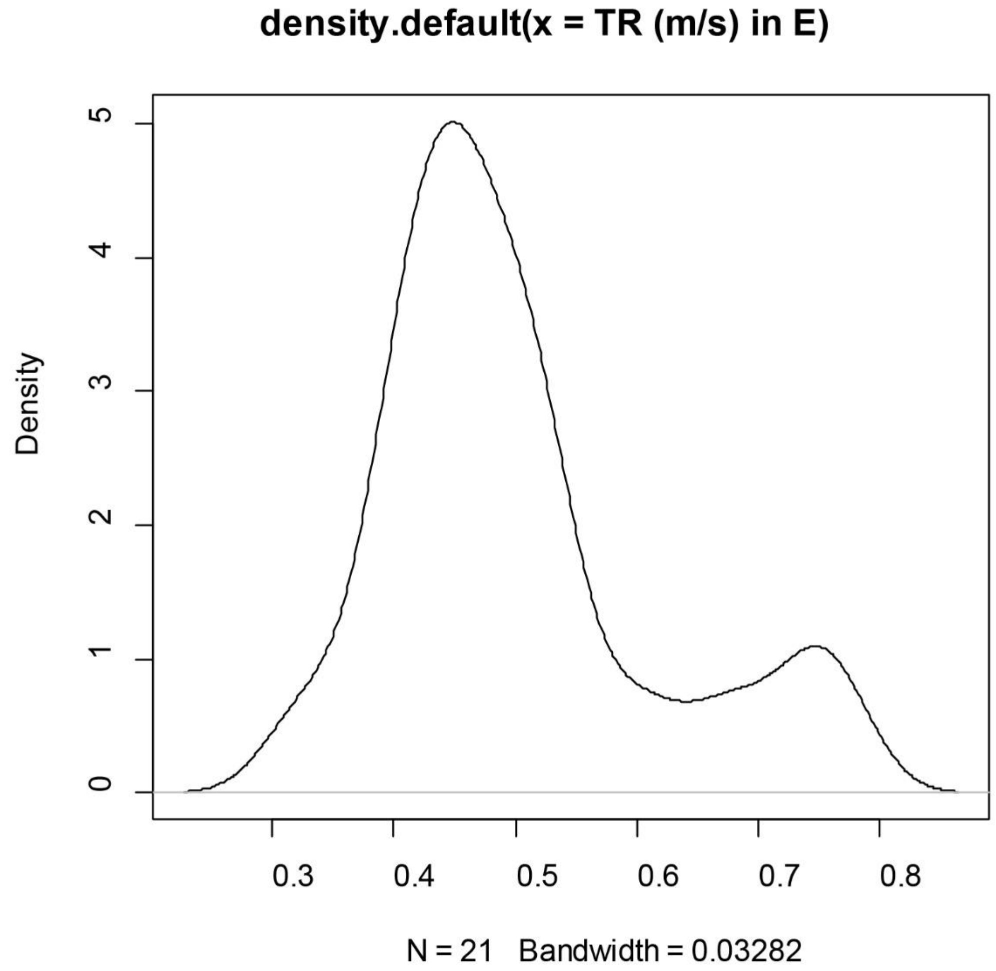
Shapiro-Wilk normality test

data: E

W = 0.89534, p-value = 0.02845

INTERPRETATION: with an alpha level of .01, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(E))



> Lower.Pass<-TR[1:21,7]

> shapiro.test(Lower.Pass)

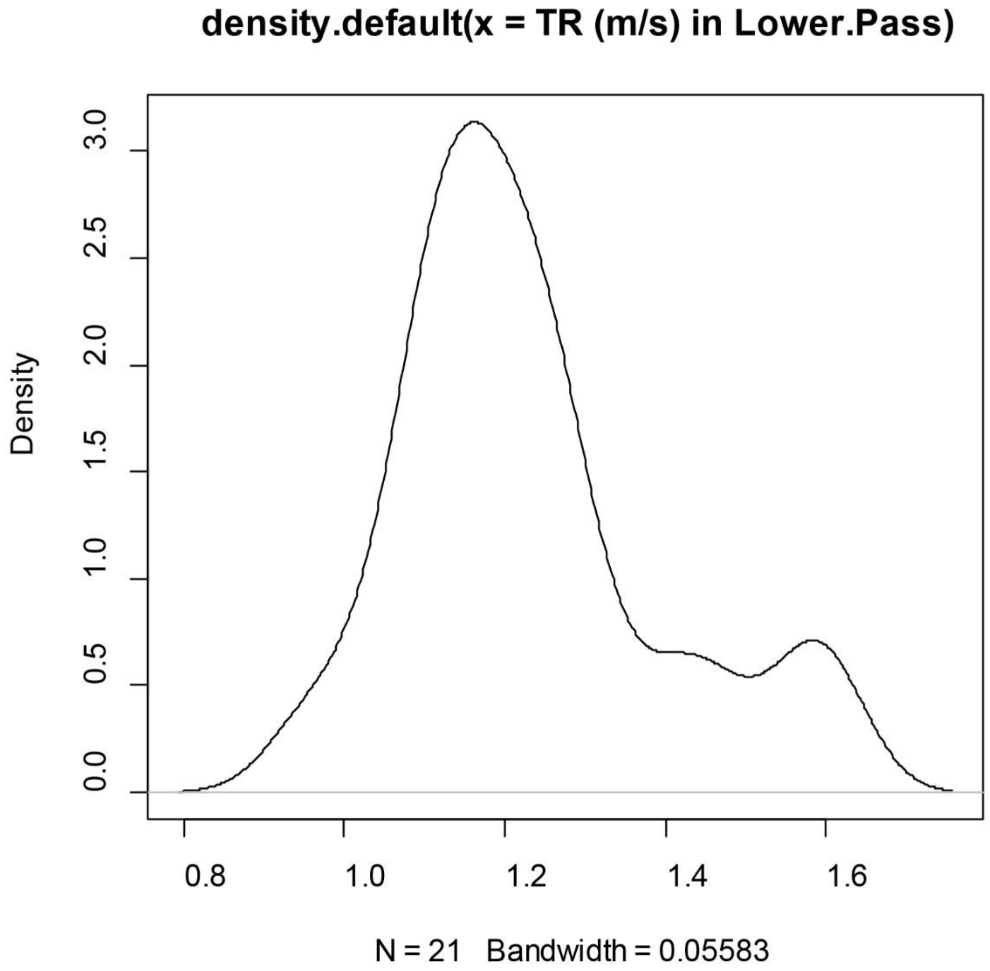
Shapiro-Wilk normality test

data: Lower.Pass

W = 0.90782, p-value = 0.04974

INTERPRETATION: with an alpha level of .01, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(Lower.Pass))



> V1<-TR[1:21,8]

> shapiro.test(V1)

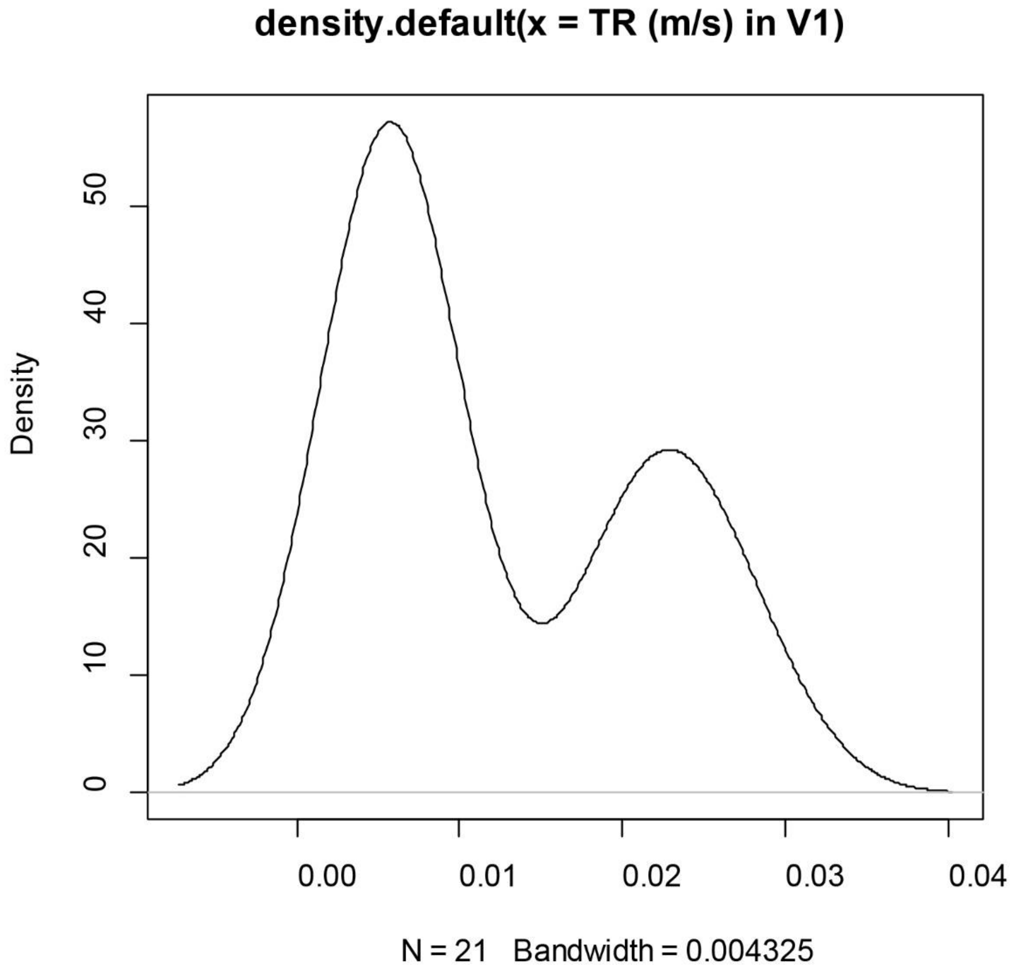
Shapiro-Wilk normality test

data: V1

W = 0.69465, p-value = 2.363e-05

INTERPRETATION: with an alpha level of .05, the null hypothesis is rejected. The variable couldn't become from a normally distributed population.

> plot(density(V1))



> V2<-TR[1:21,9]

> shapiro.test(V2)

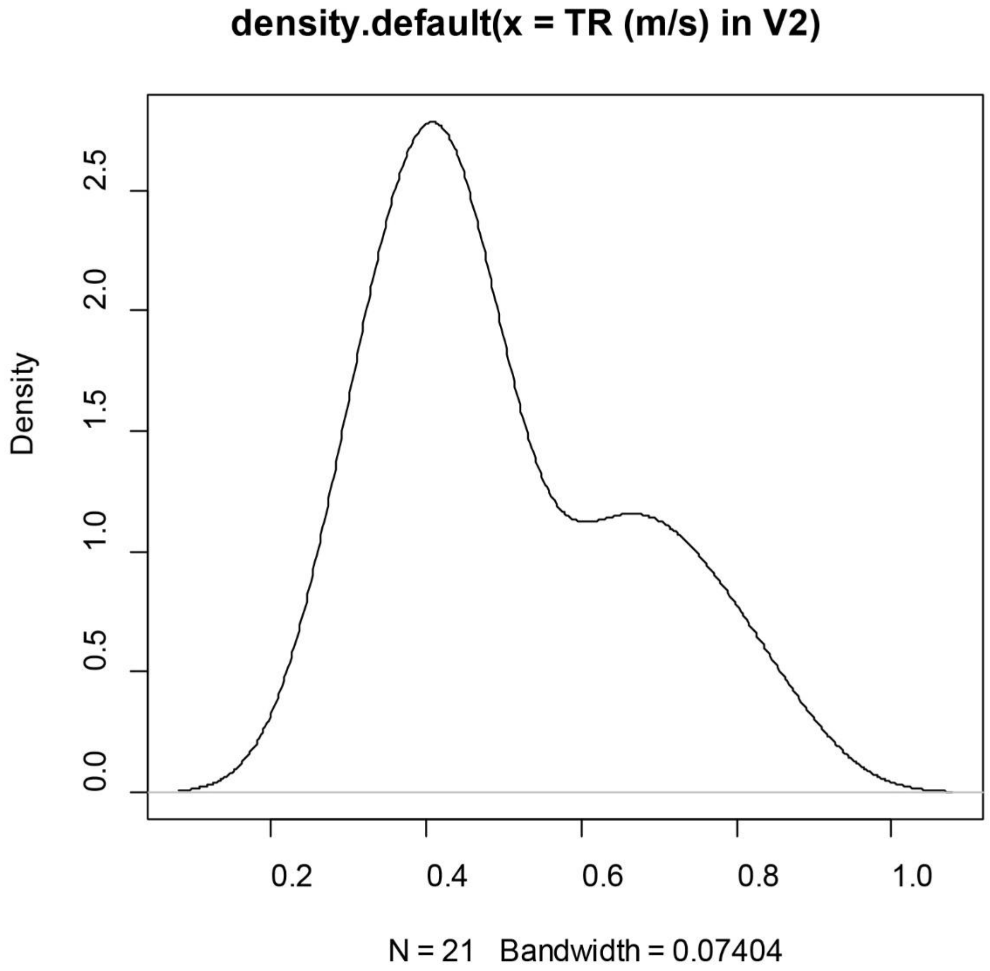
Shapiro-Wilk normality test

data: V2

W = 0.89431, p-value = 0.02718

INTERPRETATION: with an alpha level of .01, the null hypothesis is accepted. The measurement could become from a normally distributed population.

> plot(density(V2))



> V3<-TR[1:21,10]

> shapiro.test(V3)

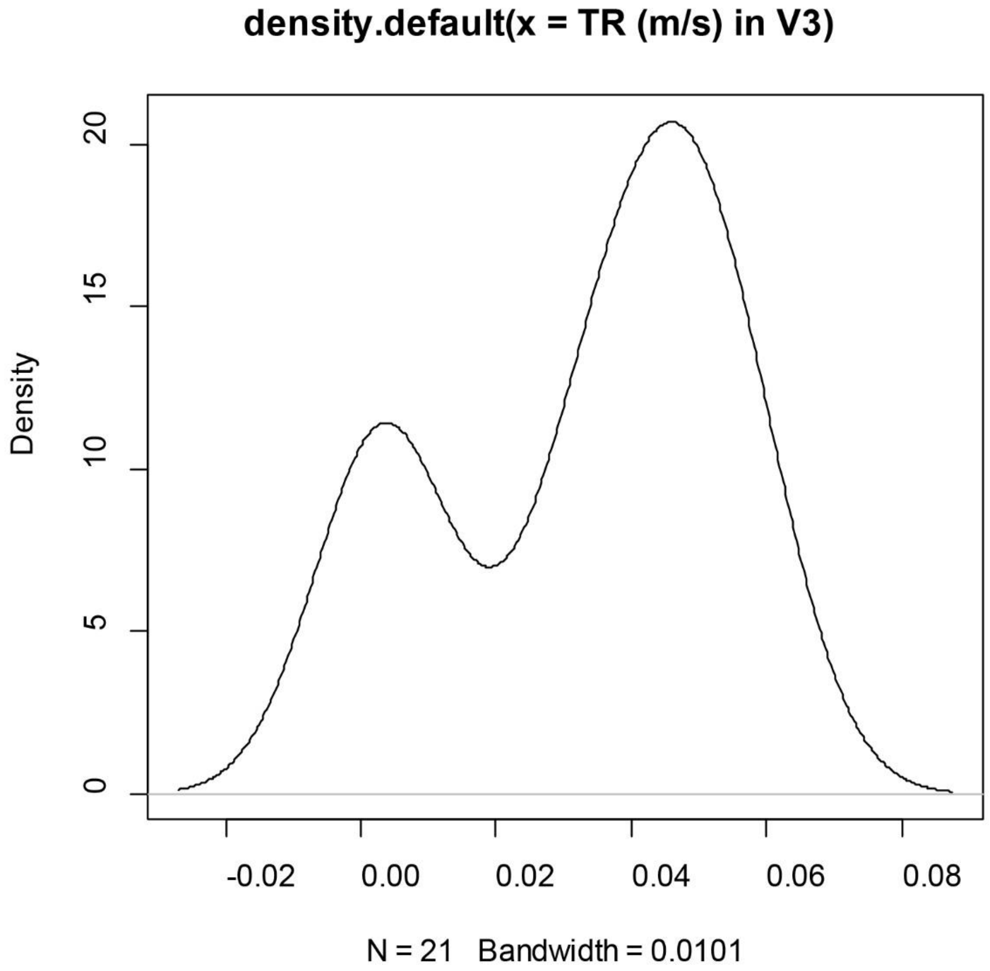
Shapiro-Wilk normality test

data: V3

W = 0.82588, p-value = 0.001678

INTERPRETATION: with an alpha level of .05, the null hypothesis is rejected. The variable couldn't become from a normally distributed population.

> plot(density(V3))



TRAVEL RATE INTERPRETATION: The measurements B, V1 and V3 could be ruled out because it could not come from a normal population. In any case, the case of measurements V1 and V3 is due to some of the participants were not able to overcome this morphological obstacles in five minutes, without any team-help or technological aid.

3)

MULTIPLE LINEAL REGRESION

3.1) First regression for Crawling and Walking movements.

```
> model<-read.xlsx("C:/Users/Table S1.xlsx",sheet=2)

> rownames<-model[,];model[,1]<-NULL

> summary(model)
```

Travel.rates	Heart.rate.growth	Height.of.the.passage	Slope
Min. : 0.8129	Min. : 6.333	Min. :0.240	Min. : 0.680
1st Qu.: 1.7460	1st Qu.:18.333	1st Qu.:1.275	1st Qu.: 2.445
Median : 2.0233	Median :30.810	Median :1.350	Median : 3.800

Mean : 3.2495	Mean :30.061	Mean :1.344	Mean : 5.956
3rd Qu.: 2.0965	3rd Qu.:42.738	3rd Qu.:1.575	3rd Qu.: 9.013
Max. :12.2253	Max. :51.143	Max. :2.120	Max. :14.300
Width			
Min. :0.430			
1st Qu.:1.445			
Median :1.950			
Mean :1.720			
3rd Qu.:2.150			
Max. :2.470			

3.1.1) Analyse the relationship between variables:

The first step in establishing a multiple linear model is to study the relationship between variables. This information is critical to identify which may be the best predictors for the model, which variables have non-linear relationships (so they cannot be included) and to identify collinearity between predictors. As a complement, it is recommended to represent the distribution of each variable using histograms.

The two main ways of doing this are through graphical representations (scatter plots) and the calculation of the correlation coefficient of each pair of variables.

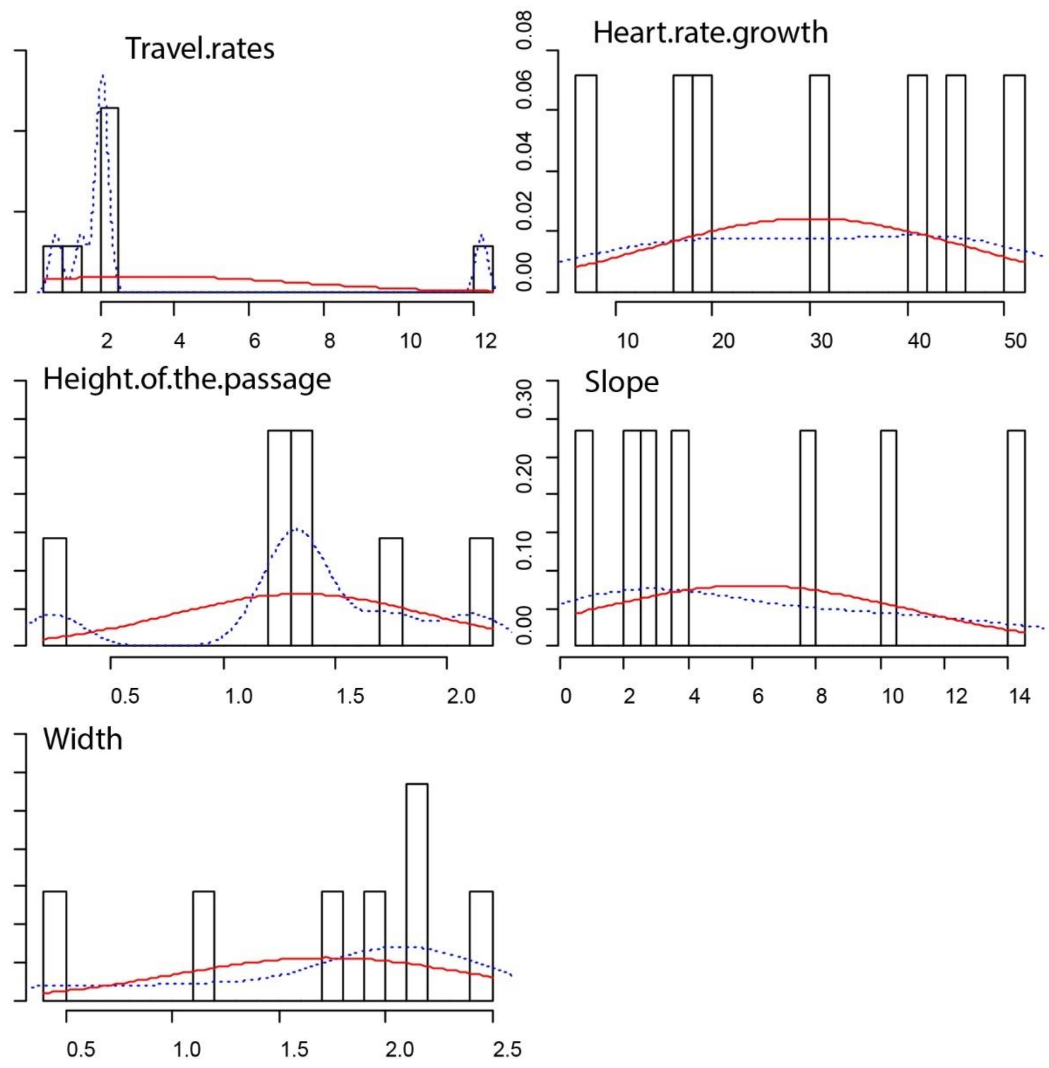
> round(cor(x = model, method = "pearson"), 3)

	Travel.rates	Heart.rate.growth	Height.of.the.passage
Travel.rates	1.000	0.602	-0.900
Heart.rate.growth	0.602	1.000	-0.656
Height.of.the.passage	-0.900	-0.656	1.000
Slope	-0.276	0.114	0.063
Width	0.062	0.131	0.266

	Slope	Width
Travel.rates	-0.276	0.062
Heart.rate.growth	0.114	0.131
Height.of.the.passage	0.063	0.266
Slope	1.000	-0.231
Width	-0.231	1.000

> library(psych)

> multi.hist(model, dcol = c("blue", "red"), dlty = c("dotted", "solid"), main = "")



Graphic of dispersion for each variable.

> library(ggplot2)

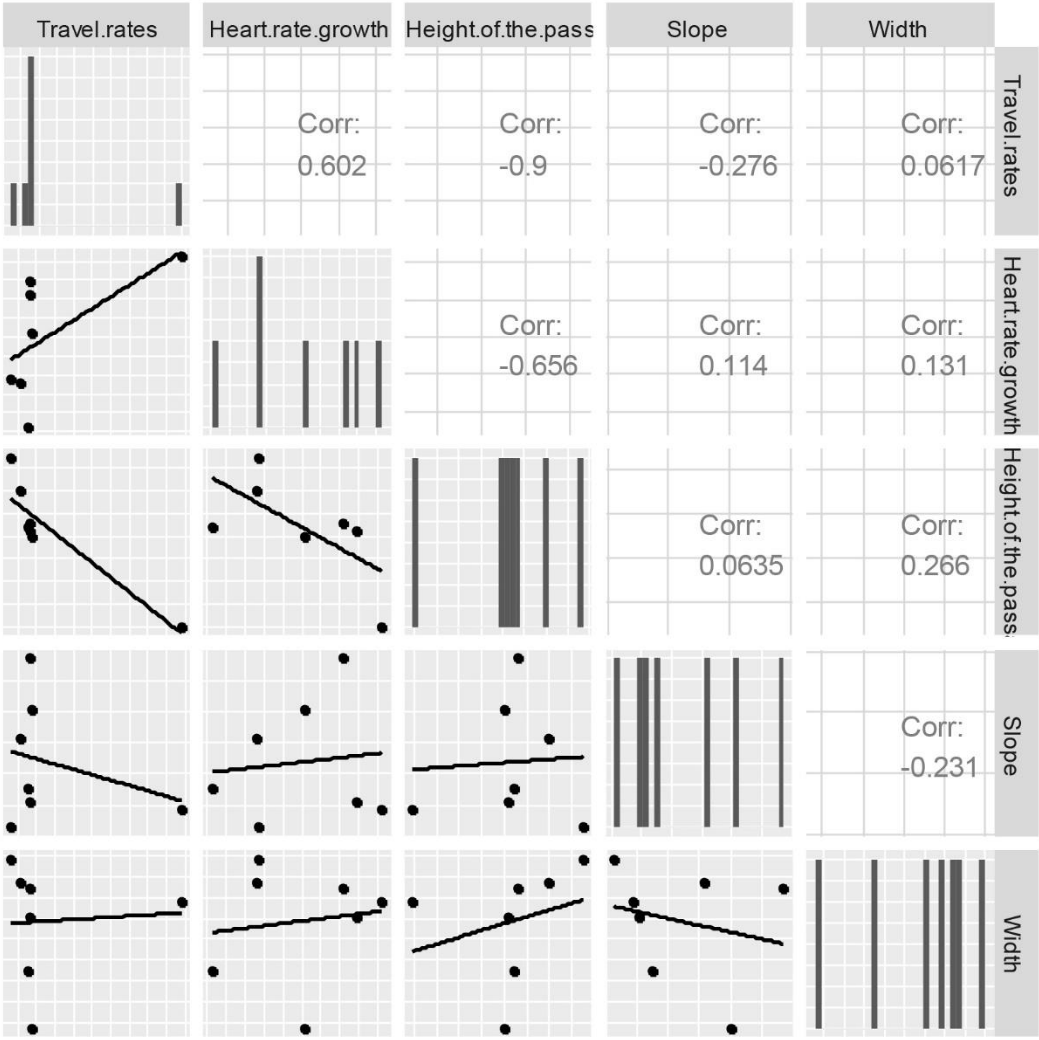
> library(GGally)

> ggpairs(model, lower = list(continuous = "smooth"),diag = list(continuous = "bar"), axisLabels = "none")

plot: [1,1] [=>---] 4% est: 0s `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

plot: [1,2] [===>---] 8% est: 1s
plot: [1,3] [=====>---] 12% est: 1s
plot: [1,4] [=======>---] 16% est: 1s
plot: [1,5] [=========>---] 20% est: 1s
plot: [2,1] [===========>---------------------------------------] 24% est: 1s
plot: [2,2] [=============>-------------------------------------] 28% est: 1s `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

```
 plot: [2,3] [==============>---------------------------------] 32% est: 1s
 plot: [2,4] [================>-------------------------------] 36% est: 1s
 plot: [2,5] [==================>-----------------------------] 40% est: 1s
 plot: [3,1] [====================>---------------------------] 44% est: 1s
 plot: [3,2] [======================>-------------------------] 48% est: 1s
 plot: [3,3] [========================>-----------------------] 52% est: 1s `stat_bin()`
using `bins = 30`. Pick better value with `binwidth`.

 plot: [3,4] [==========================>---------------------] 56% est: 1s
 plot: [3,5] [============================>-------------------] 60% est: 0s
 plot: [4,1] [==============================>-----------------] 64% est: 0s
 plot: [4,2] [================================>---------------] 68% est: 0s
 plot: [4,3] [==================================>-------------] 72% est: 0s
 plot: [4,4] [===================================>------------] 76% est: 0s
`stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

 plot: [4,5] [=====================================>----------] 80% est: 0s
 plot: [5,1] [=======================================>--------] 84% est: 0s
 plot: [5,2] [=========================================>------] 88% est: 0s
 plot: [5,3] [===========================================>----] 92% est: 0s
 plot: [5,4] [=============================================>--] 96% est: 0s
 plot: [5,5] [================================================]100% est: 0s

`stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

Warning message:

In check_and_set_ggpairs_defaults("diag", diag, continuous = "densityDiag",  :

  Changing diag$continuous from 'bar' to 'barDiag'
```



INTERPRETATION: The following conclusions can be drawn from the preliminary analysis:

The variables that have a greater linear relationship Travel rate are: height (r = -0.9), and perhaps slope (r = -0.276). This index (Travel rate) seems to be the best one to explain the cost of transit in the caves with paleolithic art.

Heart rate growth and the height variables have a negative correlation, but somewhat lower in the first case than the travel rate. We are not going to use this index to explain the cost of transit in the caves with paleolithic art.

Width has not significant correlation with both variables (Travel rate or Heart rate growth), but it has a positive relation with the height of the passages (0.231).

```
> regression <- lm(Travel.rates ~ Height.of.the.passage + Slope + Width, data = model )

> summary(regression)

Call:

lm(formula = Travel.rates ~ Height.of.the.passage + Slope + Width,

    data = model)
```

```
Residuals:
      1       2       3       4       5       6       7
-0.4825  0.4411  0.8356  0.7839 -1.9850 -0.5050  0.9119

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)            10.1797     2.1522   4.730  0.01791 *
Height.of.the.passage  -6.6742     1.1116  -6.004  0.00925 **
Slope                  -0.1192     0.1279  -0.932  0.42010
Width                   1.5999     0.9287   1.723  0.18342
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.502 on 3 degrees of freedom
Multiple R-squared:  0.929,     Adjusted R-squared:  0.858
F-statistic: 13.09 on 3 and 3 DF,  p-value: 0.03141
```

INTERPRETATION: The regression with all the variables introduced as predictors has a high R2 (0.9284), it is capable of explaining 92.84% of the variability observed in travel rates. The p-value of the model is significant (0.03182), so it can be accepted that the model is not random, at least one of the partial regression coefficients is different from 0. In any case, some of the variables are not significant (Slope and Width particularly), so we are going to repeat the regression avoiding them.

```
> regression <- lm(Travel.rates ~ Height.of.the.passage, data = model )
> summary(regression)

Call:
lm(formula = Travel.rates ~ Height.of.the.passage, data = model)

Residuals:
      1       2       3       4       5       6       7
-0.8628  0.7619 -1.6843  2.1105 -1.5013 -1.2104  2.3864

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)             11.607      1.943   5.975  0.00188 **
```

Height.of.the.passage   -6.217   1.343 -4.630 0.00568 **

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.899 on 5 degrees of freedom

Multiple R-squared: 0.8109,   Adjusted R-squared: 0.773

F-statistic: 21.44 on 1 and 5 DF, p-value: 0.005684

INTERPRETATION: This second regression has a lower R2 (0.8109), but it remains being hight, and indicate that the variable “Height of the passage” is capable of explaining 81.09% of the variability observed in travel rates. The p-value of the model is more significant that the precedent (0.005684), so it can be accepted that the model is not random, at least one of the partial regression coefficients is different from 0. Besides, the variable and the intercept are significant, with a high confidence level (0.99). Albeit, we are going to perform more test to guarantee its usefulness as a formula for calculating costs in crawling and walking movements in caves.

3.1.1.1)

CONFIDENCE INTERVAL

> confint(regression)

	2.5 %	97.5 %
(Intercept)	6.613786	16.600300
Height.of.the.passage	-9.668695	-2.765478

INTERPRETATION: Validation of conditions for linear regression.

Linear relationship between predictor and the response variable:

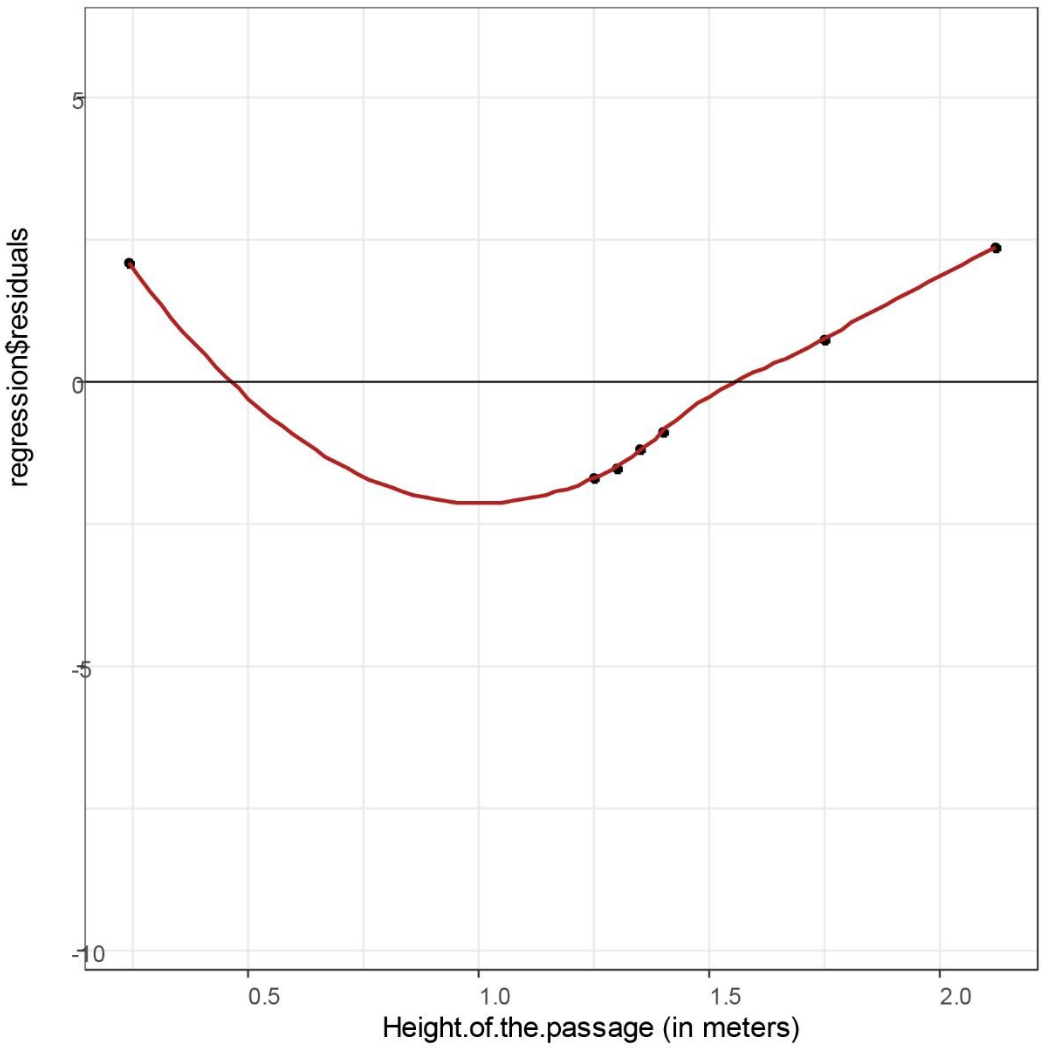
This condition can be validated either by scatterplots between the dependent variable and each of the predictors (as has been done in the preliminary analysis) or by scatterplots between each of the predictors and the model residuals. If the relationship is linear, the residuals should be randomly distributed around 0 with constant variability along the X axis. This last option is usually more indicated since it allows possible outliers to be identified.

> library(gridExtra)

> plot1 <- ggplot(model, aes(Height.of.the.passage, regression$residuals))+ geom_point() + geom_smooth(color = "firebrick")+geom_hline(yintercept = 0) + theme_bw()

> grid.arrange(plot1)

`geom_smooth()` using method = 'loess' and formula 'y ~ x'

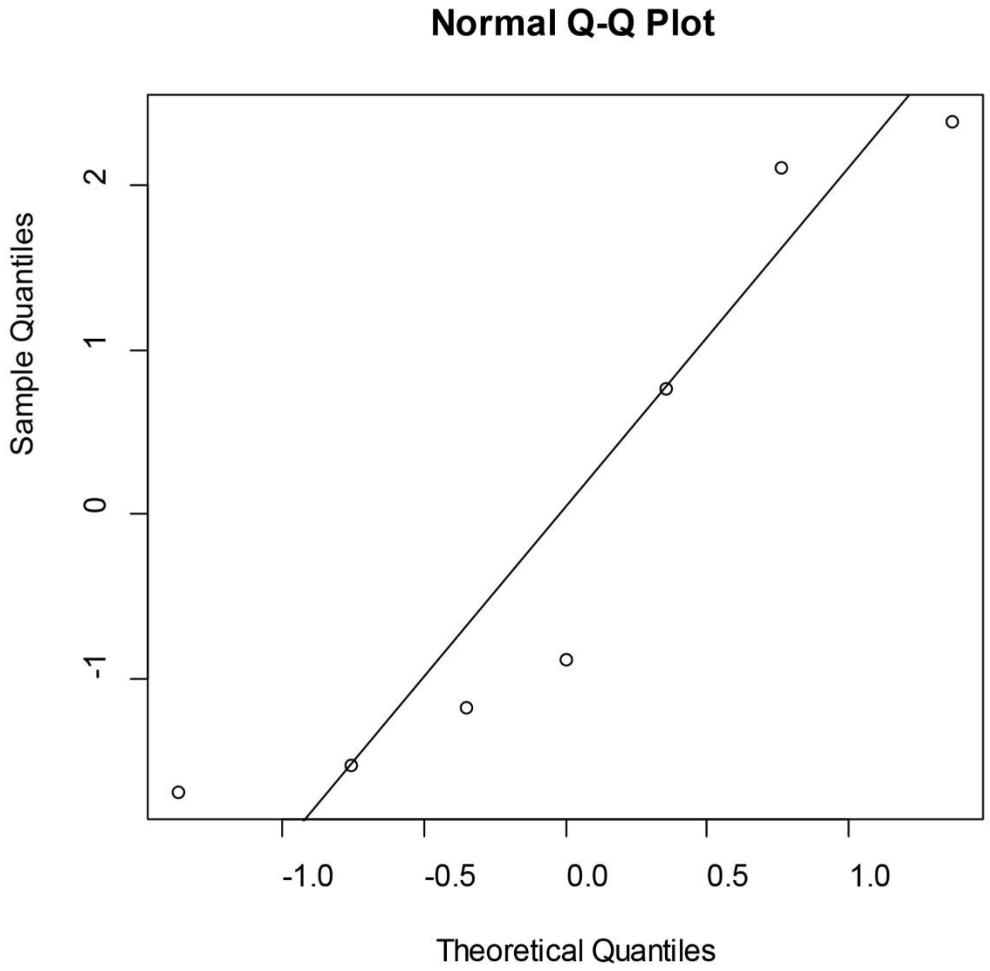


INTERPRETATION: Linearity is met for predictor

Normal distribution of waste:

> qqnorm(regression$residuals)

> qqline(regression$residuals)



> shapiro.test(regression$residuals)

Shapiro-Wilk normality test

data: regression$residuals

W = 0.84799, p-value = 0.1178

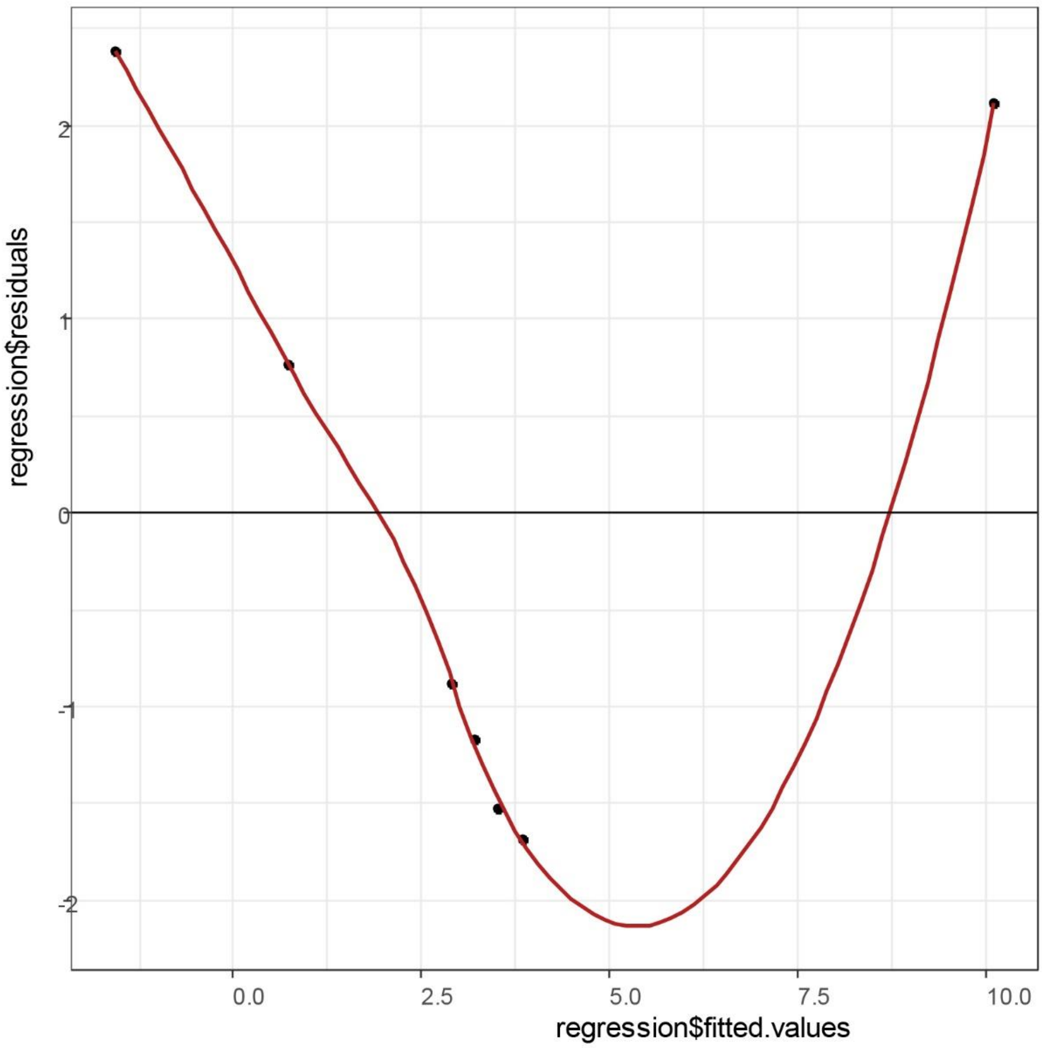
INTERPRETATION: Both the graphic analysis and the hypothesis test confirm normality.

3.1.1.2)

Constant variability of the residuals (homoscedasticity):

When representing the residuals against the values adjusted by the model, the former must be distributed randomly around zero, maintaining approximately the same variability along the X axis. If any specific pattern is observed, means that the variability is dependent on the adjusted value and therefore there is no homoscedasticity.

> ggplot(data = model, aes(regression$fitted.values, regression$residuals)) + geom_point() + geom_smooth(color = "firebrick", se = FALSE) + geom_hline(yintercept = 0) + theme_bw()



> library(lmtest)

> bptest(regression)

studentized Breusch-Pagan test

data: regression

BP = 0.054365, df = 1, p-value = 0.8156

INTERPRETATION: If the test statistic has a p-value below an appropriate threshold (e.g. p < 0.05) then the null hypothesis of homoskedasticity is rejected and heteroskedasticity assumed. So, there is no evidence of lack of homoscedasticity.

3.2) Second regression for Climbing movements.

> model<-read.xlsx("C:/Users/Table S1.xlsx",sheet=3)

> rownames<-model[,];model[,1]<-NULL

> summary(model)

Travel.rates	Slope	Height.of.the.passage	Width
Min. : 1.995	Min. :45.01	Min. :0.87	Min. :0.440

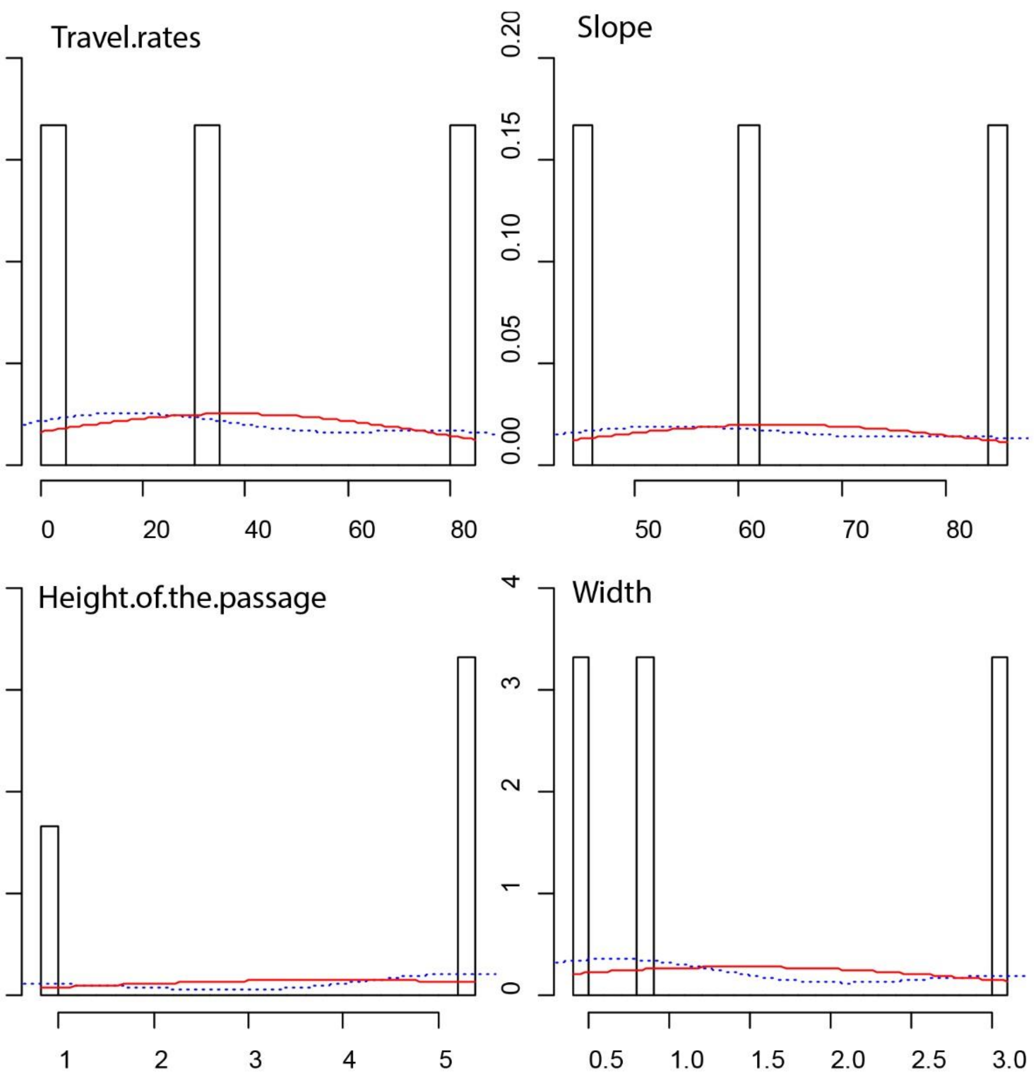
1st Qu.:16.117	1st Qu.:53.10	1st Qu.:3.12	1st Qu.:0.645
Median :30.239	Median :61.20	Median :5.37	Median :0.850
Mean :37.705	Mean :63.90	Mean :3.87	Mean :1.453
3rd Qu.:55.560	3rd Qu.:73.35	3rd Qu.:5.37	3rd Qu.:1.960
Max. :80.881	Max. :85.50	Max. :5.37	Max. :2.470

3.2.1) Analyse the relationship between variables:

```
> round(cor(x = model, method = "pearson"), 3)
```

	Travel.rates	Slope	Height.of.the.passage	Width
Travel.rates	1.000	0.999	0.162	-0.017
Slope	0.999	1.000	0.115	0.030
Height.of.the.passage	0.162	0.115	1.000	-0.989
Width	-0.017	0.030	-0.989	1.000

```
> multi.hist(model, dcol = c("blue", "red"), dlty = c("dotted", "solid"), main = "")
```



Graphic of dispersion for each variable.

> ggpairs(model, lower = list(continuous = "smooth"),diag = list(continuous = "bar"), axisLabels = "none")

plot: [1,1] [==>---]   6% est: 0s `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

plot: [1,2] [=====>--] 12% est: 0s
plot: [1,3] [========>---------------------------------------] 19% est: 0s
plot: [1,4] [===========>------------------------------------] 25% est: 0s
plot: [2,1] [==============>---------------------------------] 31% est: 0s

plot: [2,2] [=================>------------------------------] 38% est: 0s `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

plot: [2,3] [====================>---------------------------] 44% est: 1s
plot: [2,4] [=======================>------------------------] 50% est: 0s
plot: [3,1] [==========================>---------------------] 56% est: 0s
plot: [3,2] [=============================>------------------] 62% est: 0s

plot: [3,3] [================================>---------------] 69% est: 0s `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

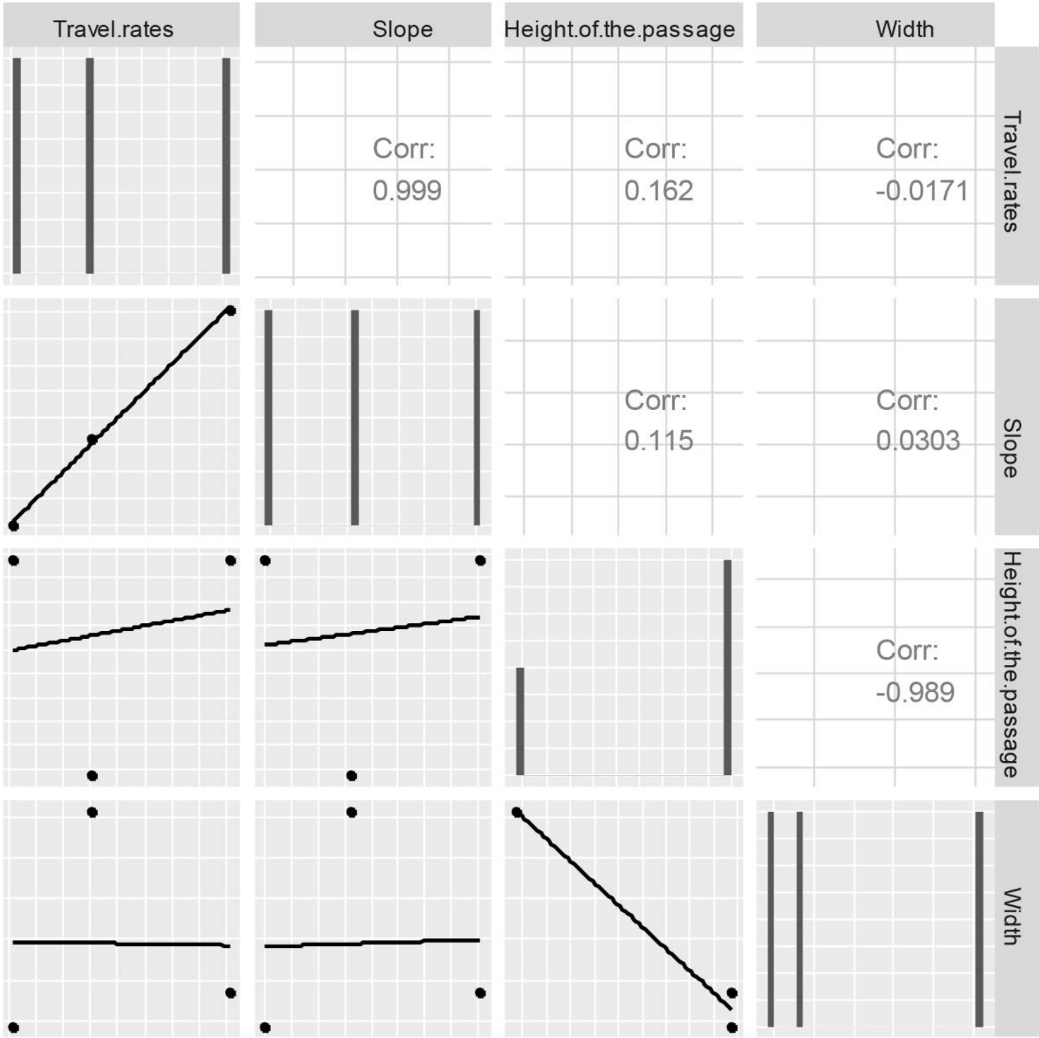
plot: [3,4] [===================================>------------] 75% est: 0s
plot: [4,1] [======================================>---------] 81% est: 0s
plot: [4,2] [===>------] 88% est: 0s
plot: [4,3] [==>---] 94% est: 0s
plot: [4,4] [==]100% est: 0s

`stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

Warning message:

In check_and_set_ggpairs_defaults("diag", diag, continuous = "densityDiag", :

  Changing diag$continuous from 'bar' to 'barDiag'



INTERPRETATION: The following conclusions can be drawn from the preliminary analysis:

The variable Slope has a quasi-perfect negative linear relationship with Travel rate are (r = -0.999).

Height of the passage or Width have not significant correlation with Travel rate (0.162 and -0.0171). So we are going to perform the regression only with the "Slope" variable.

> regression <- lm(Travel.rates ~ Slope, data = model)

> summary(regression)

Call:

lm(formula = Travel.rates ~ Slope, data = model)

Residuals:

1 2 3

-2.1701 0.8677 1.3024

Coefficients:

Estimate Std. Error t value Pr(>|t|)

(Intercept)	-87.48216	6.12996	-14.27	0.0445 *
Slope	1.95901	0.09283	21.10	0.0301 *

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.676 on 1 degrees of freedom

Multiple R-squared: 0.9978, Adjusted R-squared: 0.9955

F-statistic: 445.3 on 1 and 1 DF, p-value: 0.03014

INTERPRETATION: The regression with only one variable (slope) introduced as predictor has a very high R2 (0.9978), it is capable of explaining 99.78% of the variability observed in travel rates. The p-value of the model is significant (0.03014), so it can be accepted that the model is not random, at least one of the partial regression coefficients is different from 0. Besides, the variable and the intercept are significant, with a high confidence level (0.95). Albeit, we are going to perform more test to guarantee its usefulness as a formula for calculating costs in climbing movements in caves.

3.2.1.1)

CONFIDENCE INTERVAL

> confint(regression)

	2.5 %	97.5 %
(Intercept)	-165.3706957	-9.593619
Slope	0.7794937	3.138526

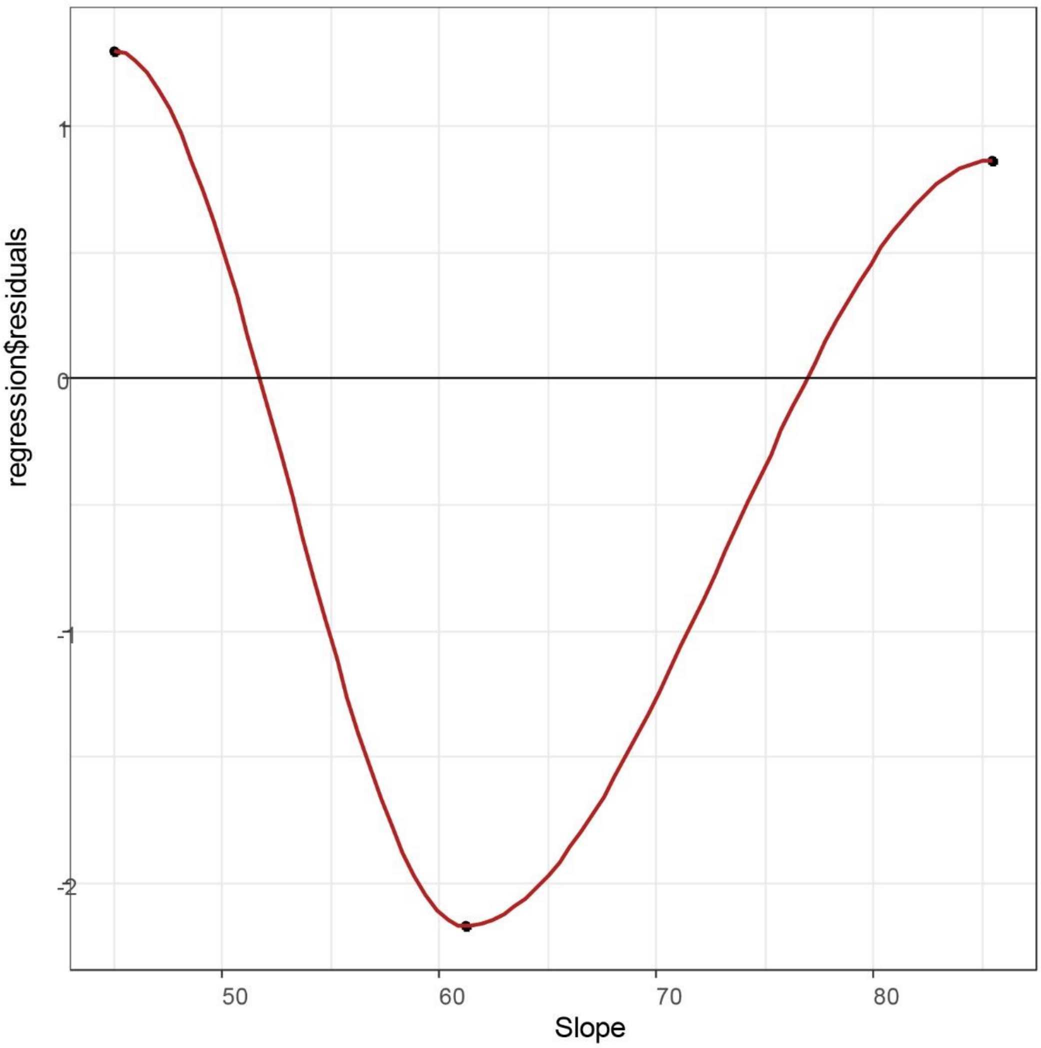
INTERPRETATION: Validation of conditions for linear regression.

Linear relationship between predictor and the response variable:

> plot1 <- ggplot(model, aes(Slope, regression$residuals))+ geom_point() + geom_smooth(color = "firebrick")+geom_hline(yintercept = 0) + theme_bw()

> grid.arrange(plot1)

`geom_smooth()` using method = 'loess' and formula 'y ~ x'

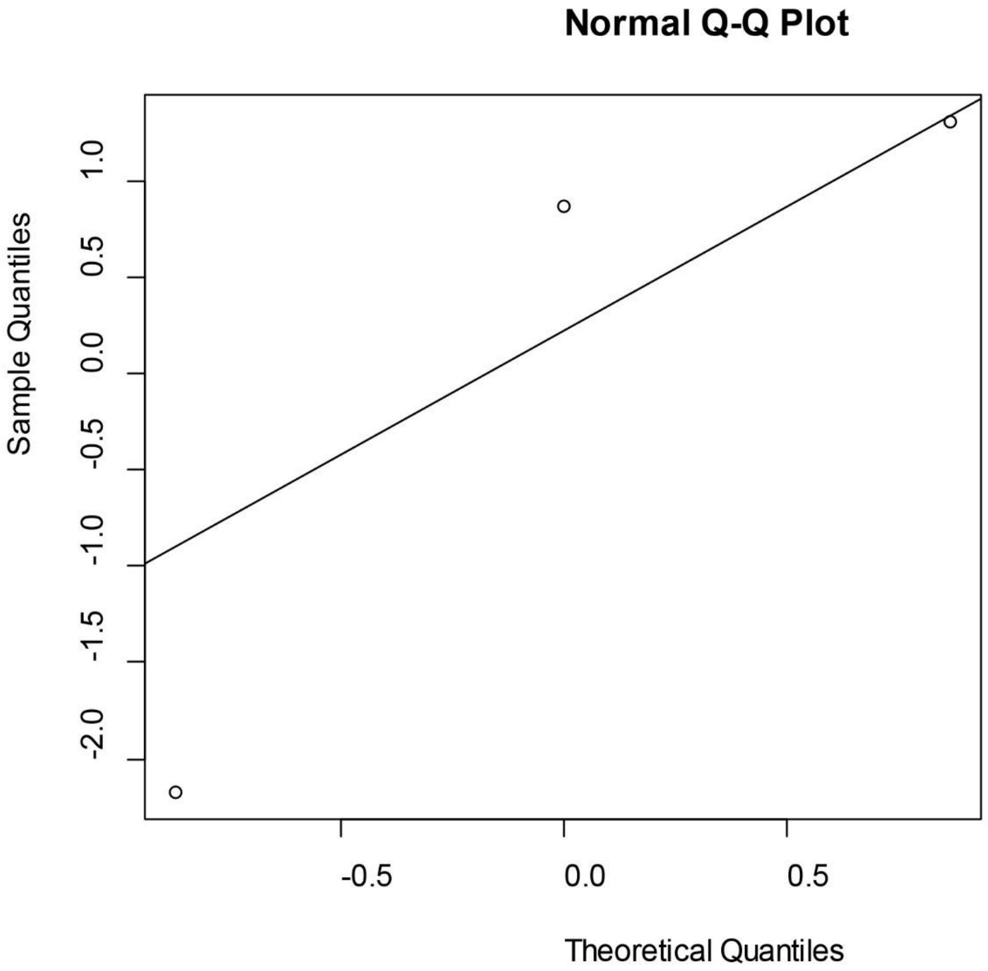


INTERPRETATION: Linearity is met for predictor

Normal distribution of waste:

> qqnorm(regression$residuals)

> qqline(regression$residuals)



> shapiro.test(regression$residuals)

Shapiro-Wilk normality test

data: regression$residuals

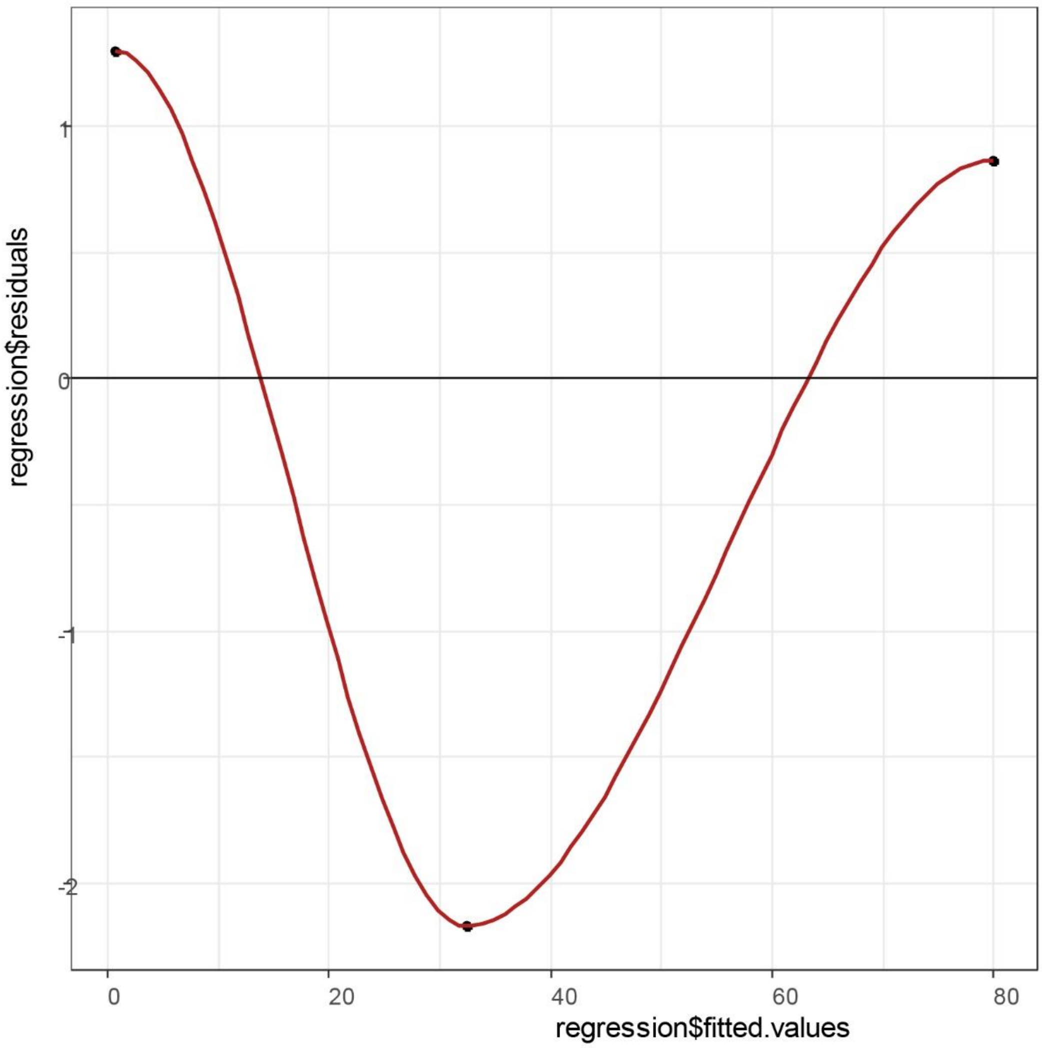
W = 0.84223, p-value = 0.2199

INTERPRETATION: Both the graphic analysis and the hypothesis test confirm normality.

3.2.1.2)

Constant variability of the residuals (homoscedasticity):

> ggplot(data = model, aes(regression$fitted.values, regression$residuals)) + geom_point() + geom_smooth(color = "firebrick", se = FALSE) + geom_hline(yintercept = 0) + theme_bw()



> bptest(regression)

studentized Breusch-Pagan test

data: regression

BP = 0.34387, df = 1, p-value = 0.5576

INTERPRETATION: If the test statistic has a p-value below an appropriate threshold (e.g. $p < 0.05$) then the null hypothesis of homoskedasticity is rejected and heteroskedasticity assumed. So, there is no evidence of lack of homoscedasticity.

3.3)

Sample size: 21

There is no established condition for the minimum number of observations, but to prevent a variable from being very influential when it really is not, it is recommended that the number of observations be between 10 and 20 times the number of predictors. In this case there should be at least 20 observations and 21 are available where appropriate.

4)

The best regressions to be able to measure the costs of movements in caves are the following (in 1 / travel rate = 1 / m per second).

- **Walking and Crawling movements:**

Slope: between 0 and 45 º.

Height of the passage: between 0.24 and 1.86 meters. Values higher than 1.86 meters (~11.607/6.217) will not affect the formula, so we will reconvert those values to 1.86 and eliminate those lower than 0.24 meters.

Travel.Rates = 11.607 – (6.217*Height.of.the.passage)

- **Climbing movements:**

Slope: between 45 º (~87.48216/1.95901) and 100 º.

Travel.Rates = -87.48216 – (1.95901*Slope)