Evaluation of a single body IMU at the girth to monitoring horizontal and vertical parameters in warmblood horses at trot – a pilot study

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Summary

Background: Inertial measurement unit (IMU) sensor-based techniques are becoming more popular with horse-owners as promising tools for objective assessment of the locomotor apparatus.

Objectives: To describe, evaluate and validate the parameters stride duration and vertical displacement at trot using a single body IMU-sensor.

Study design: Prospective validation study comparing an IMU sensor with an 3D optical motion capture.

Methods: A total of twenty-four Warmblood horses equipped with a sternal placed IMU sensor and reflective markers for optical motion capture (OMC) were hand-led in trot on a hard lane. Using algorithms, stride duration and vertical displacement were calculated for each trial from the IMU and optical motion capture data. Bias of the measured parameters was calculated as the mean difference in respectively seconds and centimeters between the IMU and OMC data, precision as the s.d. of these differences and upper and lower limits of agreement (LoAs) were also calculated using the Bland-Altman method.

Results: biases, precision and limits of agreement for stride duration were found for straight line (bias: -0,0269 s; precision: 0,01333 s; LoAs -0,05356s to -0,00024s), left circle (bias: -0,03343s; precision 0,01680s; LoAs -0,06703s to -0,00017s) and right circle (bias: -0,0353s; precision 0,01268s; LoAs -0,06066s to -0,00994s). For vertical displacement, biases lie between -3 and -4 cm, straight line (bias: -3,88077 cm: precision 0,91961 cm; LoAs -5,71999 cm to -2,04155 cm), left circle (bias: -3,03007 cm; precision: 0,72853 cm; LoAs -4,48713 cm to -1,57301 cm) and right circle (bias -3,1944 cm; precision: 0,78589 cm; LoAs -4,76622 cm to -1,62266 cm).

Main limitations: the two measuring systems were not synchronized in time, so small errors between starting the systems occurred. A stride per stride analysis was therefore not possible The measurements were only performed at unridden trot.

Conclusions: the single body inertial measurement unit can be used to quantify stride temporal parameters and vertical displacement at trot. However, precision of the kinematic parameter vertical displacement may not be sufficient yet to detect lameness-related changes. Further ‘big data’ research is warranted to evaluate whether this IMU is suitable for consumer use in the field.

Keywords: horse; inertial measurement unit; optical motion capture; kinematics

Introduction

Lameness is an important equine health issue, resulting in high costs for horse owners [1]. It is the most common medical condition affecting horses [2], which makes it also an important welfare problem. Lameness is a clinical interpretation of abnormal gait and is defined as an alteration of the normal gait pattern as a result of a functional or structural disorder in the locomotion system [3, 4]. This alteration of the normal gait pattern is an expression of the compensation mechanism horses use to adapt to lameness.

Until to date, in most cases routine lameness detection still visually detected routinely by experienced observers in the field. However, the human eye is not able to detect movement asymmetries below a level of 20 to 25 percent [5, 6]. In a gait laboratory setting, optical motion capture (OMC) is the gold standard to assess 3-dimensional movement and orientation [7, 8]. However, this equipment can be expensive and not suitable for use in the field.

Currently, quantitative gait analysis in horses can be achieved using small, wireless inertial measurement units (IMUs), which enable objective measurement in the field [6]. These IMUs could be used by horse owners or trainers to monitor the gait quality of their horses during exercises. Validation studies of IMUs have attempted to quantify lameness, to enable the incorporation of IMU data into clinical lameness examinations with the aim of helping equine clinicians to detect and quantify mild to moderate lameness [2, 9]. In these studies IMUs were placed at different positions of the equine body (e.g. the equine head, poll, tuber coxae or sacrum) and horses are examined in hand or at an equine treadmill.

Experts have worked towards consumer friendly hardware to monitoring horses. For this purpose, consumer grade smartphones and different pieces of inertial sensors are used [9,10]. To date, the results of research on these systems have been encouraging, but limits of agreement (LoAs) should be taken into account when comparing consumer-grade devices with specialist systems [10].

Subjectively, gait quality of warmblood horses in trot at hand can be scored by using stride length, impulsion and suppleness [11]. To *objectively* measure the gait quality at trot, three kinematic variables (forelimb stride duration, scapula rotation and maximal fetlock extension) have been defined, which could describe the total variation in the subjective gait score of the judge [12].

Inertial measurement units (IMUs) contain accelerometers, gyroscopes and magnetometers. Using tri-axial (3D) accelerometers, the acceleration in the X, Y and Z direction can be measured, which can be used to determine the parameters velocity and position of the horse [13].

The purpose of this pilot study was to describe, evaluate and pre-validate a new single body IMU sensor, placed at the sternum, on a hard surface in trot. It was hypothesized that no significant differences in the temporal parameter stride duration and kinematic parameter vertical displacement would be found between the output of the optical motion system and the single body IMU sensor, which would mean a perfect agreement between the systems.

Materials and methods

Horses

A total of twenty-four Warmblood horses (fifteen mares, two stallions and seven geldings) with a body mass range of 512-712 kg (mean 569,83 kg), height at the withers range 1,59 – 1,75 (mean 1,67)[1] and age range of 4-22 (mean 9,08 years) were used for this study. No lameness was observed during visual examination at walk and trot on a straight line prior to data collection. The horses were used with written permission of the owners.

Data collection

All subjects were instrumented with one inertial measurement unit (IMU) sensor (Equisense Motion)[a] on an attachment on the girth at the sternum and reflective markers on the withers.

[1] Specific height of six horses is unknown.

The IMU is a 9-axis sensor, containing a 3-axis accelerometer, a 3-axis gyrometer and a 3-axis magnetometer. The IMU data was recorded at a sampling frequency of 59,5 Hz. The sensor weighs 38 grams, has a low-energy Bluetooth smart 4.1 connectivity and synchronizes with the smartphone's GPS.

Also, nine reflective markers (12.5 mm ø, spherical passive marker) were placed in clusters of three markers at the head, withers and pelvis. Optical motion capture (OMC)[b] data was recorded at 200 Hz using 18 infrared cameras positioned along the track. The system needs the nine markers to be able to analyze how and where the horse trots in the space. For comparison with our sensor at the girth, we decided only to use OMC data from the withers, since the girth and withers measure the same section of the horse.

All trials were recorded by video synchronized with the OMC using standard equipment for retrospective analysis of the collected data. Prior to data collection, all instruments were calibrated in accordance with the manufacturers' instructions.

All subjects were equipped with the instruments and were led in trot over a hard surface by an experienced handler. A trial was considered valid if the horse was trotting at a constant speed on a constant straight line/circle.

Kinematic analysis

Collected data was separately processed and analyzed. Data obtained from the optical motion capture system was analyzed by custom made matlab algorithms by the University of Utrecht, whereas data obtained from the IMU was processed by the manufacturer. The processed data were received and used for further analysis.

Data analysis

Using the optical motion capture system as the gold standard reference for stride duration and vertical displacement, accuracy of the measured parameters was calculated as the difference in seconds between the IMU and the OMC generated data. A positive difference between the systems indicates an overestimation of the parameter calculated by the IMU, and a negative difference indicates an underestimation of the parameter by the IMU.

Open software (IBM SPSS Statistics version 24)[c] was used for statistical analysis.
Since the OMC and IMU systems were not synchronized, an unequal amount of measurements (strides) were acquired. To be able to statistically compare data a trial to trial basis had to be used. For every horse the means of vertical displacement and stride duration were calculated, so 24 (straight line) and 23 (left and right circle) values (means) were obtained. For calculations concerning the Bland-Altman plot, the mean of that parameter of all horses was used. For details of data processing see Appendix I (amount of data per horse) and II (filtration of the data).

To evaluate a new method, usually a comparison to an established technique is made. The Bland-Altman plot and analysis is the best method to perform this comparison, rather than a correlation and regression method. Bland-Altman compares two measurements of the same variable, while correlation studies the relationship between one variable and another, not the differences [14, 15].
When comparing two systems, neither provides an absolute correct measurement, therefore we try to assess the degree of agreement between them [14]. To do so, we study the mean difference and construct limits of agreement. A bias can be established between the mean differences and an agreement interval can be estimated [15].

Even though the Bland-Altman plot defines the intervals of agreement, it does not determine whether these intervals are acceptable or not. Acceptable limits must be defined in advance [15].

Results

A total of 60 trials were collected; 24 for the straight line, 23 for the left circle and 23 for the right circle. Every trial provided data for the two measured parameters: stride duration and vertical displacement. The amount of values per horse and per system are presented in Appendix I. Larger graphs and the process towards the Bland-Altman plot are presented in Appendix IV.

High correlations were found between the IMU and optical motion capture, but for specifications on the agreement between the systems, Bland-Altman plots and calculations were made.
For stride duration, highest correlation was found on the right circle (0,961), followed by straight line (0,934) and lowest correlation was found on the left circle (0,900). For vertical displacement, highest correlation was found on the left circle (0,925), followed by the right circle (0,885) and lowest correlation was found on the straight line (0,831). Results are summarized in Table 1. Full correlationplots are presented in Appendix IIIa and IIIb.

Table 1 - Correlations found between IMU and OMC.

Parameter	**Trial**	**Correlation**
Stride duration	Straight line	0,934
	Left circle	0,900
	Right circle	0,961
Vertical displacement	Straight line	0,831
	Left circle	0,925
	Right circle	0,885

Stride duration

The performance of the IMU compared to 'gold standard' optical motion capture for parameter stride duration is summarized in Table 2. Bias of the IMU is lowest when trotting on the straight line (bias: -0,0269 s; precision: 0,01333 s). When trotting on a circle, bias of the IMU is smallest on the left (-0,03343s; precision 0,01680s) and greatest on the right circle (bias: -0,0353s; precision 0,01268s).

For straight line assessment, LoAs were with -0,05356s for lower limit of agreement (LLA) and -0,00024s for upper limit of agreement (ULA), narrower than LoAs on the circle.

On the left circle, LoAs were widest with LLA of -0,06703s and ULA of -0,00017s.

Narrower than on the left circle, but wider than LoAs on the straight line were the LoAs of the right circle, with LLA of -0,06066s and ULA -0,00994s.

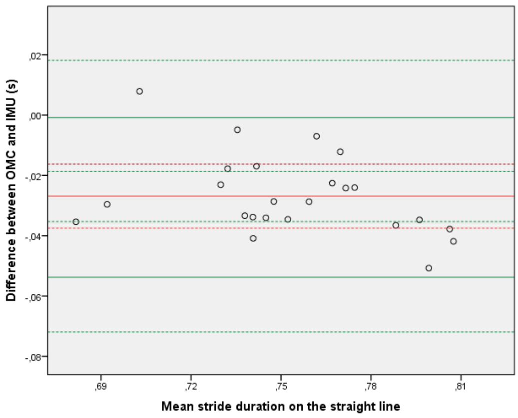
For visual inspection, Bland-Altman plots of stride duration are presented in Figure 1.

Table 2 - Descriptive statistics of stride duration of the Inertial measurement unit (IMU) vs. 'gold standard' optical motion capture (OMC)

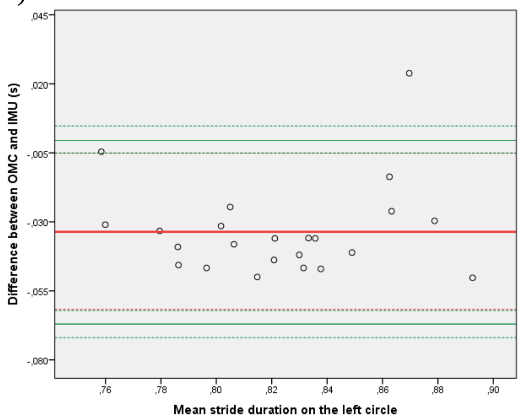
	Bias (s)	Precision (s)	Lower limits of agreement	Upper limits of agreement
Straight line	-0,0269	0,01333	-0,05356	-0,00024
Left circle	-0,03343	0,01680	-0,06703	-0,00017
Right circle	-0,0353	0,01268	-0,06066	-0,00994

Bias, mean difference in seconds (s) between the IMU calculated and the OMC; precision, s.d. of the mean difference between the IMU and the OMC. Bias and precision are deemed better if closer to zero.

a)



b)



c)

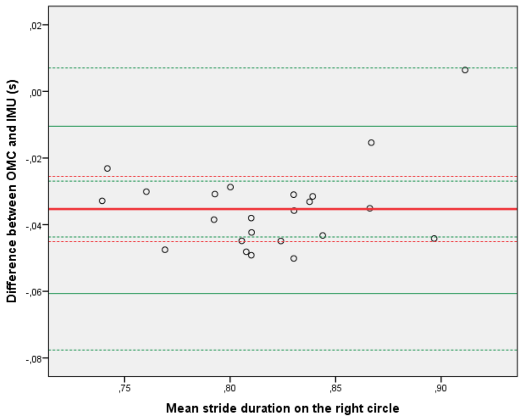


Figure 1 - Bland-Altman plots of stride duration on a) the straight line, b) the left circle and c) the right circle, with bias (solid red line), and upper and lower limits of agreement (solid green lines) including all confidence intervals (indicated with dotted lines). If agreed perfectly, all values (dots) were to be on the null-line (not indicated in the graphs).

Vertical displacement

The bias of vertical displacement lies between -3 and -4 cm, and seems to be least on the left circle (bias: -3,03007 cm; precision: 0,72853 cm). On the right circle, bias was close to the bias of the left circle (-3,1944 cm; precision: 0,78589 cm). Highest bias was found on the straight line (bias: -3,88077 cm: precision 0,91961 cm).
Assessing vertical displacement, LoAs were narrowest on the left circle (-4,48713 cm LLA to -1,57301 cm ULA), followed by the right circle (-4,76622 cm LLA to -1,62266 cm ULA). Widest limits of agreement were found on the straight line: -5,71999 cm LLA to -2,04155 cm ULA.
The performance of the IMU compared to ‘gold standard’ optical motion capture for parameter vertical displacement is summarized in Table 2. Bland-Altman plots of stride duration are presented in Figure 2.

Table 3 - Descriptive statistics of vertical displacement of the Inertial measurement unit (IMU) vs. 'gold standard' optical motion capture (OMC)

	Bias (cm)	Precision (cm)	Lower limits of agreement	Upper limits of agreement
Straight line	-3,88077	0,91961	-5,71999	-2,04155
Left circle	-3,03007	0,72853	-4,48713	-1,57301
Right circle	-3,19444	0,78589	-4,76622	-1,62266

Bias, mean difference in centimeters (cm) between the IMU calculated and the OMC; precision, s.d. of the mean difference between the IMU and the OMC. Bias and precision are deemed better if closer to zero.

a) b)

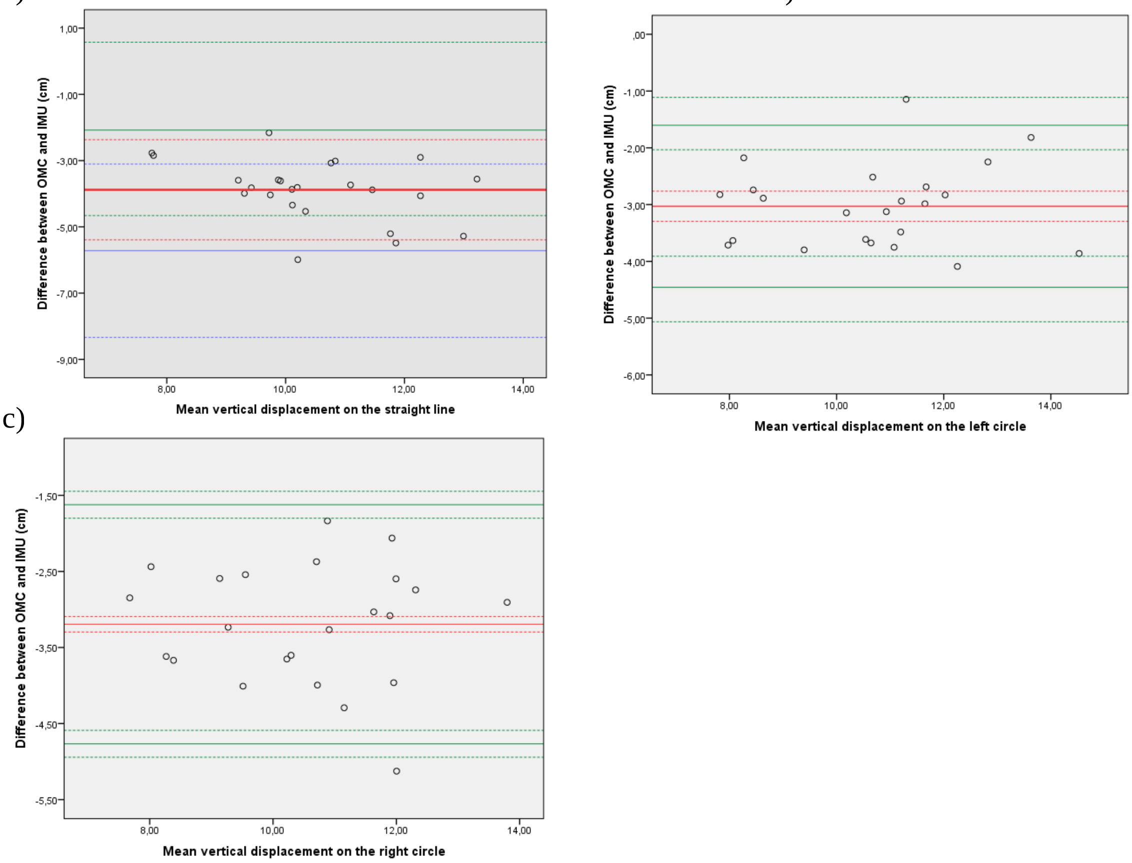


Figure 2 - Bland-Altman plots of vertical displacement on a) the straight line, b) the left circle and c) the right circle, with bias (solid red line), and upper and lower limits of agreement (solid green lines) including all confidence intervals (indicated with dotted lines). If agreed perfectly, all values (dots) were to be on the null-line (not indicated in the graphs).

Discussion

In this pilot study, limits of agreement (LoAs) for a temporal (stride duration) and kinematic parameter (vertical displacement) were calculated between a single body IMU based analysis system and data collected with optical motion capture (OMC).

Equine gait analysis mostly focusses on head nod [16] or hip hike [17] for detecting lameness, and research concerning IMUs is most often focused on these anatomical places too. Experiments with a consumer grade smartphone mounted the IMU on the sacrum to detect asymmetery [10]. Only a few studies have focused on an IMU mounted on the sternum.

Small biases of stride duration were found between the IMU and OMC, which could be due to a difference in the manor of calculating this value. Also, resolution of the systems differs, the IMU has a resolution of 60 Hertz, while the optical motion capture has a resolution of 200 Hertz. The difference in sampling frequency has influence on the results and would make it hard to have a perfect agreement between the systems. The results found in this study are within the expected resolution- “error” between the systems.

When examining the results found for vertical displacement, an obvious influence of trotting on the circle is found. A systematic bias to vertical displacement of sound horses trotting on the circle has been proven before [18]. An explanation for this difference in bias between straight line and circle is the lean angle a horse has to make to be able to trot on the circle [19]. Since the IMU bases its calculations on gravity, vertical displacement is lower when trotting on the circle.

A source of possible mismatch between the systems is not having the software synchronized. To resolve this problem, no stride to stride basis was used for calculations, but trial to trial basis. The influence of exact time synchronization when comparing between different inertial sensor systems should be further investigated. Stride to stride based calculations could give narrower limits of agreement between the systems.

A bias was determined in the results, and by plotting OMC and IMU data it could be defined that the IMU has a continuous small underestimation of stride duration and a moderate underestimation of vertical displacement (see Appendix VI for the plots).

Conclusions

The single body inertial measurement unit can be used to quantify temporal and kinematic parameters at trot. However, precision of the kinematic parameter vertical displacement may not be sufficient yet to detect all possible lameness-related changes. The data seem promising enough to warrant further research to evaluate whether this IMU is useful for consumer uses.

Recommendations for further research would be synchronizing algorithms to be able to make a stride to stride comparison of the data. This may result in better set LoAs and smaller bias. A larger sample size will also give a better estimation of the limits of agreement.

Acknowledgements

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Manufacturers’ addresses

[a] Equisense, Lille, France.

[b] Qualysis AB, Motion Capture Systems, Göteborg, Sweden.

[c] IBM Corporation, New York, USA.

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Two YouTube films were used in the Bland Altman plotting and calculations:

- "How to use SPSS-Bland-Altman plot" by TheRMUoHP Biostatistics Resource Channel
    - https://www.youtube.com/watch?v=vo7oQ_8OOhk
- "Constructing a Bland-Altman Plot in SPSS" by Todd Grande
    - https://www.youtube.com/watch?v=9w7zfnrBSEk

Appendix I: amount of data per horse

Horse	**System and trial**					
	S_H_T		**L_H_T**		**R_H_T**	
	QHorse	**Equisense**	**QHorse**	**Equisense**	**QHorse**	**Equisense**
GOO	15	6	16	13	31	17
GUC	18	5	37	12	X	16
H.	14	6	20	21	20	13
HAR	18	5	12	10	24	15
HEE	15	5	25	10	26	12
HIG	9	5	23	8	32	6
HOC	18	6	26	12	29	12
HUR	16	6	29	15	27	11
IAM	8	6	25	19	26	12
IBR	7	6	X	9	50	12
INI	14	5	27	14	23	15
ISA	13	6	19	13	33	12
AMA	20	5	43	15	36	14
AXI	18	5	28	18	50	20
BRI	19	6	21	11	34	13
COL	19	7	30	12	32	14
CUZ	19	6	31	13	50	21
DIA	14	3	33	13	39	14
EMM	16	5	33	12	37	17
FAL	19	6	32	18	33	16
NAN	18	5	30	15	31	14
RIN	17	7	23	8	25	9
WIL	20	5	37	15	25	10
WON	18	4	49	21	45	17

As data from trial R_H_T of horse GUC and trial L_H_T of horse IBR went missing, these horses were left out of further calculations for these trials.

S_H_T: Straight Hard Trot
L_H_T: Left Hard Trot
R_H_T: Right Hard Trot

Appendix II: Data processing

After receiving the data, it was filtered by deleting values as follows:

- Data of which gait was measured as 0 or NaN. 0 indicates the horse was standing still, NaN indicates the systems was not able to recognize the gait the horse was going in.
- If a trial did not have a simultaneous measurement of QHorse, this data was removed and another trial was performed.
- On the straight line (trials SD_S_H_T and VD_S_H_T) the first and last value of trot before the transition to walk were removed, because it is not clear if the horse moved differently since it was preparing to go faster or slower.
- On the circle, recording was started and stopped while the horse trotted in a constant pace (visually).

Limitations of our trial design:

- Algorithms of the two systems were not encoded together. The two systems were started manually, so there is a small time difference in every trial between the recording moments. When comparing the data, no stride to stride basis was used, because there could be little differences of the moment of capturing the stride. Therefore, a trial to trial basis was used, to get an overall look on the strides of the horses.
- No speed was set, the horses trotted at their own speed. It's known that speed influences stride duration, so this has some influence on the data.

Appendix IIIa: Correlations QHorse and Equisense stride duration

Straight line_trot

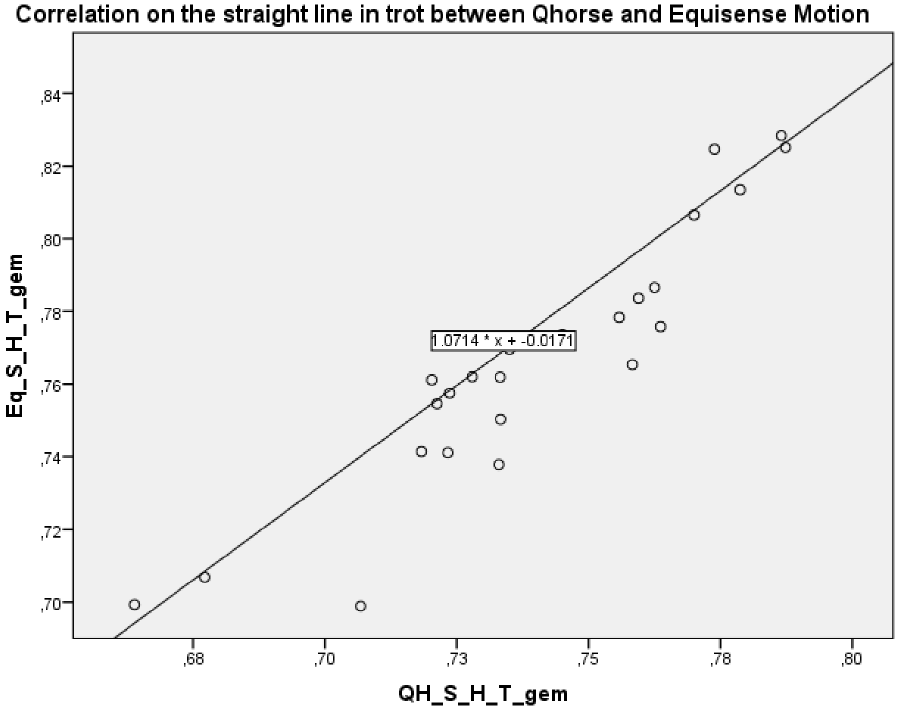
Correlations

		QH_S_H_T_gem	Eq_S_H_T_gem
QH_S_H_T_gem	Pearson Correlation	1	,934**
	Sig. (2-tailed)		,000
	N	24	24
Eq_S_H_T_gem	Pearson Correlation	,934**	1
	Sig. (2-tailed)	,000	
	N	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

Pearsons correlation – Qhorse and Equisense are highly correlated: 0,934.

Scatterplot: use Eq as dependent variable, and QH as independent (assuming it is the reference).



Scatterplot including reference line from equation. (1,074 * x + - 0,0171)

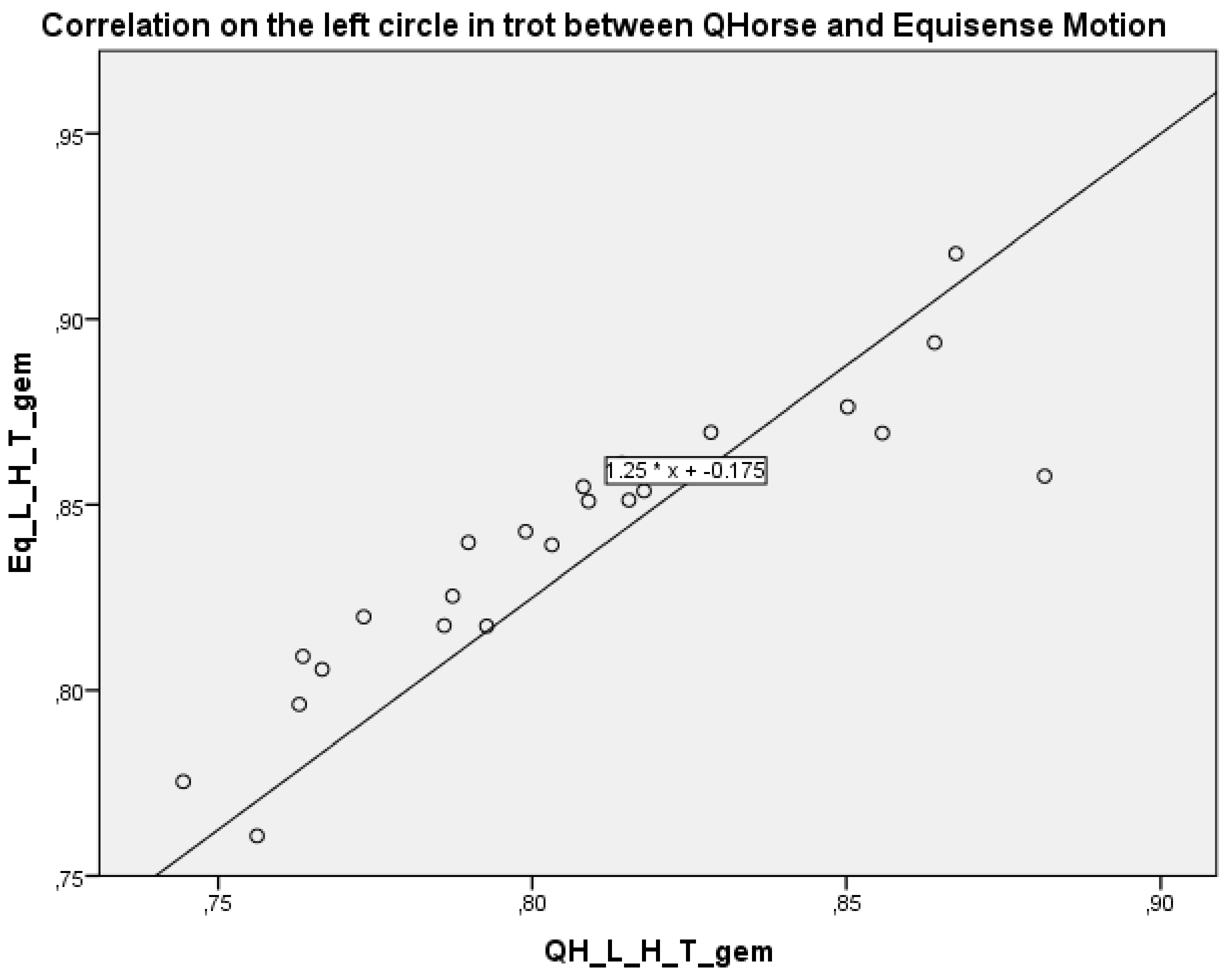
Left circle_trot

Correlations

		QH_L_H_T_gem	Eq_L_H_T_gem
QH_L_H_T_gem	Pearson Correlation	1	,900**
	Sig. (2-tailed)		,000
	N	23	23
Eq_L_H_T_gem	Pearson Correlation	,900**	1
	Sig. (2-tailed)	,000	
	N	23	23

**. Correlation is significant at the 0.01 level (2-tailed).

Pearsons correlation – Qhorse and Equisense are highly correlated: 0,900.



Right circle_trot

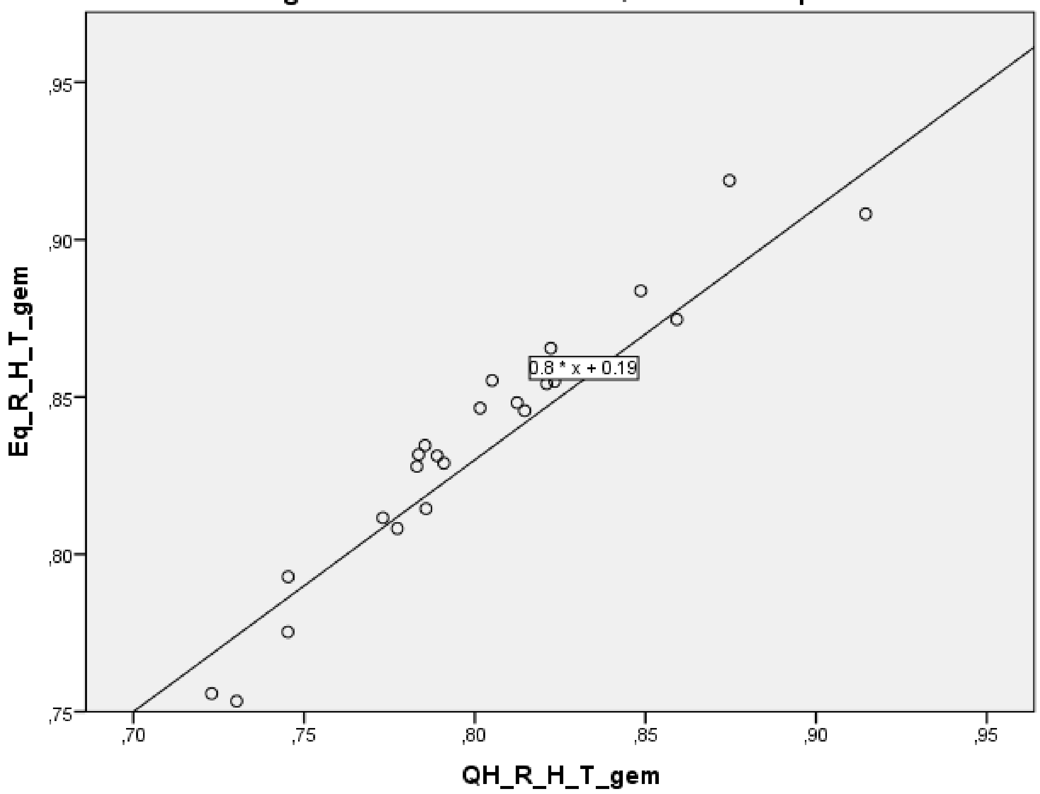
Correlations

		QH_R_H_T_gem	Eq_R_H_T_gem
QH_R_H_T_gem	Pearson Correlation	1	,961**
	Sig. (2-tailed)		,000
	N	23	23
Eq_R_H_T_gem	Pearson Correlation	,961**	1
	Sig. (2-tailed)	,000	
	N	23	23

**. Correlation is significant at the 0.01 level (2-tailed).

Pearsons correlation – Qhorse and Equisense are highly correlated: 0,961.

Correlation on the right circle in trot between QHorse and Equisense Motion



Appendix IIIb: Correlations QHorse and Equisense vertical displacement

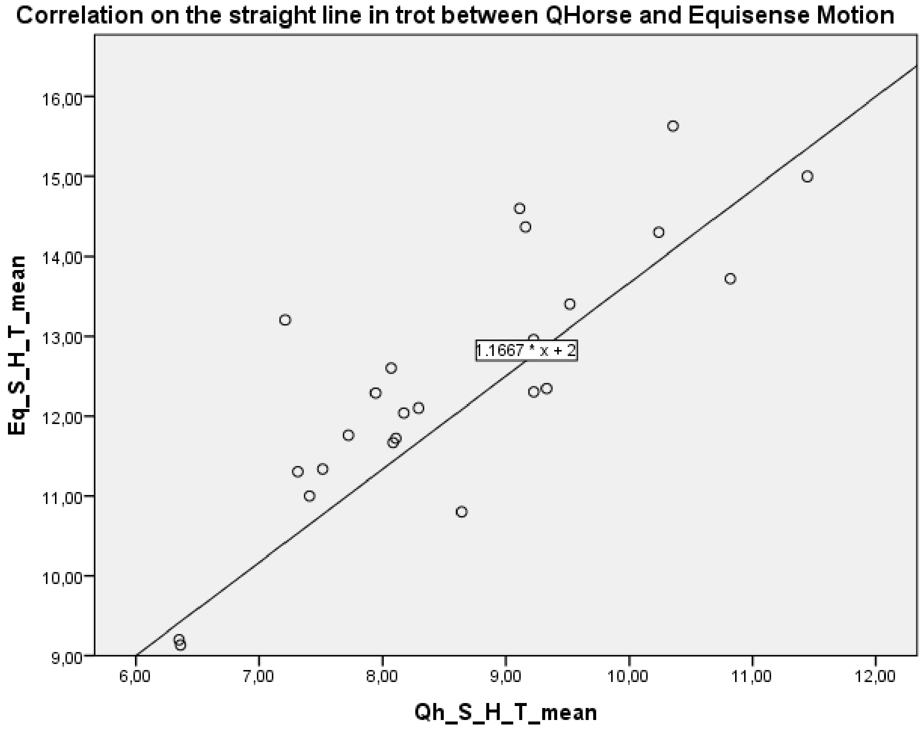
In comparing vertical displacement I used "vertical displacement" (Equisense Motion) and "Withers vertical displacement"(QHorse)

Straight line_trot

Correlations

		Qh_S_H_T_mean	Eq_S_H_T_mean
Qh_S_H_T_mean	Pearson Correlation	1	,831**
	Sig. (2-tailed)		,000
	N	24	24
Eq_S_H_T_mean	Pearson Correlation	,831**	1
	Sig. (2-tailed)	,000	
	N	24	24

**. Correlation is significant at the 0.01 level (2-tailed).

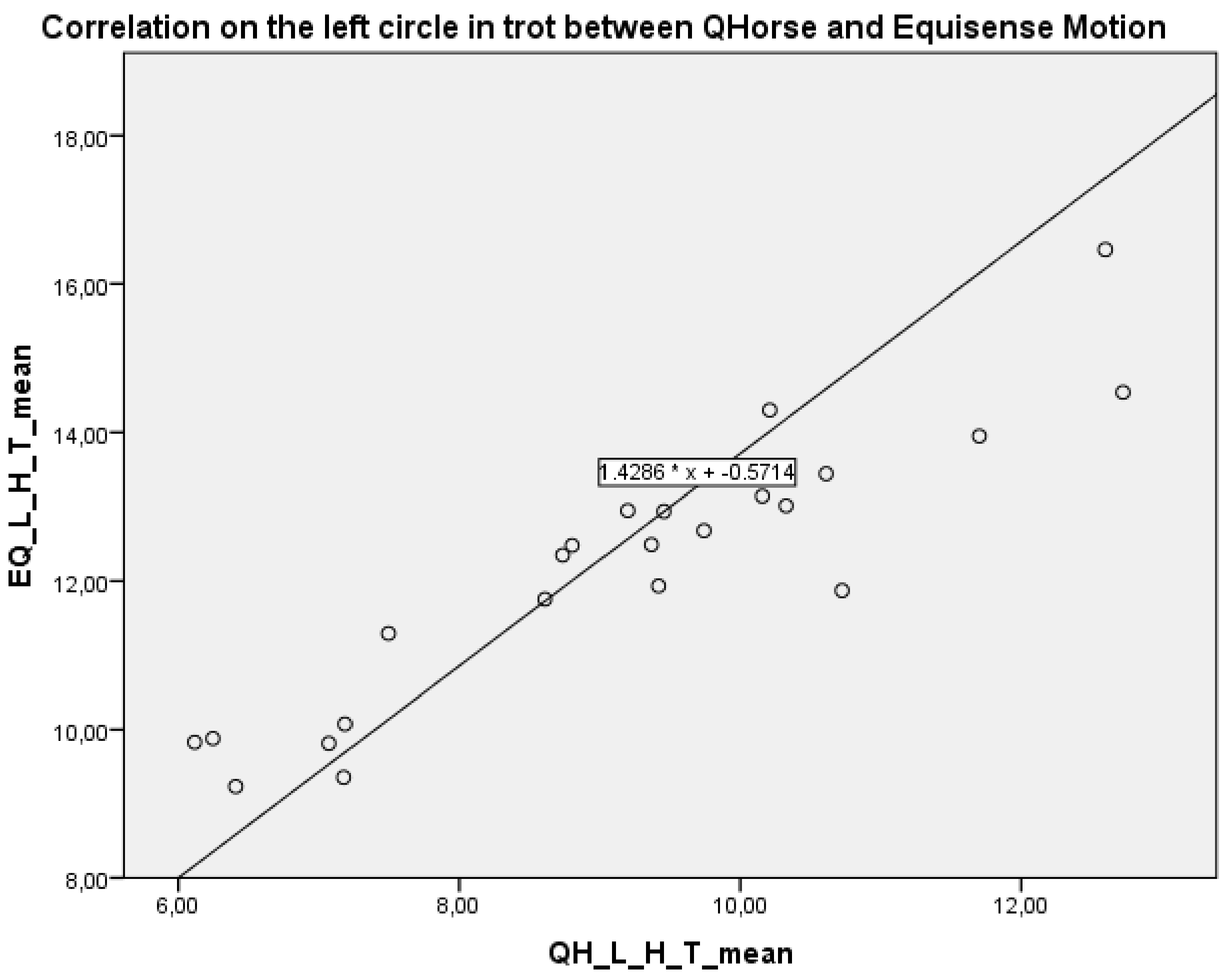


Left circle_trot

Correlations

		QH_L_H_T_mean	EQ_L_H_T_mean
QH_L_H_T_mean	Pearson Correlation	1	,925**
	Sig. (2-tailed)		,000
	N	23	23
EQ_L_H_T_mean	Pearson Correlation	,925**	1
	Sig. (2-tailed)	,000	
	N	23	23

**. Correlation is significant at the 0.01 level (2-tailed).

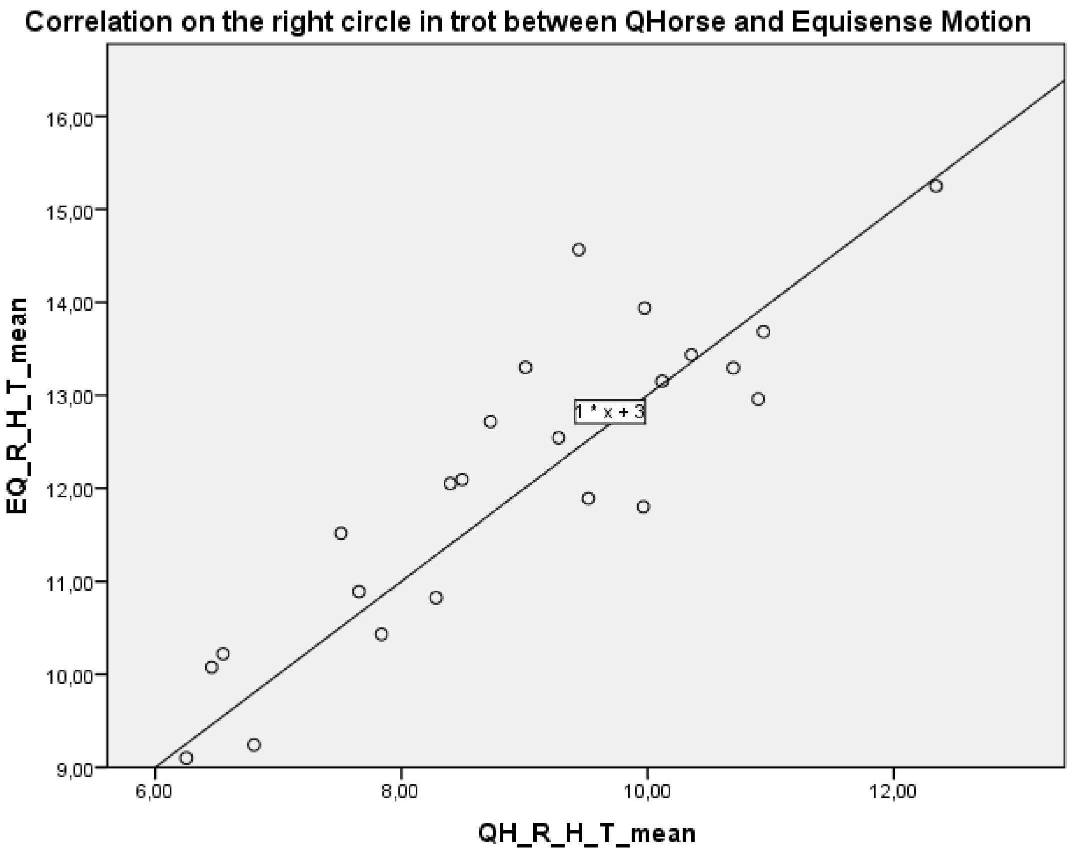


Right circle_trot

Correlations

		QH_R_H_T_mean	EQ_R_H_T_mean
QH_R_H_T_mean	Pearson Correlation	1	,885**
	Sig. (2-tailed)		,000
	N	23	23
EQ_R_H_T_mean	Pearson Correlation	,885**	1
	Sig. (2-tailed)	,000	
	N	23	23

**. Correlation is significant at the 0.01 level (2-tailed).



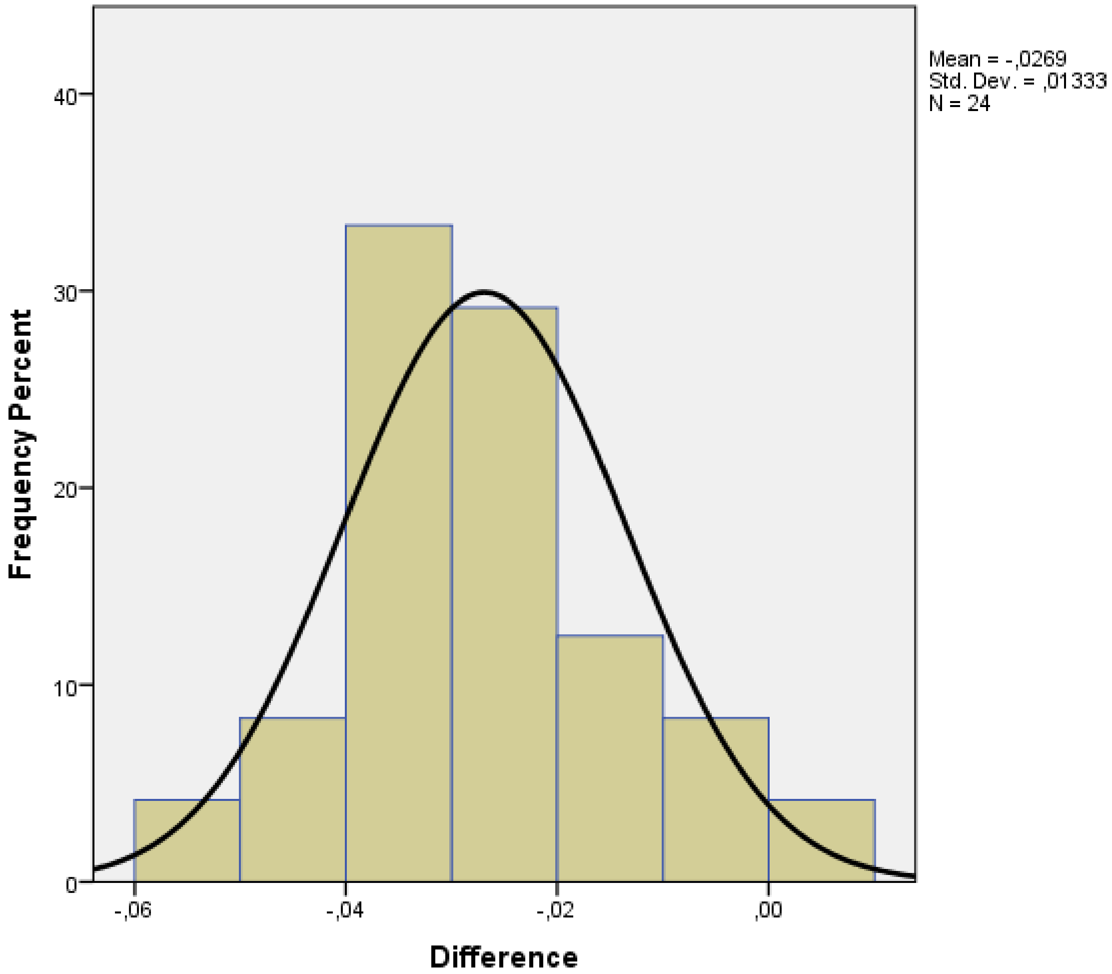
Appendix IV: Bland-Altman graphs and tables from SPSS

Approach

For every parameter the same approach was used:

- Make a histogram to see if the data is Normally distributed;
- Do a one sample T test on the differences between the systems;
- Make a Bland-Altman plot, containing the mean, upper and lower limits of agreement;
- Do a regression test to find the significance.

Stride duration on the straight line (SD_S_H_T)

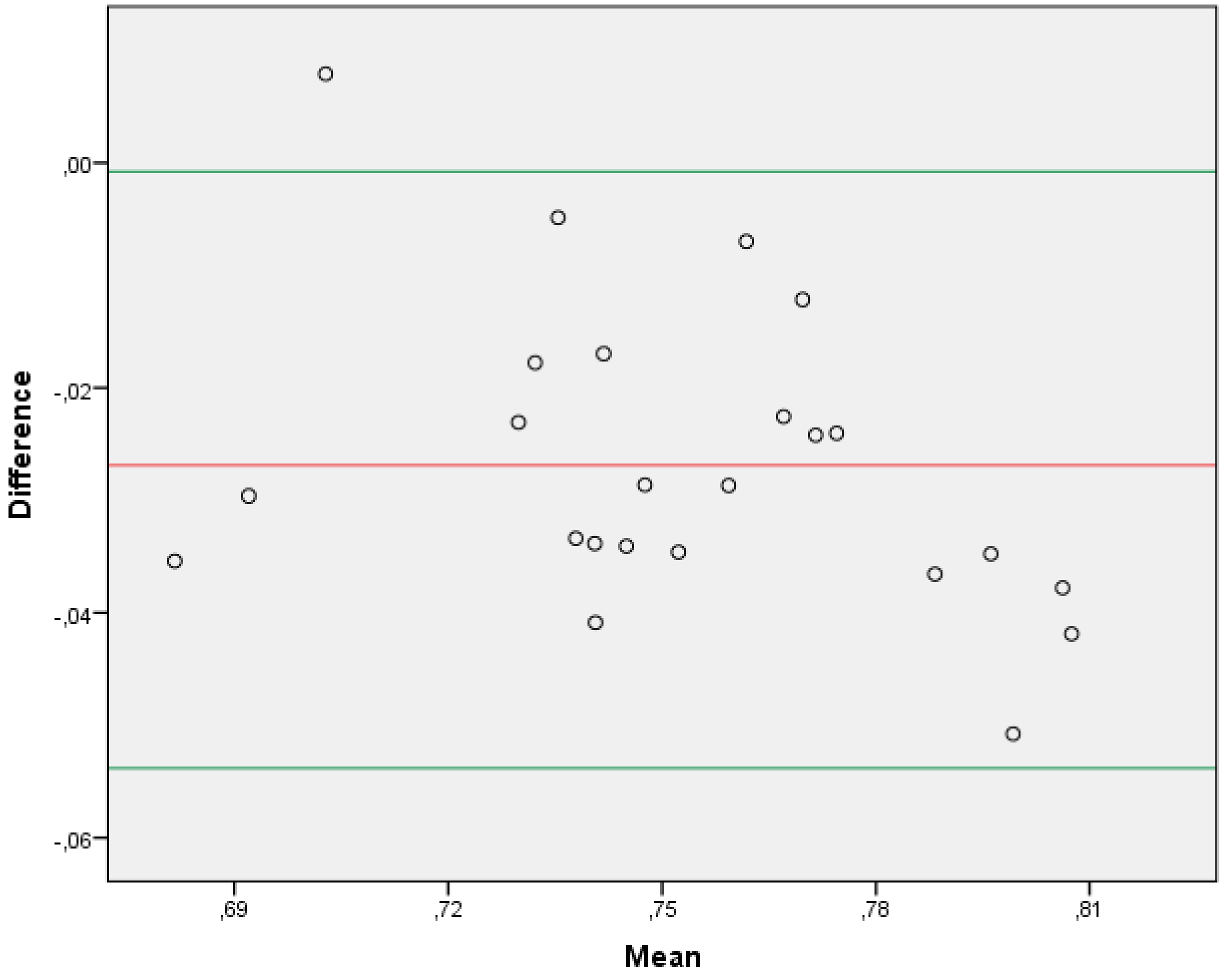


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Difference	24	-,0269	,01333	,00272

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Difference	-9,886	23	,000	-,02690	-,0325	-,0213



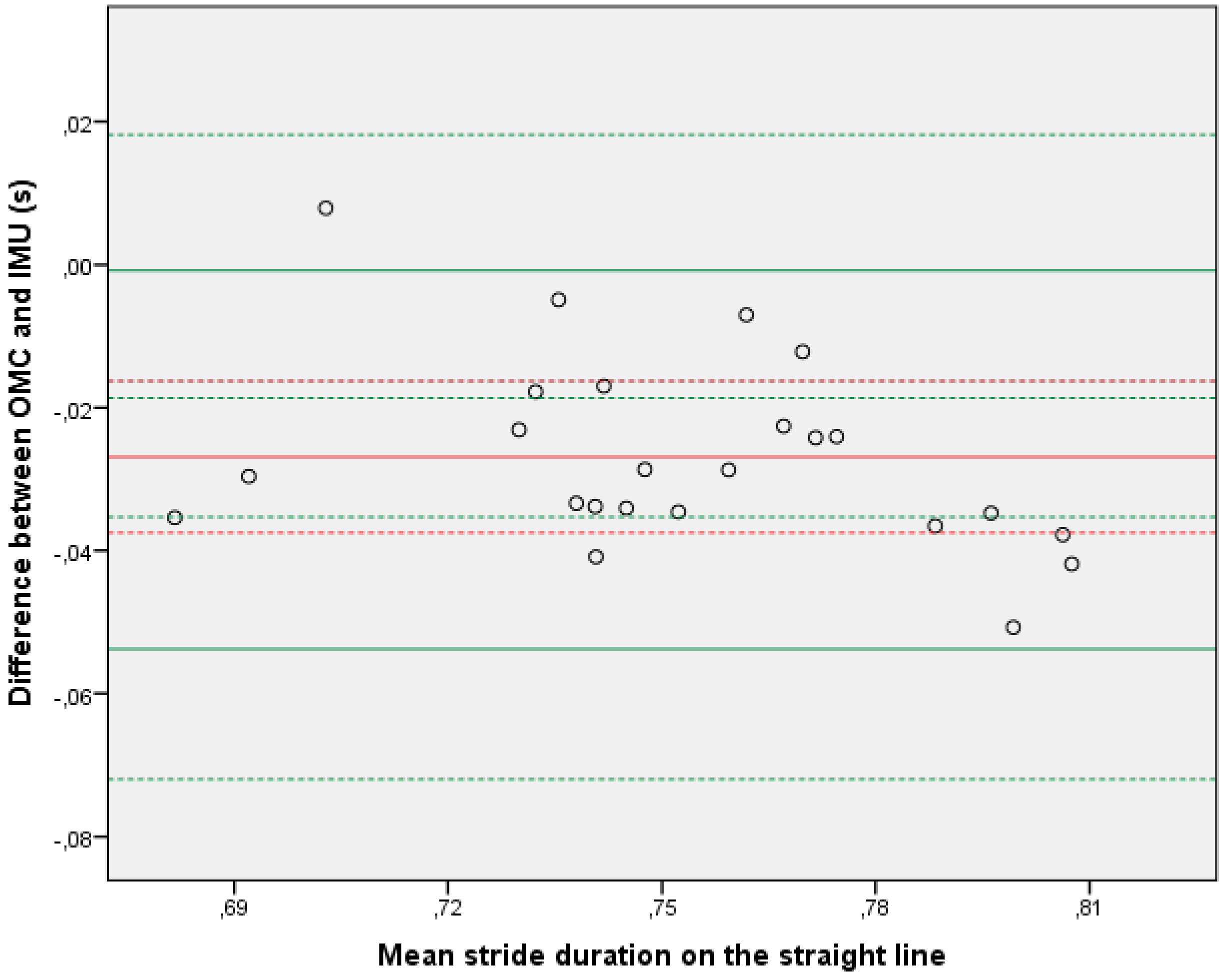
Regression

Coefficients[a]

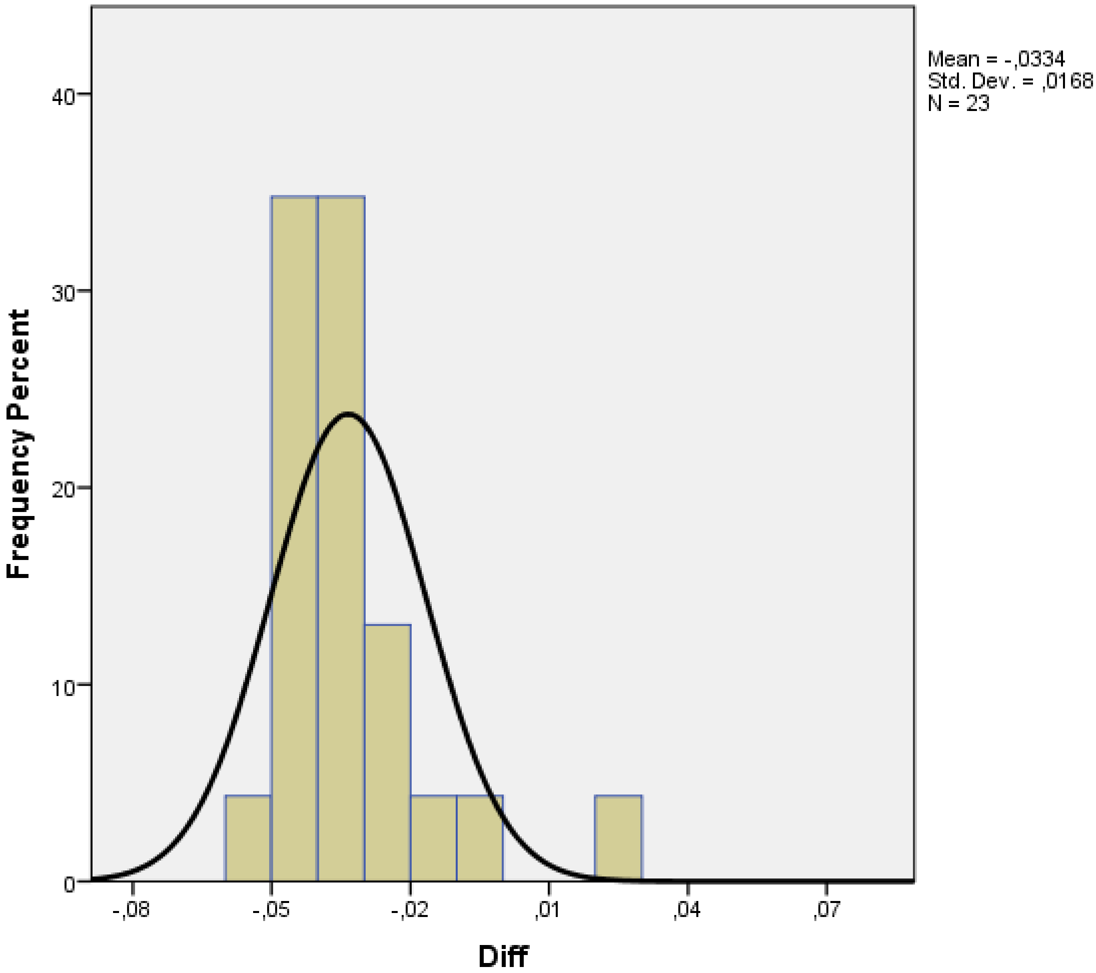
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	,087	,059		1,478	,154
	Mean	-,152	,078	-,381	-1,935	,066

a. Dependent Variable: Difference

Graph incl confidence lines



Stride duration on the left circle (SD_S_H_T)

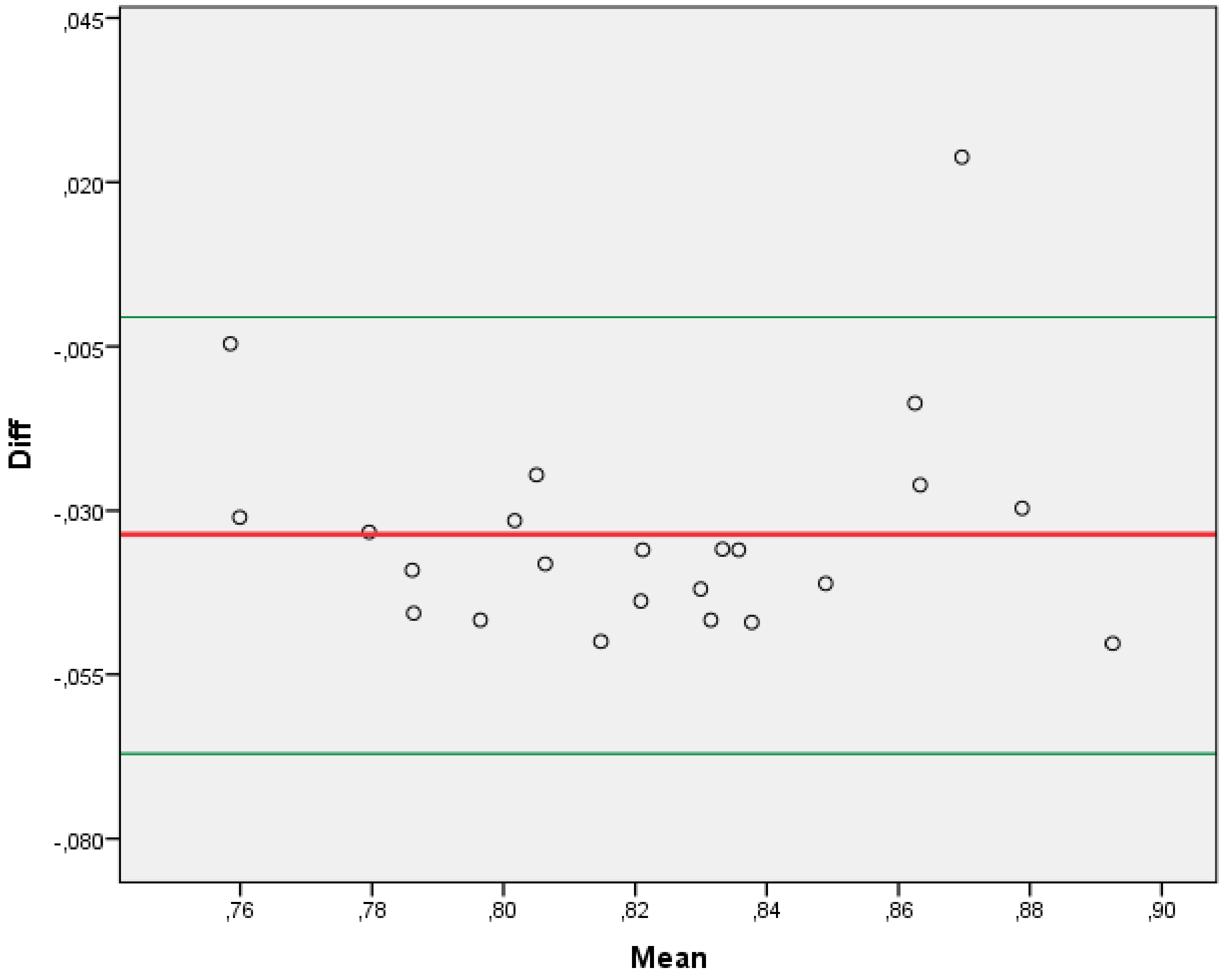


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Diff	23	-,0334	,01680	,00350

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Diff	-9,542	22	,000	-,03343	-,0407	-,0262



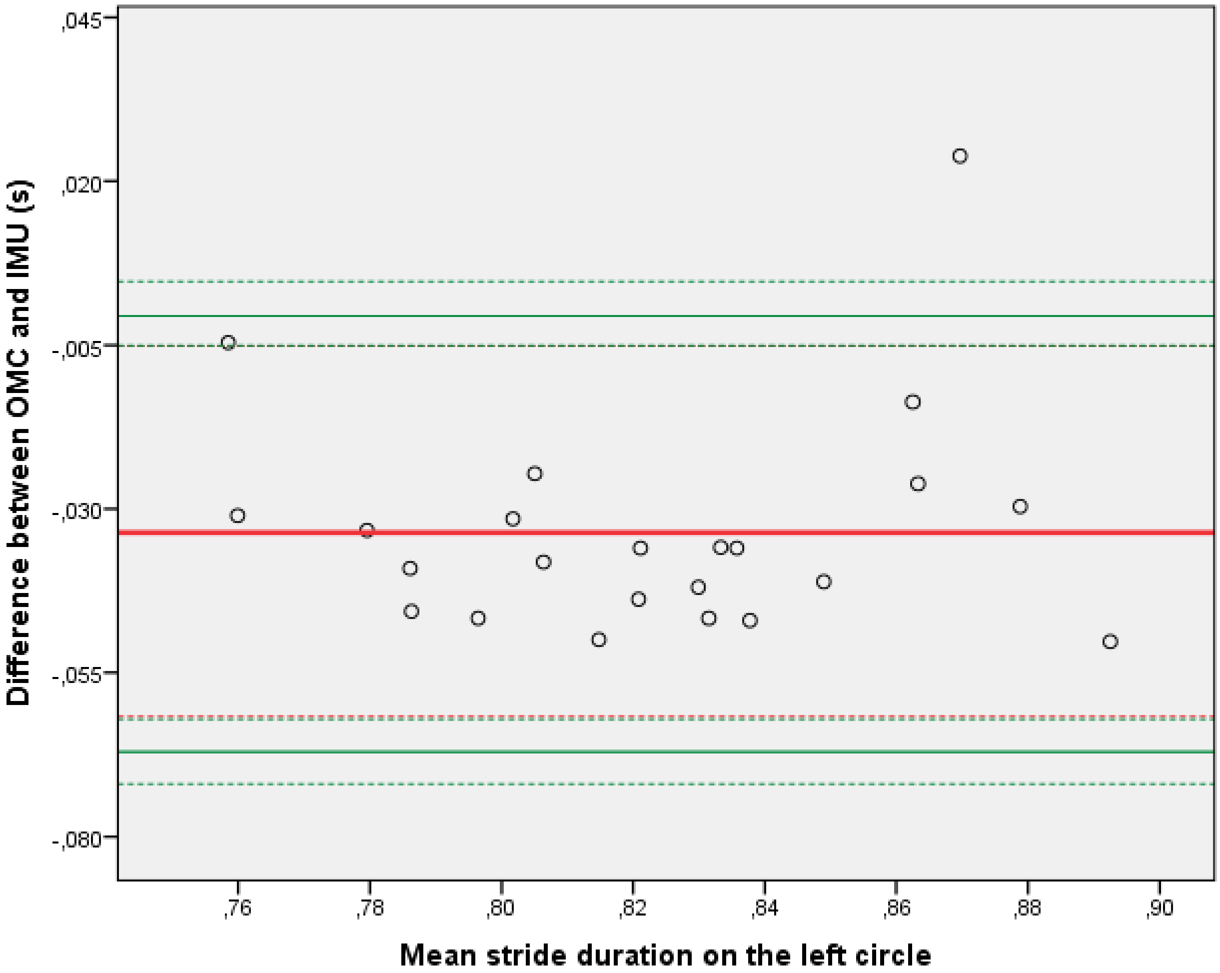
Regression

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-,067	,083		-,810	,427
	Mean	,041	,100	,088	,406	,689

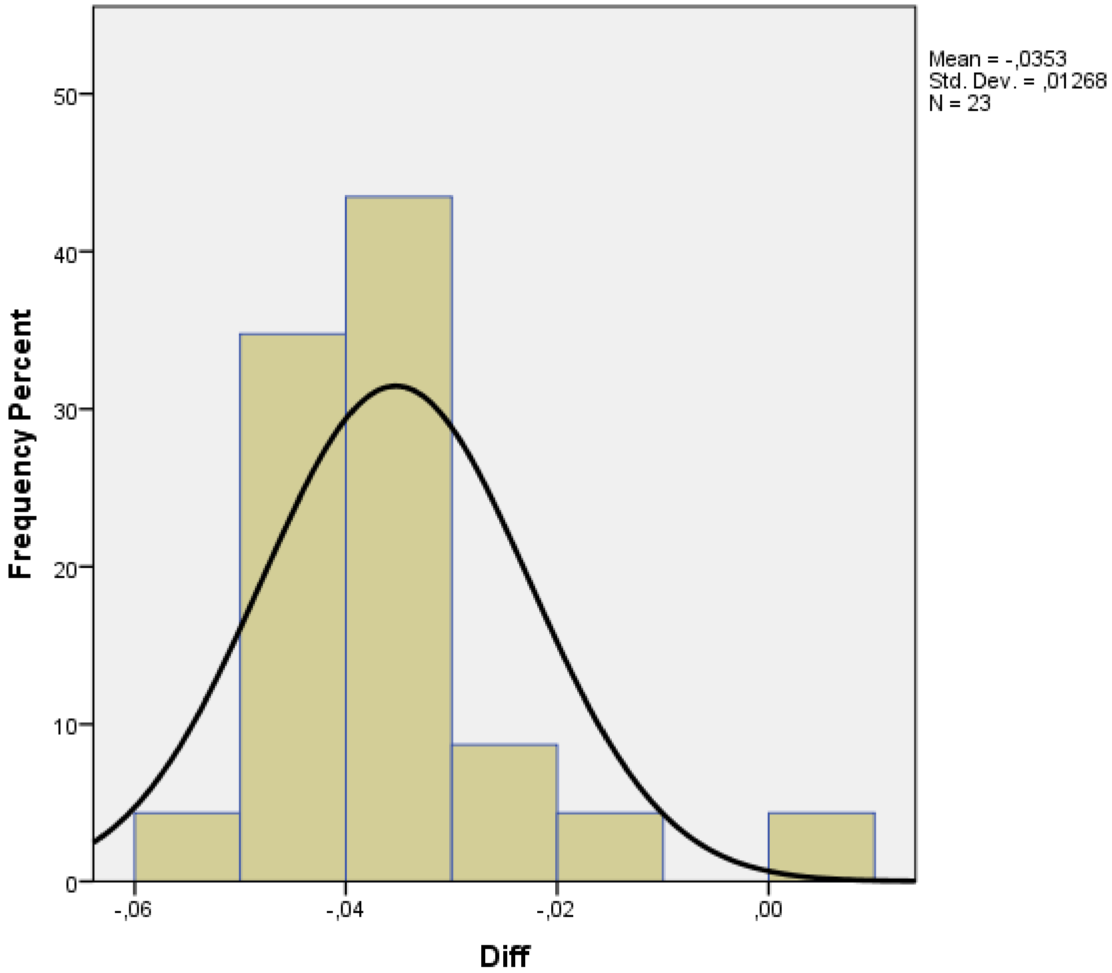
a. Dependent Variable: Diff

Graph incl confidence lines



The lower confidence line of the ULA and the upper confidence line of the mean_bias are not separate for the eye (at about -0,005).

Stride duration on the right circle (SD_R_H_T)

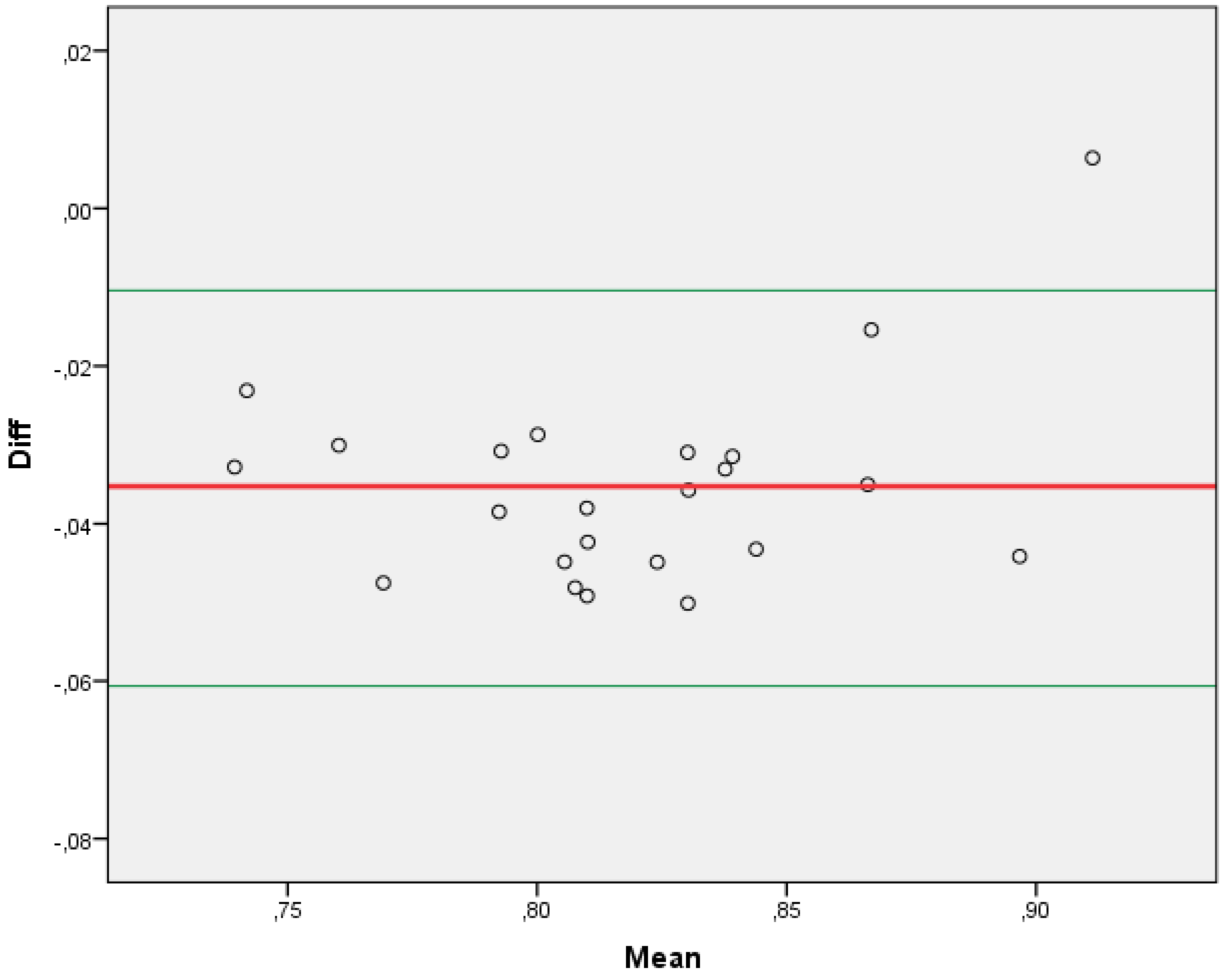


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Diff	23	-,0353	,01268	,00264

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Diff	-13,355	22	,000	-,03530	-,0408	-,0298



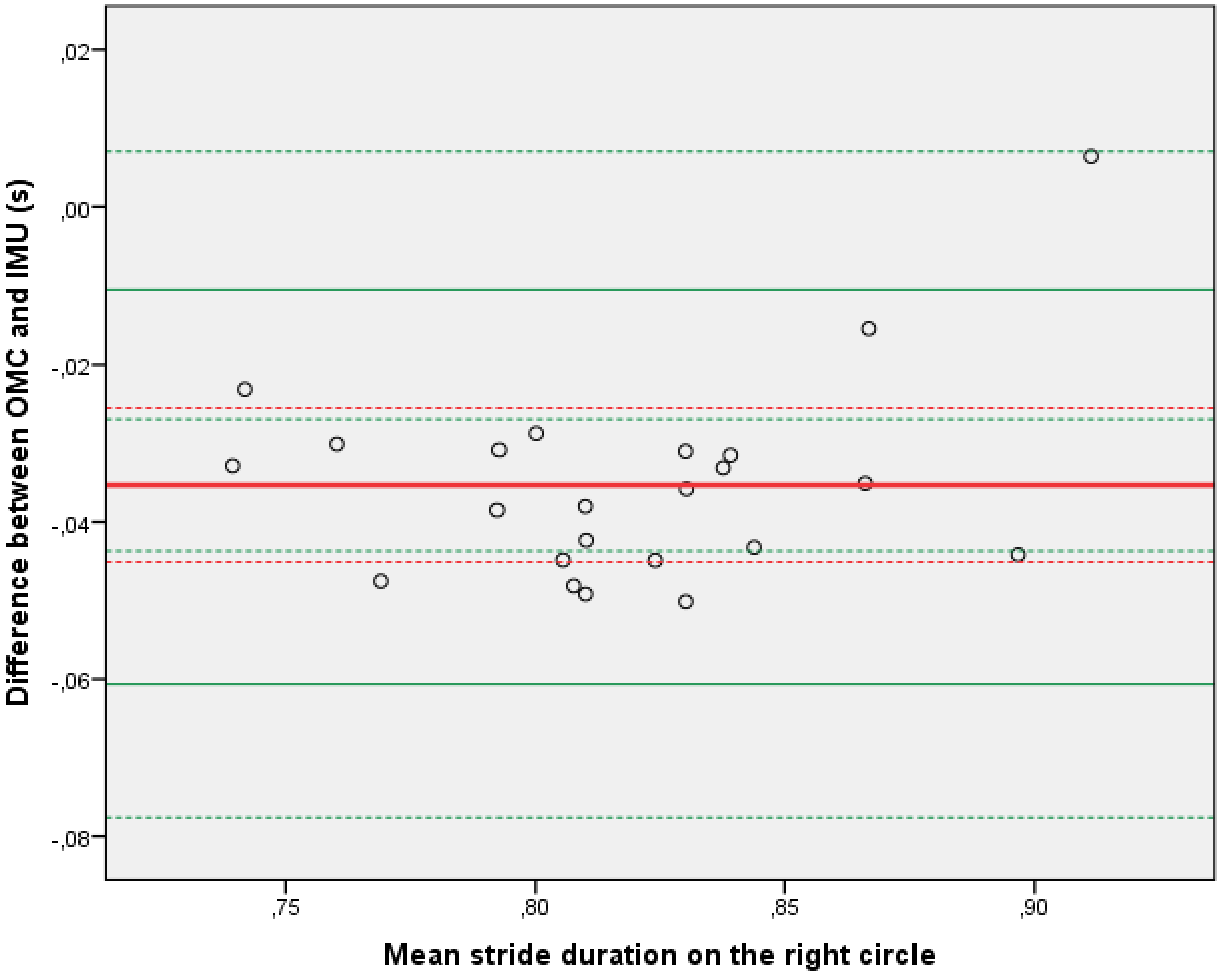
Regression

Coefficients[a]

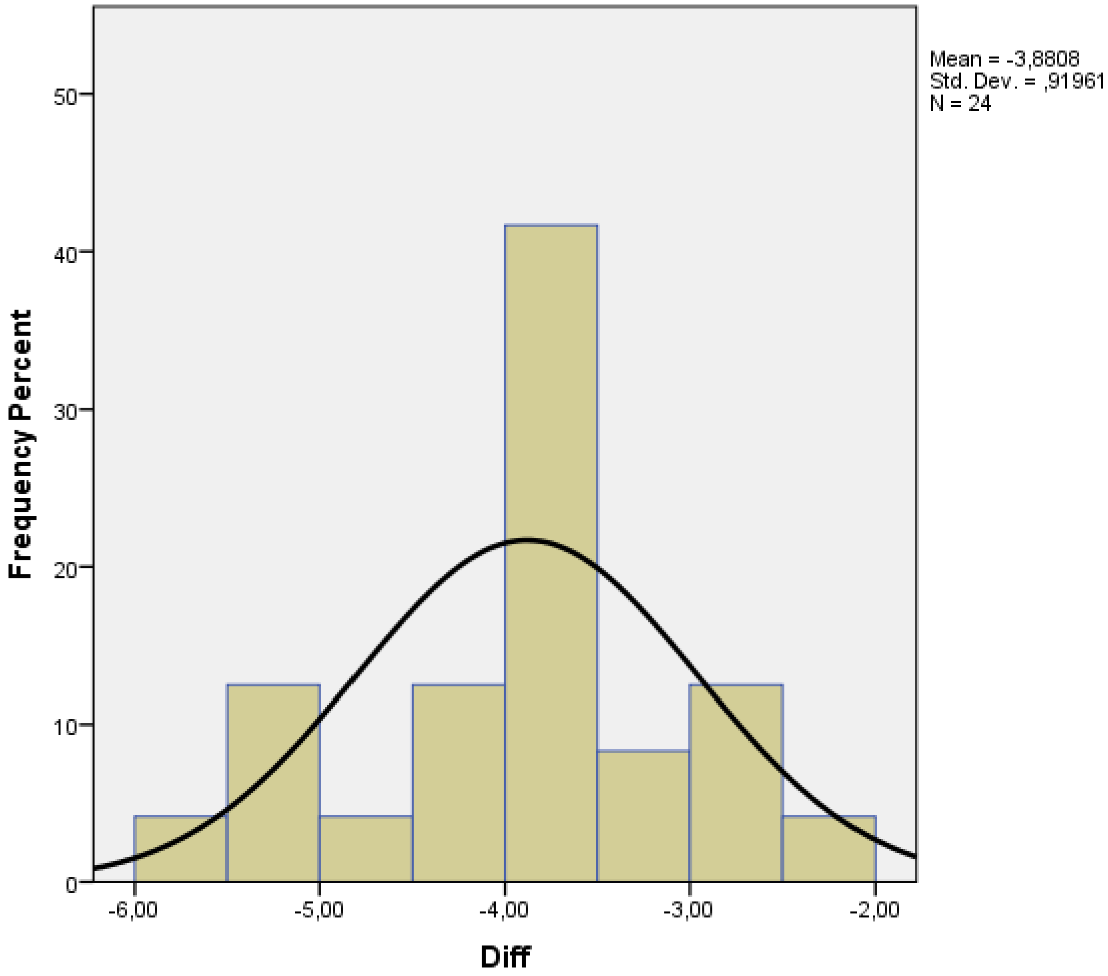
Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-,102	,050		-2,032	,055
	Mean	,082	,061	,279	1,331	,198

a. Dependent Variable: Diff

Graph incl confidence lines and titles



Vertical displacement on the straight line (VD_S_H_T)

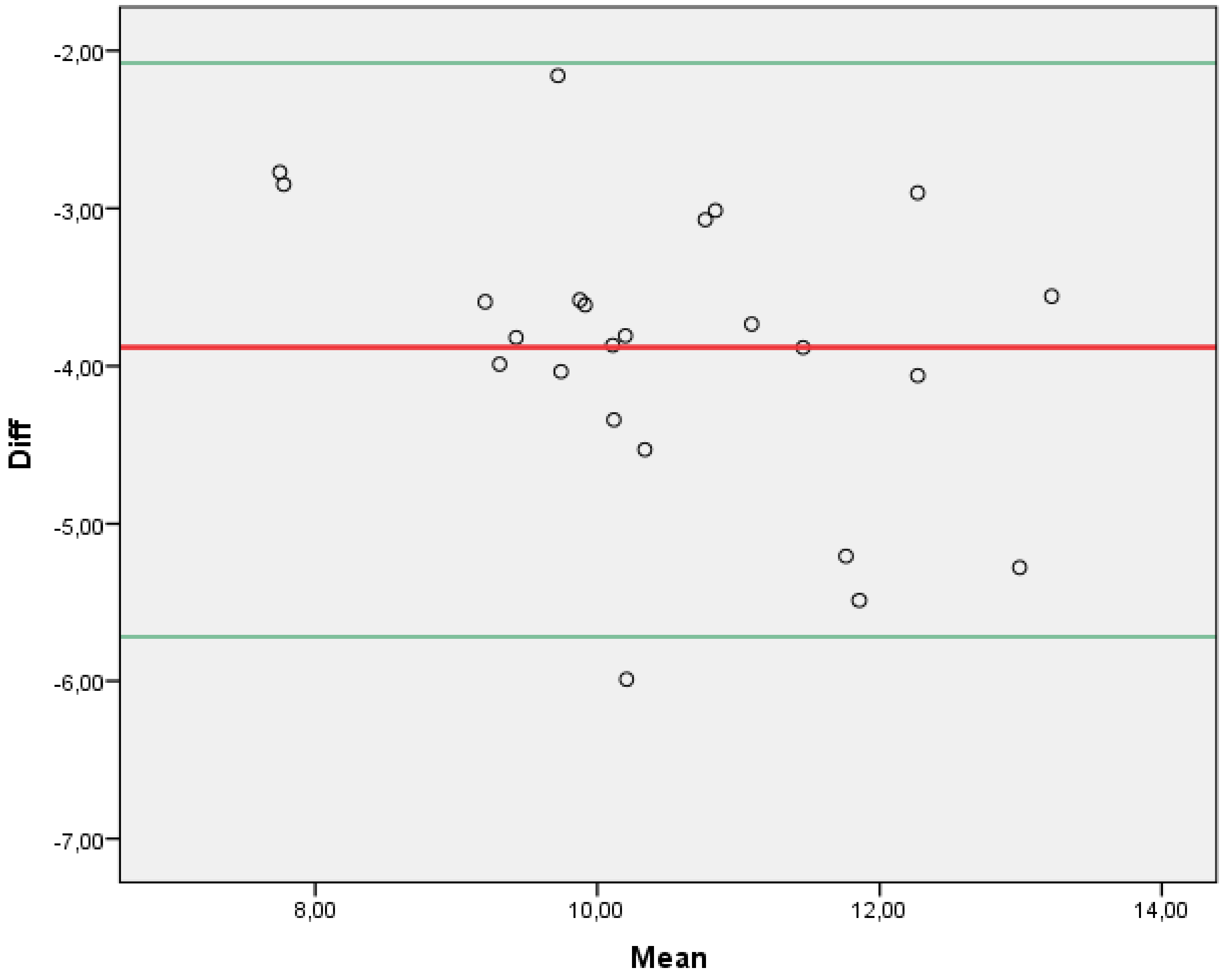


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Diff	24	-3,8808	,91961	,18772

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Diff	-20,674	23	,000	-3,88077	-4,2691	-3,4925



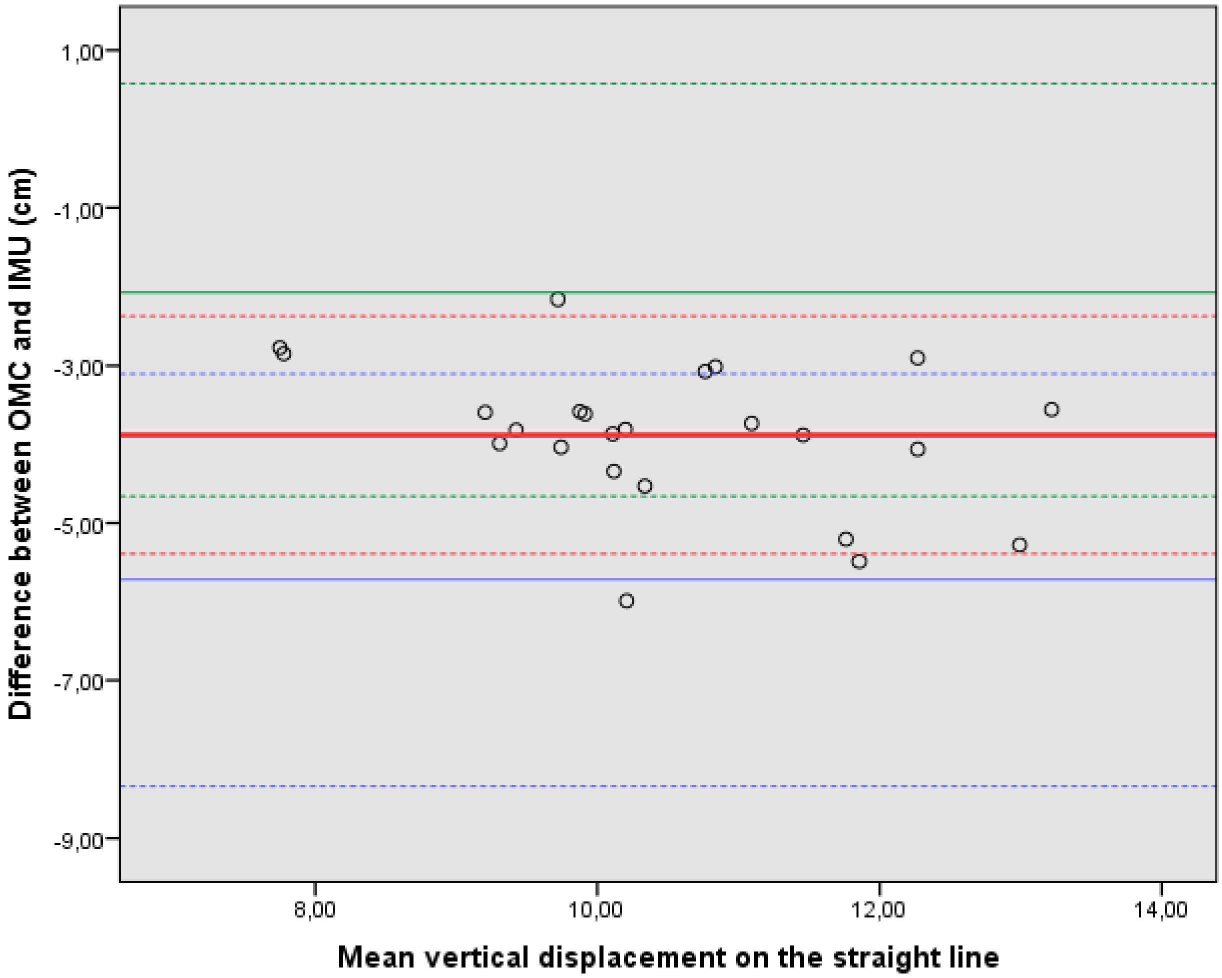
Regression

Coefficients[a]

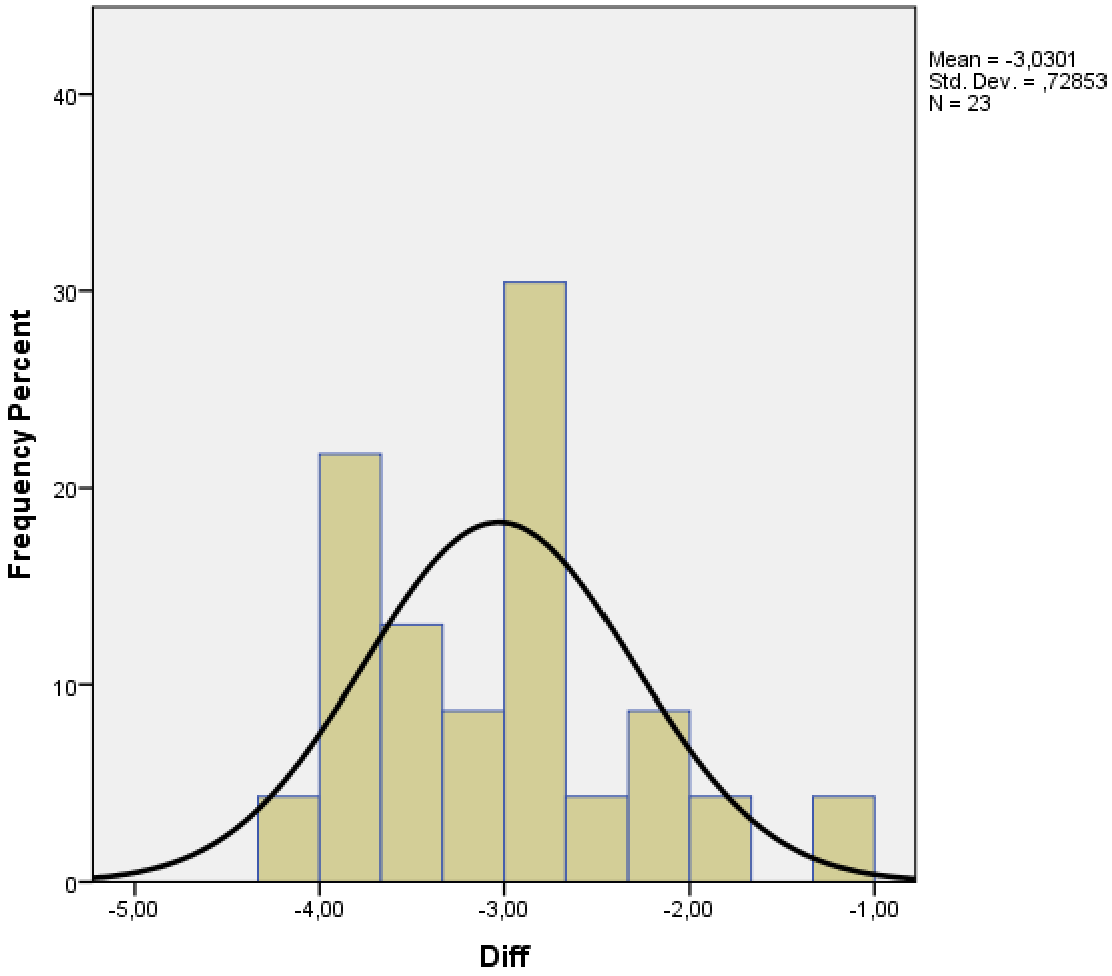
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1,319	1,354		-,974	,341
	Mean	-,244	,128	-,377	-1,908	,070

a. Dependent Variable: Diff

Graph incl confidence lines



Vertical displacement on the left circle (VD_L_H_T)

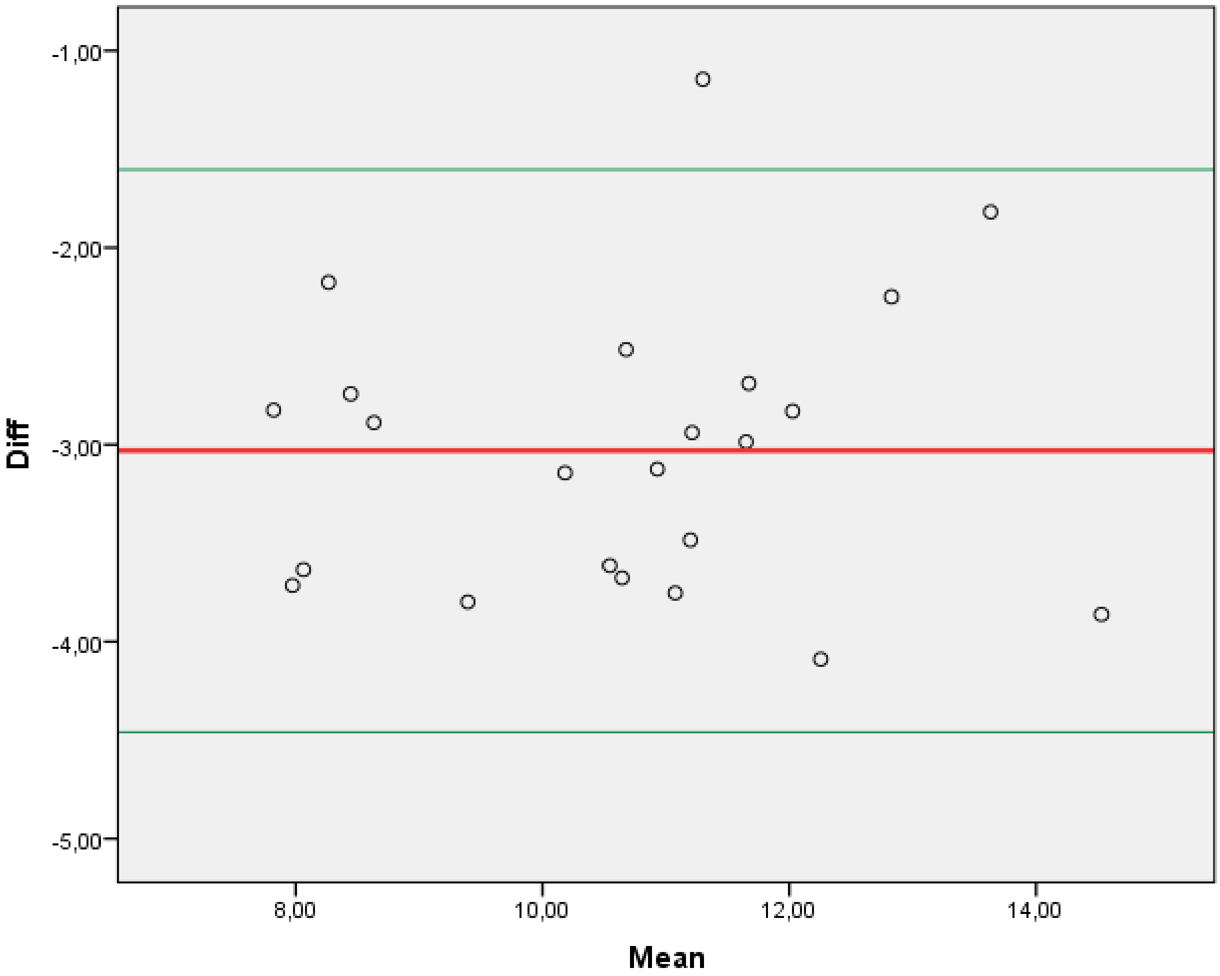


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Diff	23	-3,0301	,72853	,15191

One-Sample Test

	Test Value = 0					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
Diff	-19,947	22	,000	-3,03007	-3,3451	-2,7150



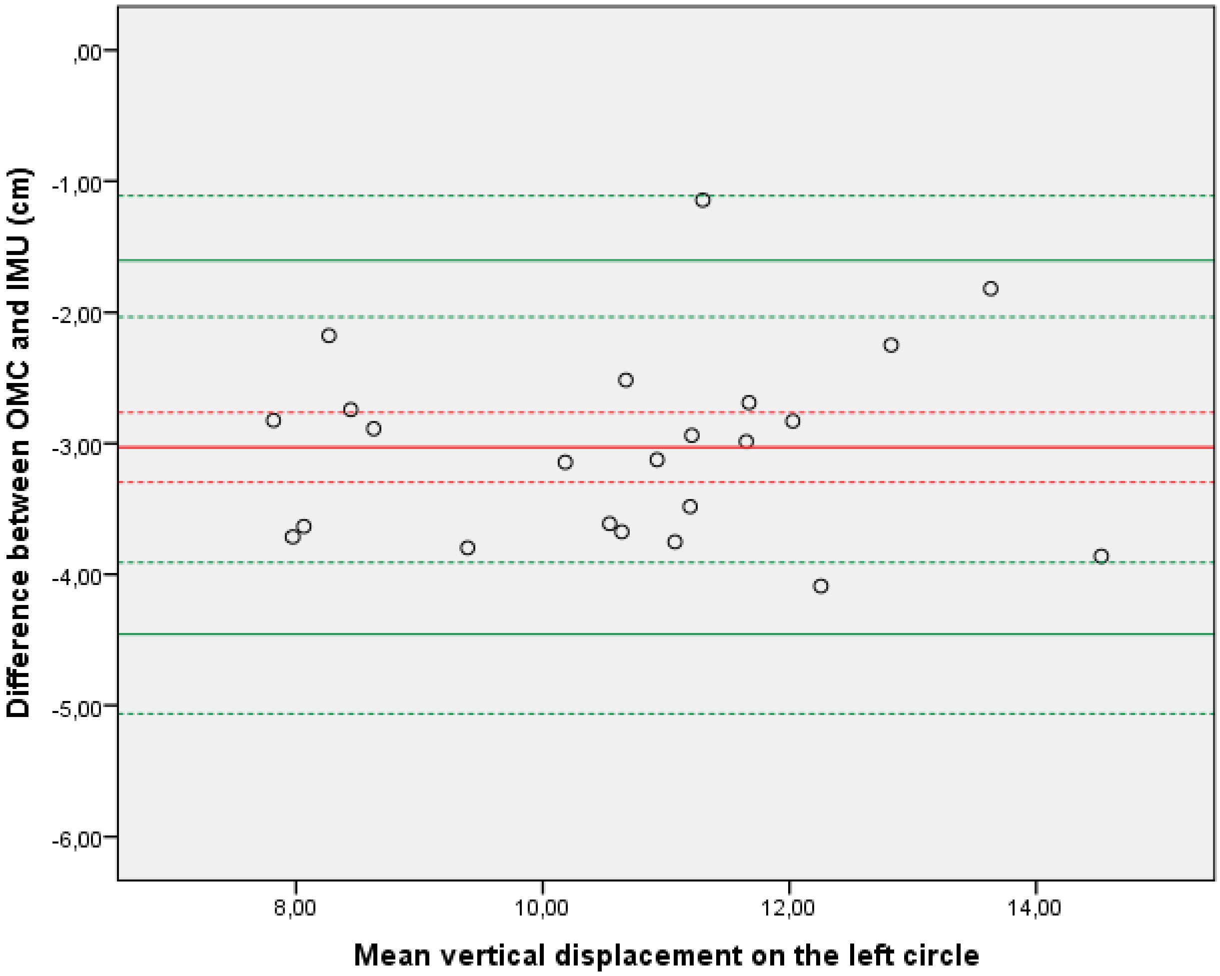
Regression

Coefficients[a]

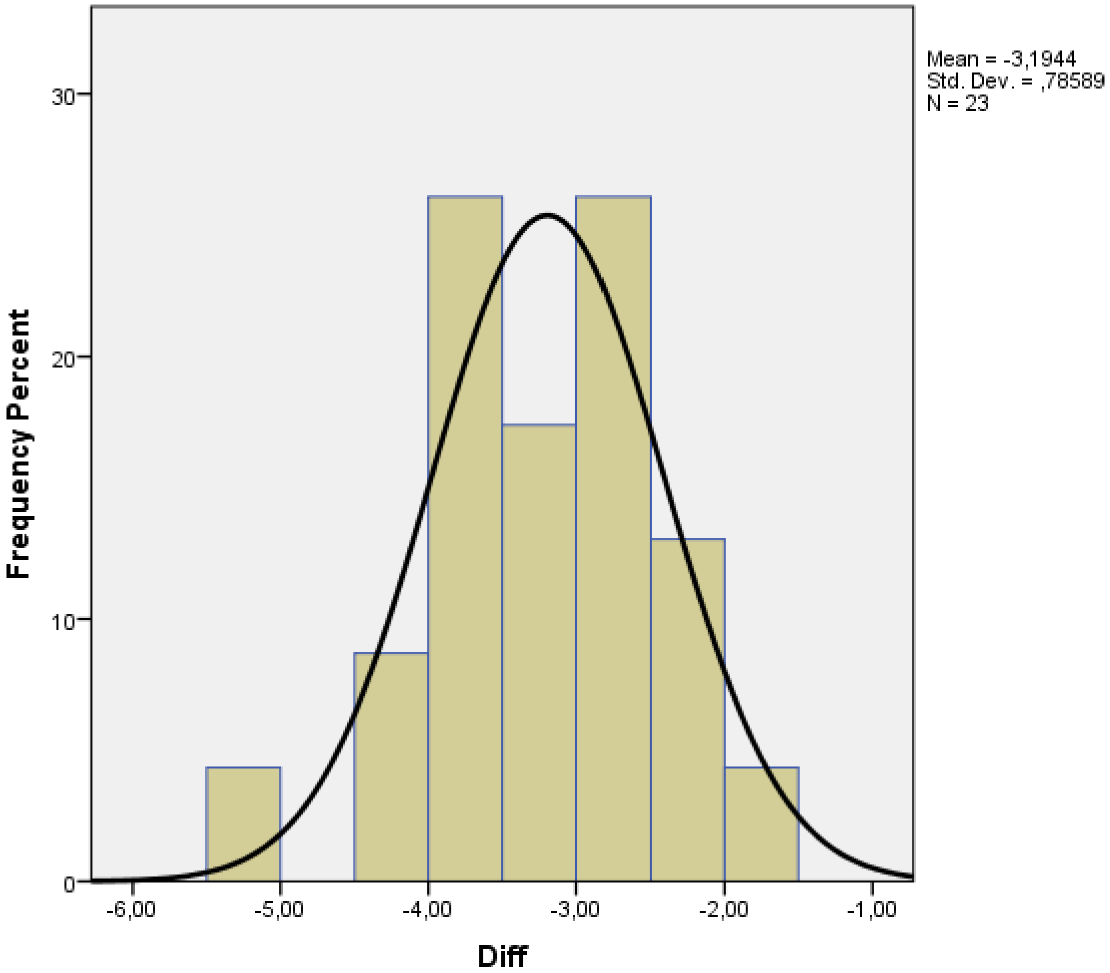
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3,415	,928		-3,681	,001
	Mean	,036	,086	,091	,421	,678

a. Dependent Variable: Diff

Graph incl confidence lines



Vertical displacement on the right circle (VD_R_H_T)

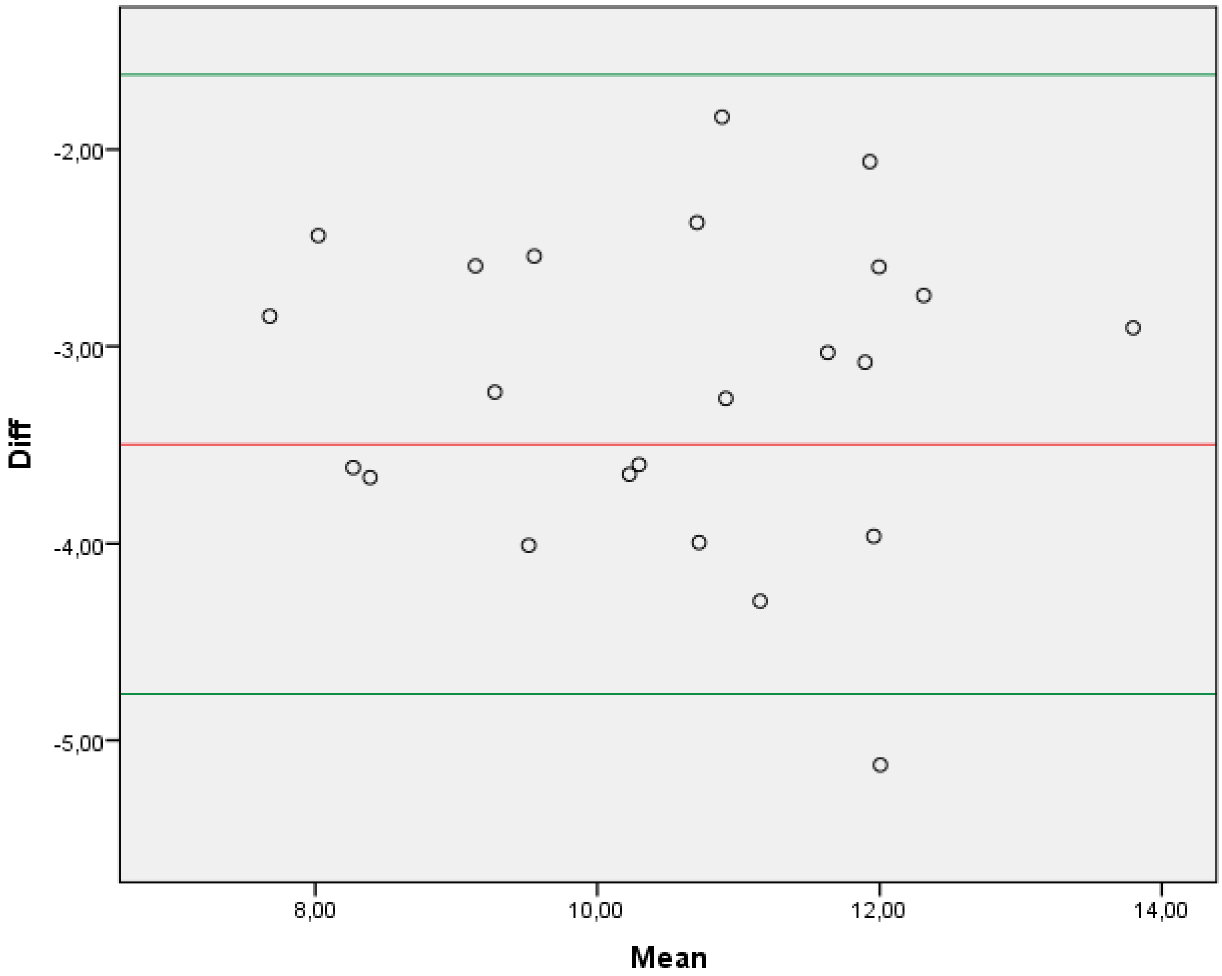


One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Diff	23	-3,1944	,78589	,16387

One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Diff	-19,494	22	,000	-3,19444	-3,5343	-2,8546



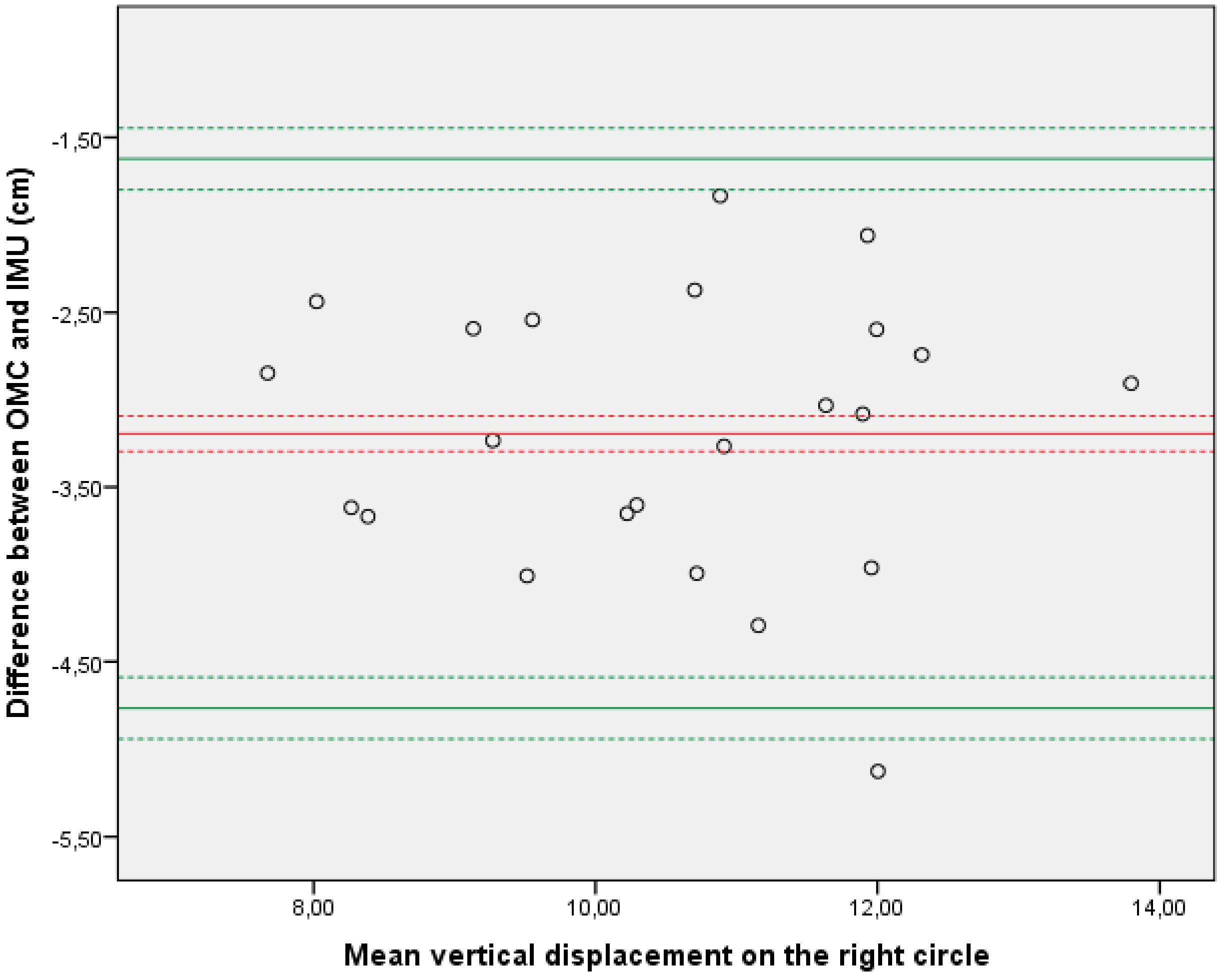
Regression

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-3,021	1,146		-2,636	,015
	Mean	-,016	,108	-,033	-,153	,880

a. Dependent Variable: Diff

Graph incl confidence lines



Appendix V: Bland-Altman calculations

Limits of Agreement (LOA)

The agreement between the two systems is estimated by calculating the bias, estimated by the mean difference (d) and the standard deviation of the differences (s).
For every trial, these factors have a different value, so we have to calculate them all. Formulas for calculating the limits of agreement (LOA) were found in the "Statistical methods for assessing agreement between two methods of clinical measurement" by J.M. Bland and D.G. Altman.

In general:

- Mean difference (d) is found by performing a "one sample T-Test" on the differences between the systems (this value is substracted from SPSS);
- Standard deviation of the differences (s) is also found by performing a "one sample T-Test" on the differences between the systems (this value is substracted from SPSS);
- The Upper Limit of Agreement (ULA) is found for every trial by the following calculation: d + 2s
- The Lower Limit of Agreement (LLA) is found for every trial by the following calculation: d – 2s

LOA stride duration (SD) (sec)				
Trial	Mean_diff (d)	SD_diff (s)	ULA	LLA
S_H_T	-0,0269	0,01333	-0,00024	-0,05356
L_H_T	-0,03343	0,01680	-0,00017	-0,06703
R_H_T	-0,0353	0,01268	-0,00994	-0,06066
LOA vertical displacement (VD) (cm)				
Trial	Mean_diff (d)	SD_diff (s)	ULA	LLA
S_H_T	-3,88077	0,91961	-2,04155	-5,71999
L_H_T	-3,03007	0,72853	-1,57301	-4,48713
R_H_T	-3,19444	0,78589	-1,62266	-4,76622

This means that 95% of the differences between the systems will lie between the described limits. The LOA are only estimates of the values which apply to the whole population.

Precision of estimated limits of agreement

The standard error of d = $\sqrt{\frac{s^2}{n}}$, where *n* is the sample size.

The standard error of d – 2s and d + 2s = $\sqrt{\frac{3s^2}{n}}$

95% confidence intervals can be calculated by finding the appropriate point of the t distribution with n – 1 degrees of freedom, on most tables the columns marked 5% or 0,05, and then the confidence interval will be from the observed value minus *t* standard errors to the observed value plus *t* standard errors.

Again, we need to calculate this for every trial.

Trial	s	SE_d	df (n-1)	t (from SPSS)
SD_S_H_T	-0,0269	0,005491	23	-1,935
SD_L_H_T	-0,03343	0,069706	22	0,406
SD_R_H_T	-0,0353	0,007361	22	1,331
VD_S_H_T	-3,88077	0,792159	23	-1,908

VD_L_H_T	-3,03007	0,631813	22	0,421
VD_R_H_T	-3,19444	0,666087	22	-0,153

The 95% confidence interval for the bias is d - (t x SE_ d) to d + (t x SE_d), giving:

Trial	95% confidence interval of the bias		
SD_S_H_T	-0,01627	to	-0,03753
SD_L_H_T	-0,06173	to	-0,00513
SD_R_H_T	-0,0451	to	-0,0255
VD_S_H_T	-2,36933	to	-5,39221
VD_L_H_T	-3,29606	to	-2,76408
VD_R_H_T	-3,09253	to	-3,29635

The 95% confidence intervals for the Limits of Agreement are: LLA or ULA +/- (t x SE_LA)
First, we calculate the standard errors of the lower and upper limit:

Trial	SE_LLA and SE_ULA
SD_S_H_T	0,009510586
SD_L_H_T	0,012073497
SD_R_H_T	0,012748862
VD_S_H_T	1,372059392
VD_L_H_T	1,094332686
VD_R_H_T	1,153696154

Next, we can fill in the formula mentioned above and find the following confidence intervals for the limits of agreement:

Trial	95% confidence interval of LLA		95% confidence interval of ULA	
SD_S_H_T	-0,03516	-0,07196	0,01816	-0,01864
SD_L_H_T	-0,07193	-0,06213	-0,00507	0,00473
SD_R_H_T	-0,07763	-0,04369	-0,02691	0,00703
VD_S_H_T	-3,10210	-8,33788	0,57634	-4,65944
VD_L_H_T	-5,06477	-3,90949	-2,03372	-1,11230
VD_R_H_T	-4,5897	-4,94274	-1,44614	-1,79918

Implementation of calculation of the bias. Formula: d – (t * SE_d) to d + (t * SE_d).

SD_S_H_T: -0,0296 – (-1,935 * 0,005491) to -0,0296 + (-1,935 * 0,005491) = -0,01629 to -0,03753

SD_L_H_T: -0,03343 – (0,406 * 0,069706) to -0,03343 + (0,406 * 0,069706)

SD_R_H_T: -0,0353 – (1,331 * 0,007361) to -0,0353 + (1,331 * 0,007361)

VD_S_H_T: -3,88077 – (-1,908 * 0,792159) to -3,88077 + (-1,908 * 0,792159)

VD_L_H_T: -3,03007 – (0,421 * 0,631813) to -3,03007 + (0,421 * 0,631813)

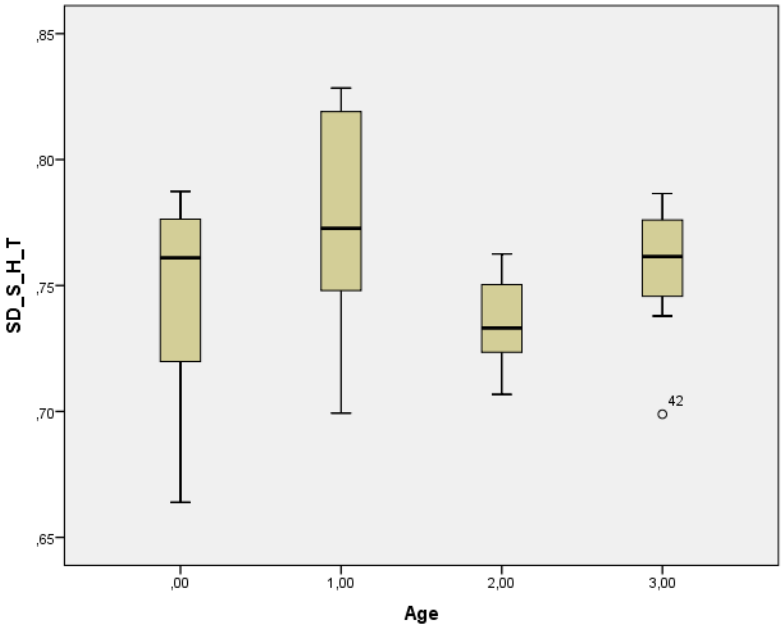
VD_R_H_T: -3,19444 – (-0,153 * 0,666087) to -3,19444 + (-0,153 * 0,666087)

Appendix VI: Equisense – Qhorse plots

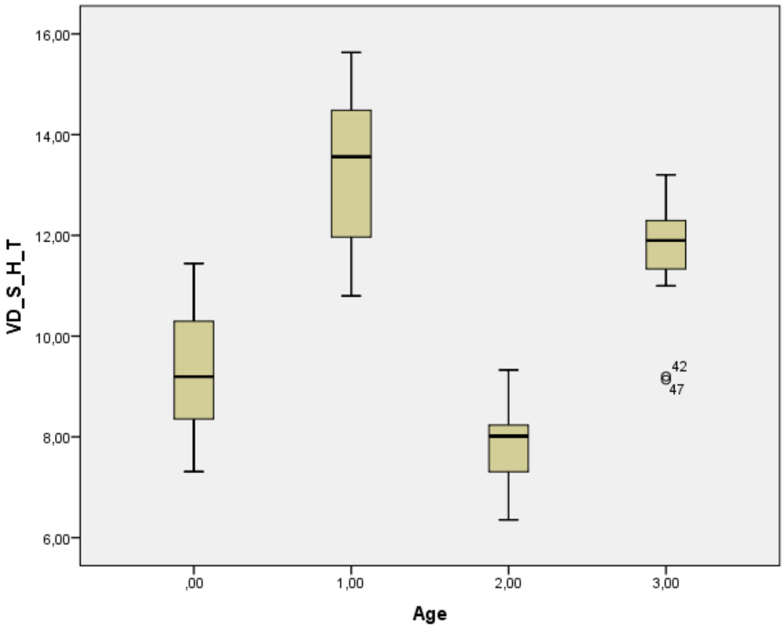
0 = Qh young
1 = Eq young
2 = Qh old
3 = Eq old

Straight line

Stride duration

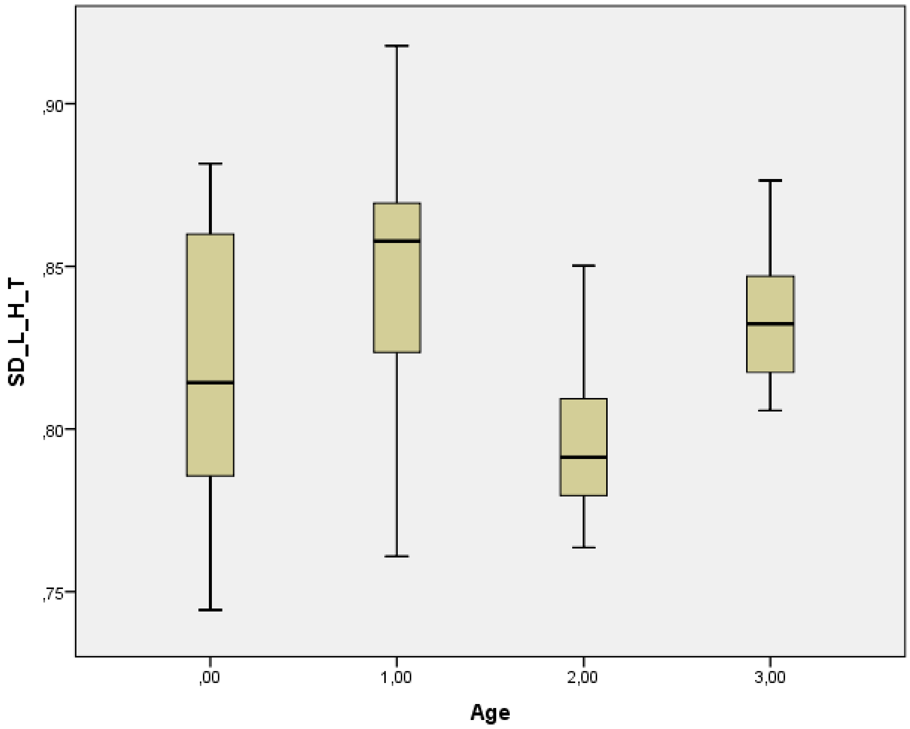


Vertical displacement



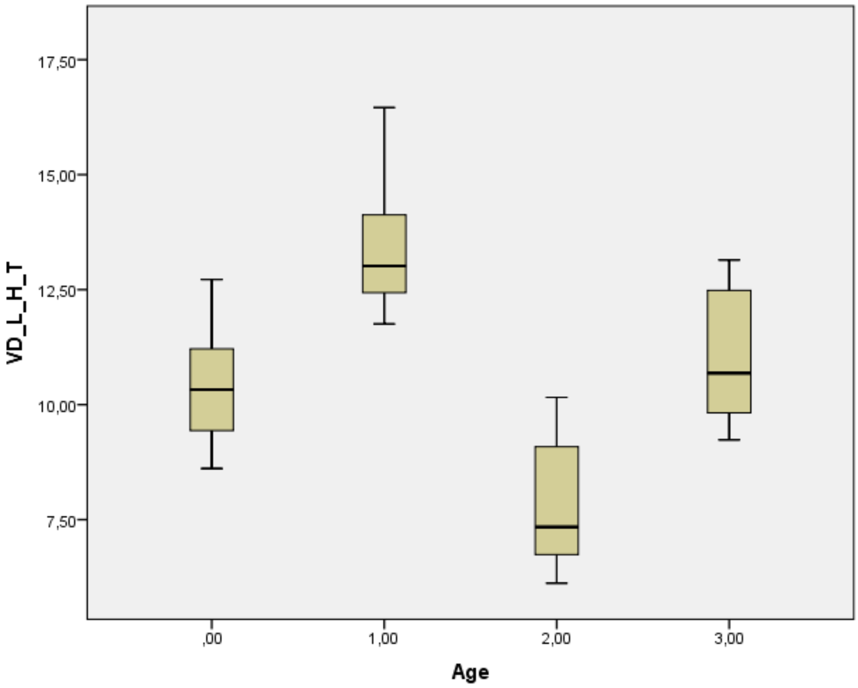
Left circle

Stride duration



0 = Qh young
1 = Eq young
2 = Qh old
3 = Eq old

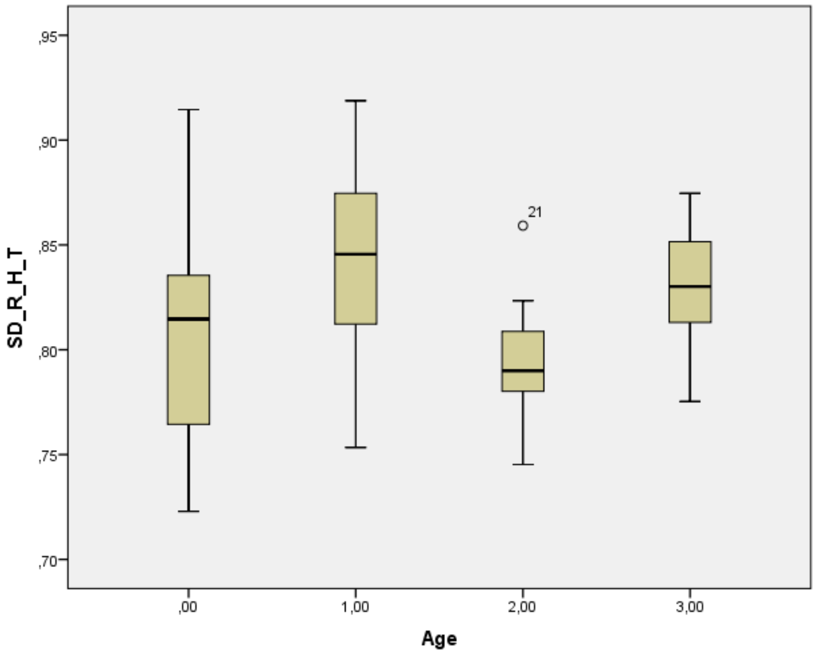
Vertical displacement



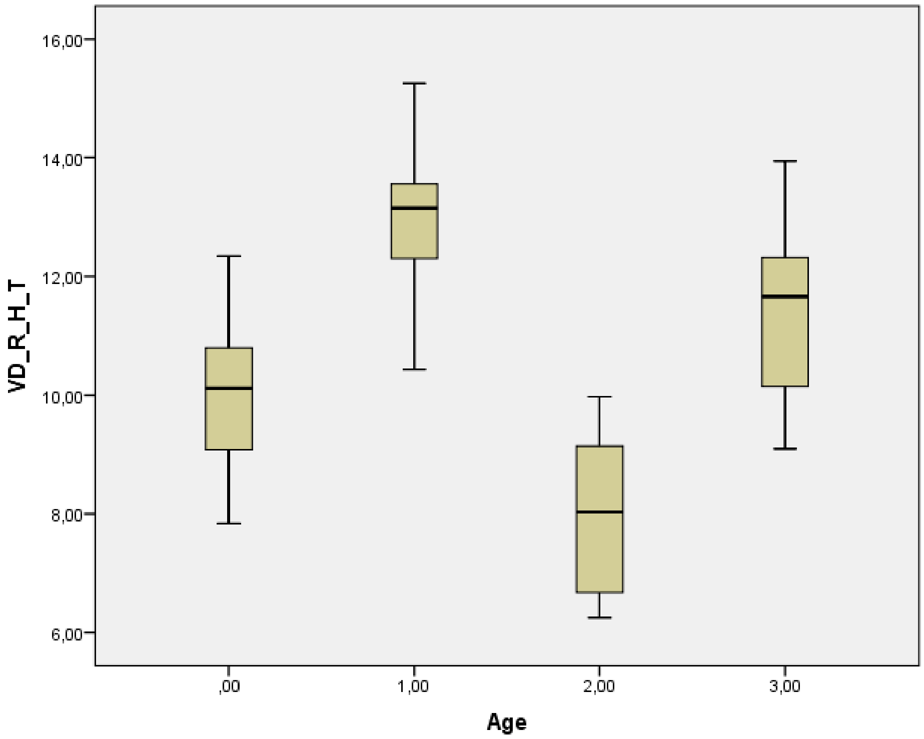
Right circle

0 = Qh young
1 = Eq young
2 = Qh old
3 = Eq old

Stride duration



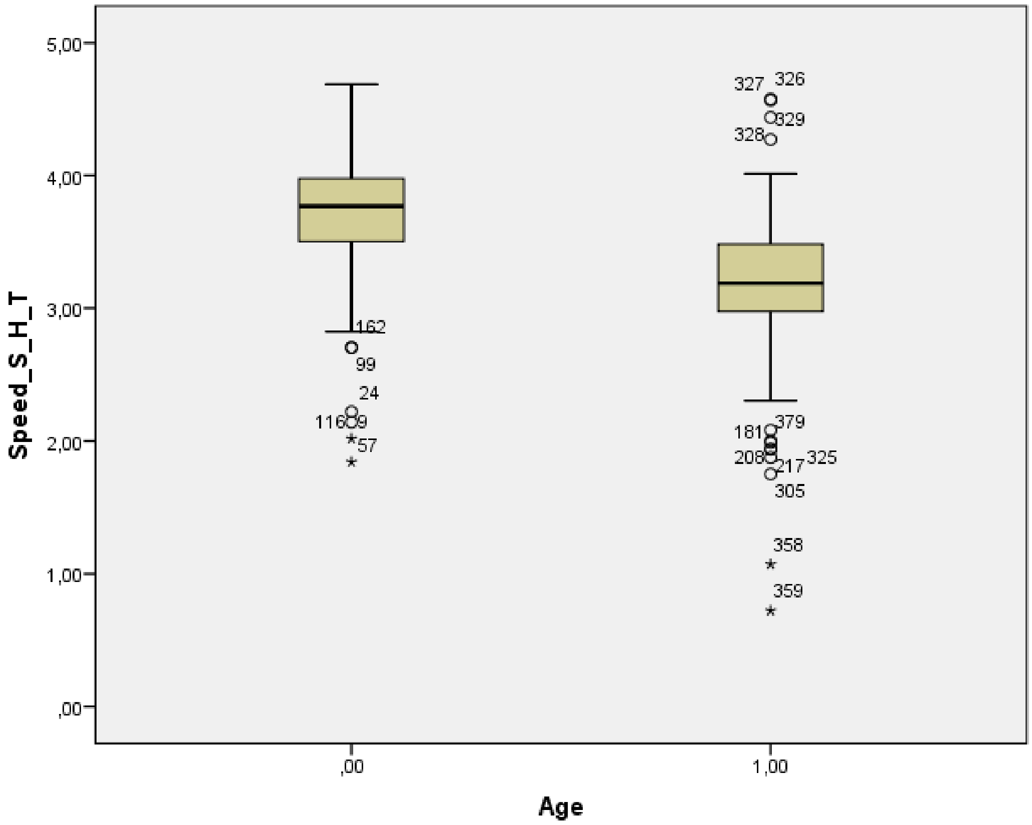
Vertical displacement



Appendix VII: Comparing speed

0 = young
1 = old

Straight line



Mean_young: 3,7028
Mean_old: 3,1801

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Speed_S_H_T	387	96,8%	13	3,3%	400	100,0%

Descriptives

			Statistic	Std. Error
Speed_S_H_T	Mean		3,4097	,02733
	95% Confidence Interval for Mean	Lower Bound	3,3560	
		Upper Bound	3,4635	
	5% Trimmed Mean		3,4338	

	Median	3,4591	
	Variance	,289	
	Std. Deviation	,53773	
	Minimum	,72	
	Maximum	4,69	
	Range	3,96	
	Interquartile Range	,70	
	Skewness	-,863	,124
	Kurtosis	2,363	,247

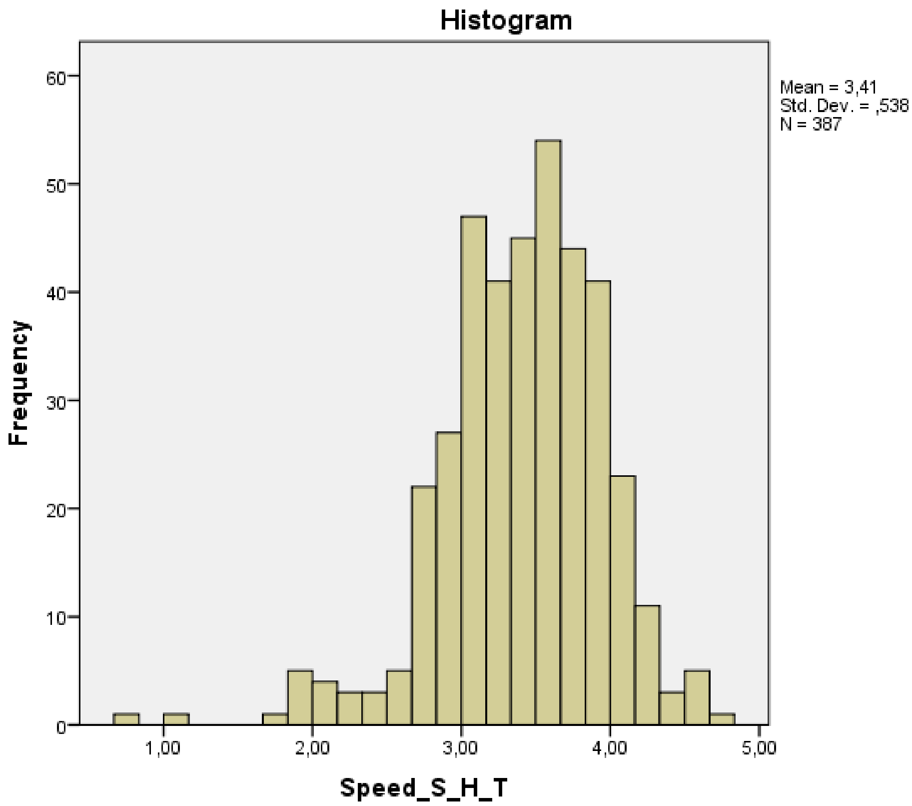
Extreme Values

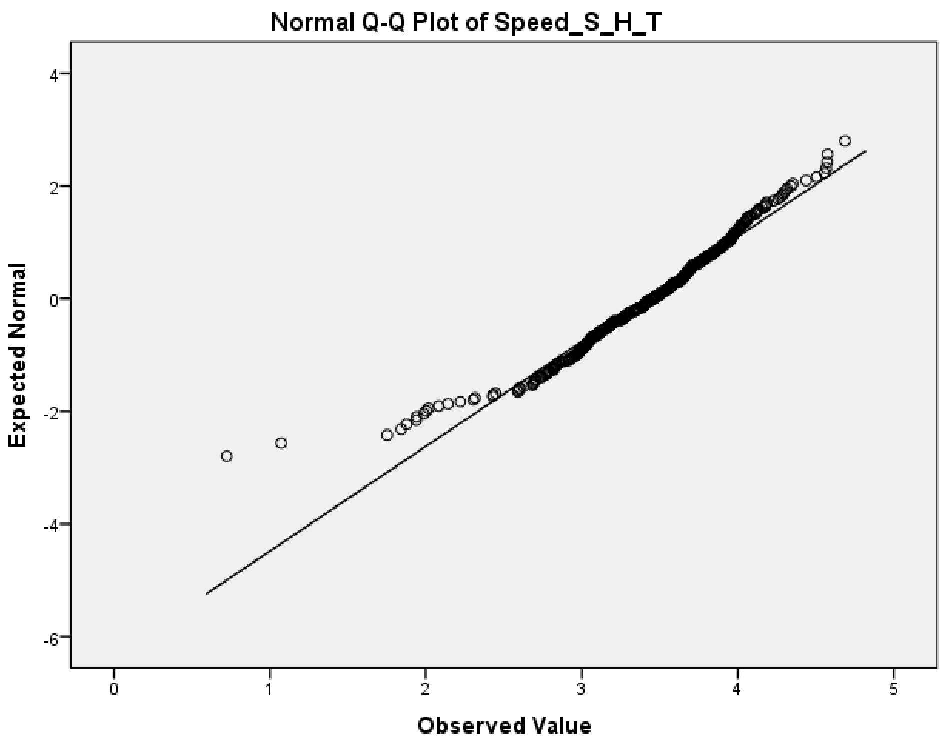
			Case Number	Value
Speed_S_H_T	Highest	1	81	4,69
		2	326	4,58
		3	127	4,57
		4	327	4,57
		5	126	4,56
	Lowest	1	359	,72
		2	358	1,07
		3	305	1,75
		4	57	1,84
		5	325	1,88

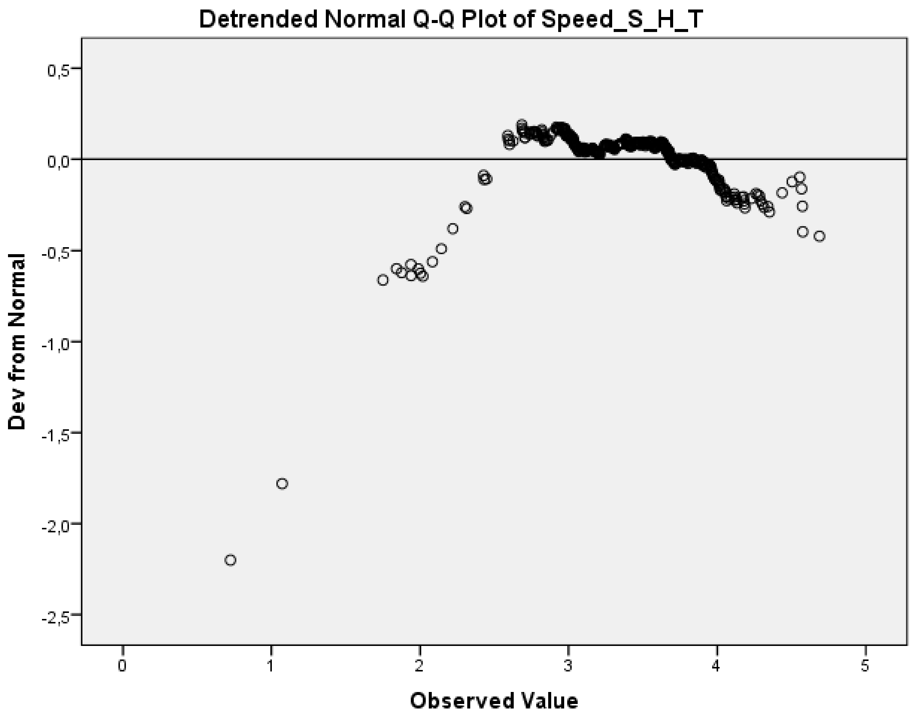
Tests of Normality

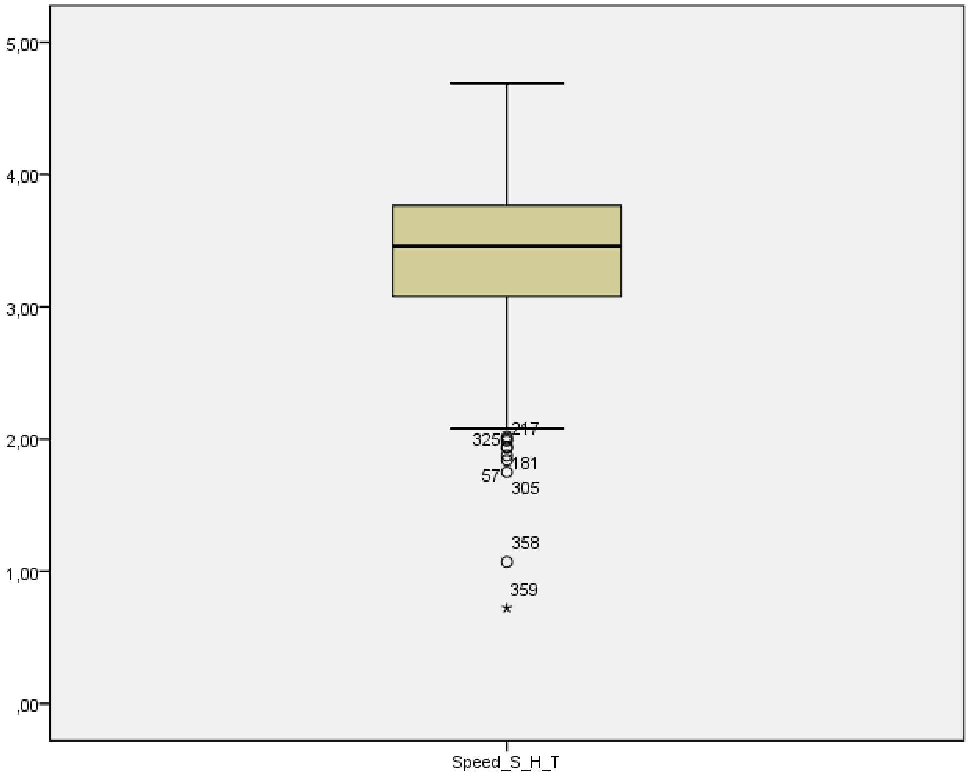
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Speed_S_H_T	,048	387	,035	,961	387	,000

a. Lilliefors Significance Correction

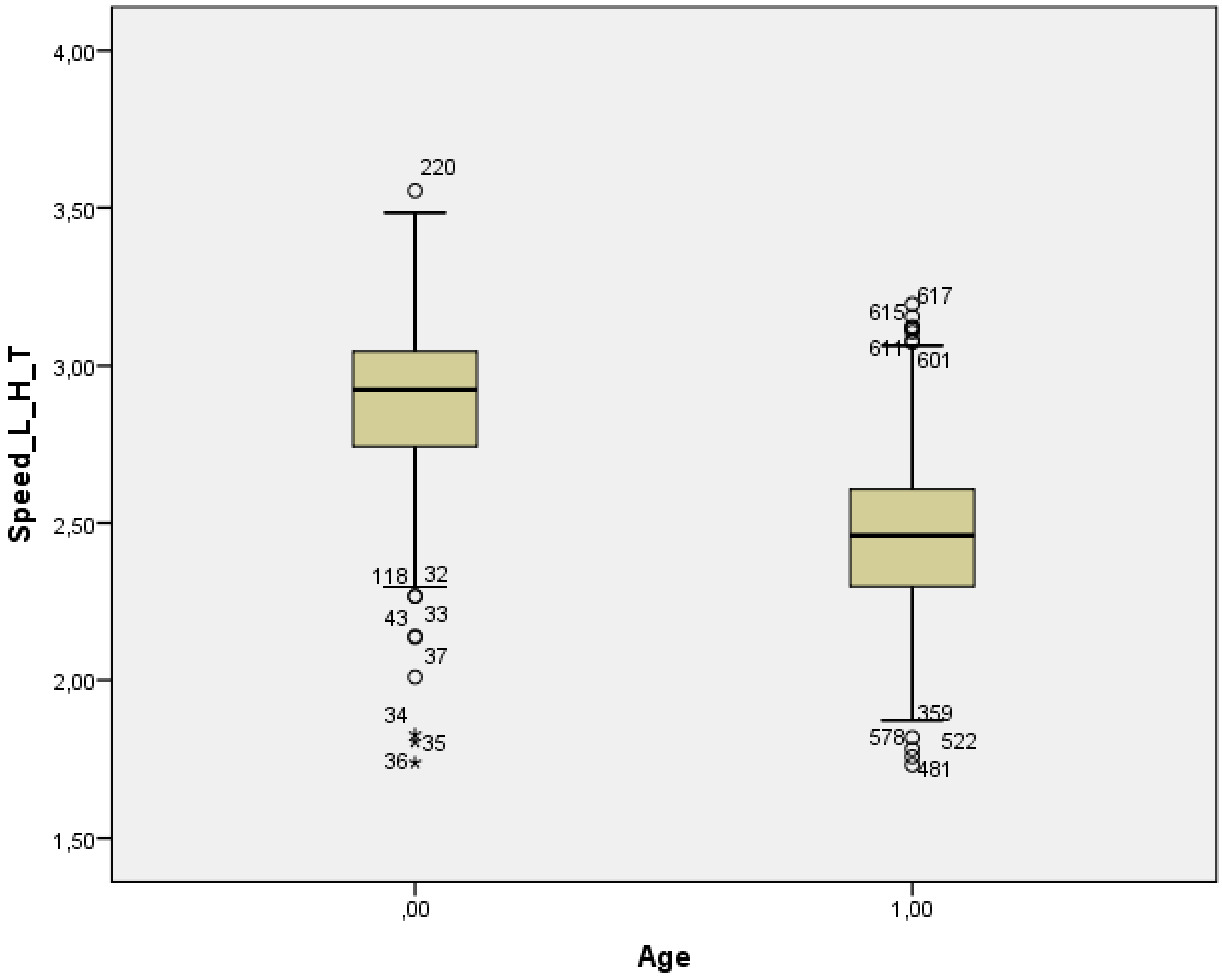

Histogram
Mean = 3,41
Std. Dev. = ,538
N = 387
Frequency
0
10
20
30
40
50
60
1,00
2,00
3,00
4,00
5,00
Speed_S_H_T


Normal Q-Q Plot of Speed_S_H_T
Expected Normal
4
2
0
-2
-4
-6
0
1
2
3
4
5
Observed Value


Detrended Normal Q-Q Plot of Speed_S_H_T
Dev from Normal
Observed Value
0,5
0,0
-0,5
-1,0
-1,5
-2,0
-2,5
0
1
2
3
4
5


5,00
4,00
3,00
2,00
1,00
,00
217
325
181
57
305
358
359
Speed_S_H_T

Left circle



Mean_young: 2,8783

Mean_old: 2,4531

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Speed_L_H_T	620	99,0%	6	1,0%	626	100,0%

Descriptives

			Statistic	Std. Error
Speed_L_H_T	Mean		2,6109	,01370
	95% Confidence Interval for Mean	Lower Bound	2,5840	
		Upper Bound	2,6378	
	5% Trimmed Mean		2,6107	
	Median		2,5911	
	Variance		,116	
	Std. Deviation		,34111	
	Minimum		1,73	
	Maximum		3,55	
	Range		1,82	
	Interquartile Range		,51	
	Skewness		,058	,098
	Kurtosis		-,416	,196

Extreme Values

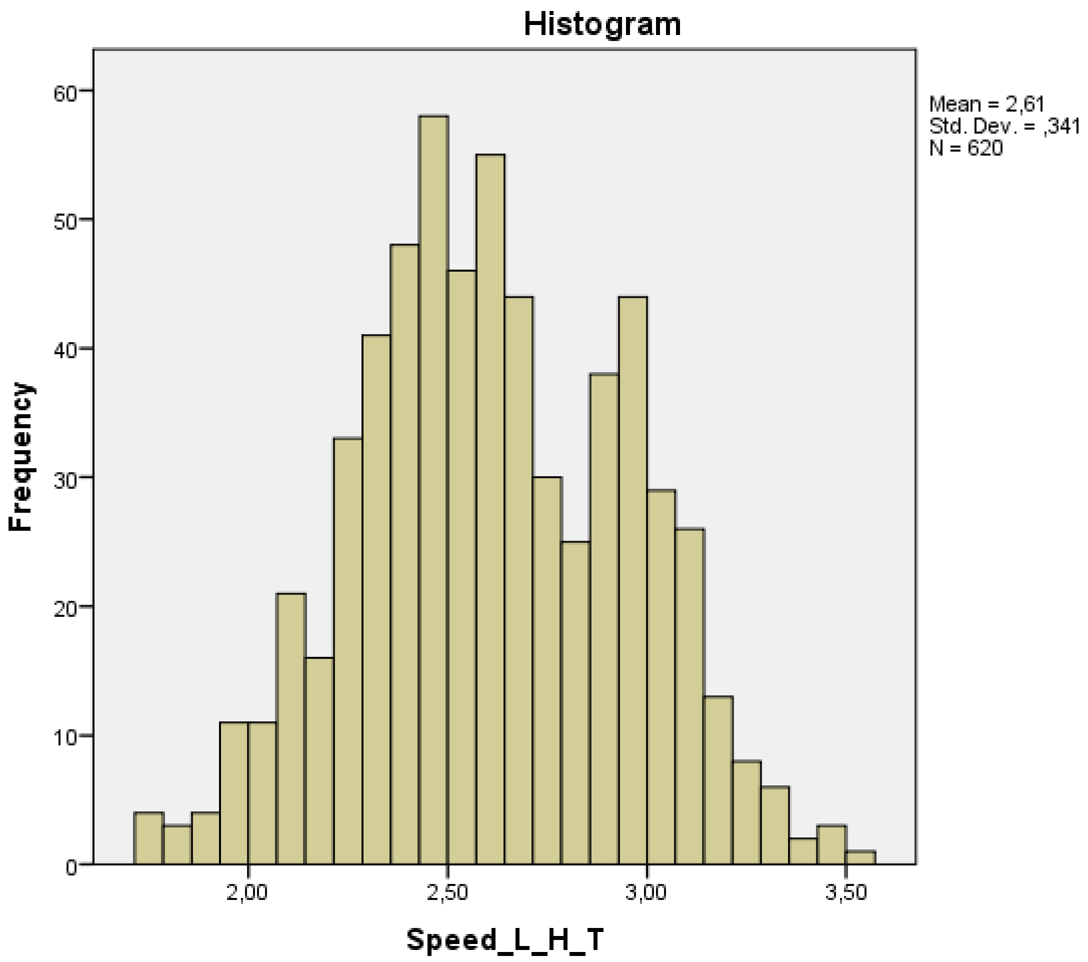
			Case Number	Value
Speed_L_H_T	Highest	1	220	3,55
		2	214	3,48
		3	72	3,48
		4	73	3,44
		5	215	3,41
	Lowest	1	522	1,73
		2	35	1,74
		3	578	1,76
		4	481	1,78
		5	36	1,81

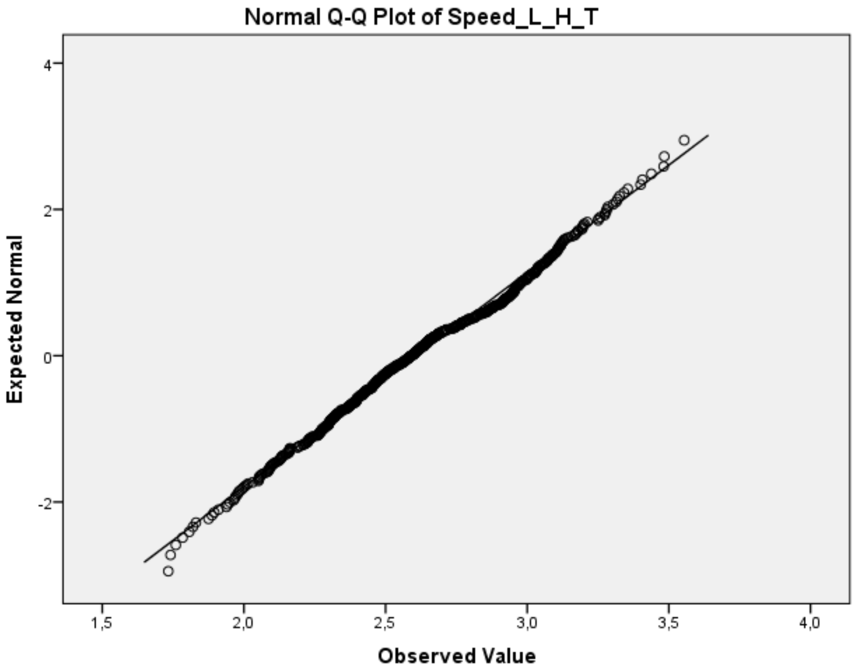
Tests of Normality

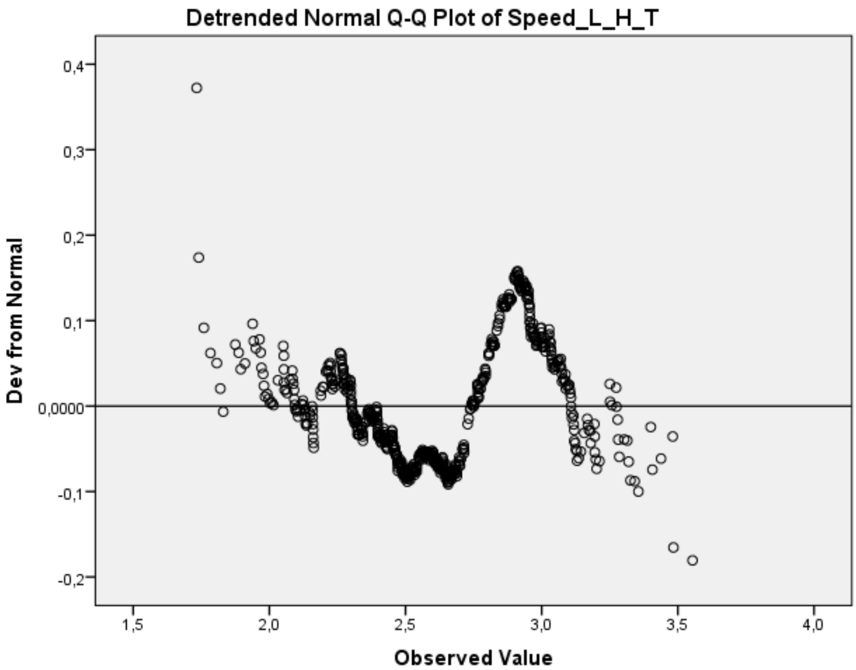
	Kolmogorov-Smirnov[a]	Shapiro-Wilk

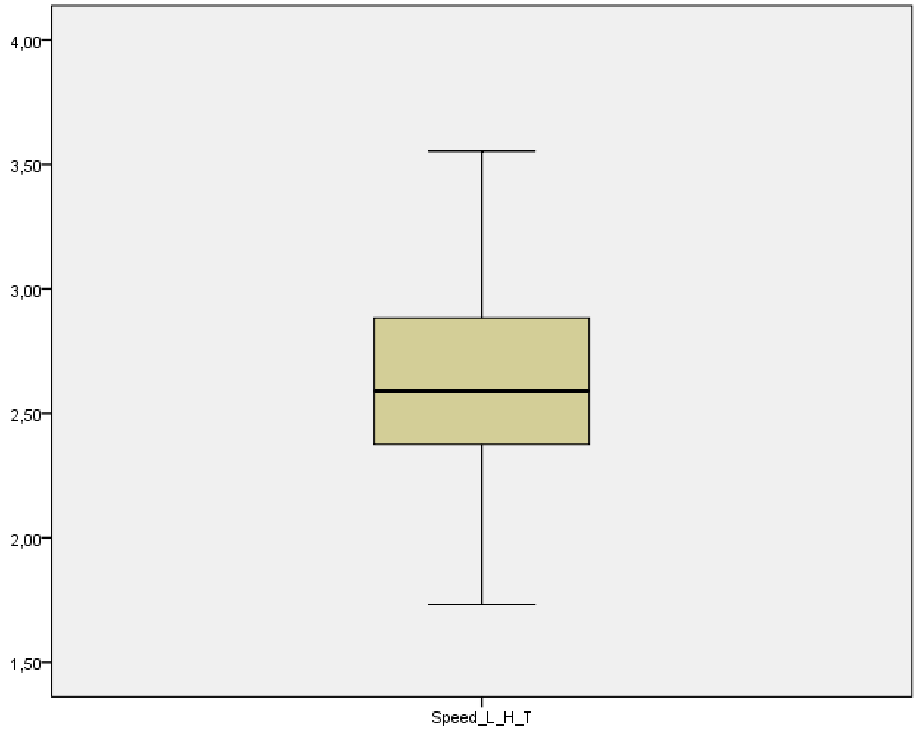
	Statistic	df	Sig.	Statistic	df	Sig.
Speed_L_H_T	,046	620	,003	,994	620	,014

a. Lilliefors Significance Correction

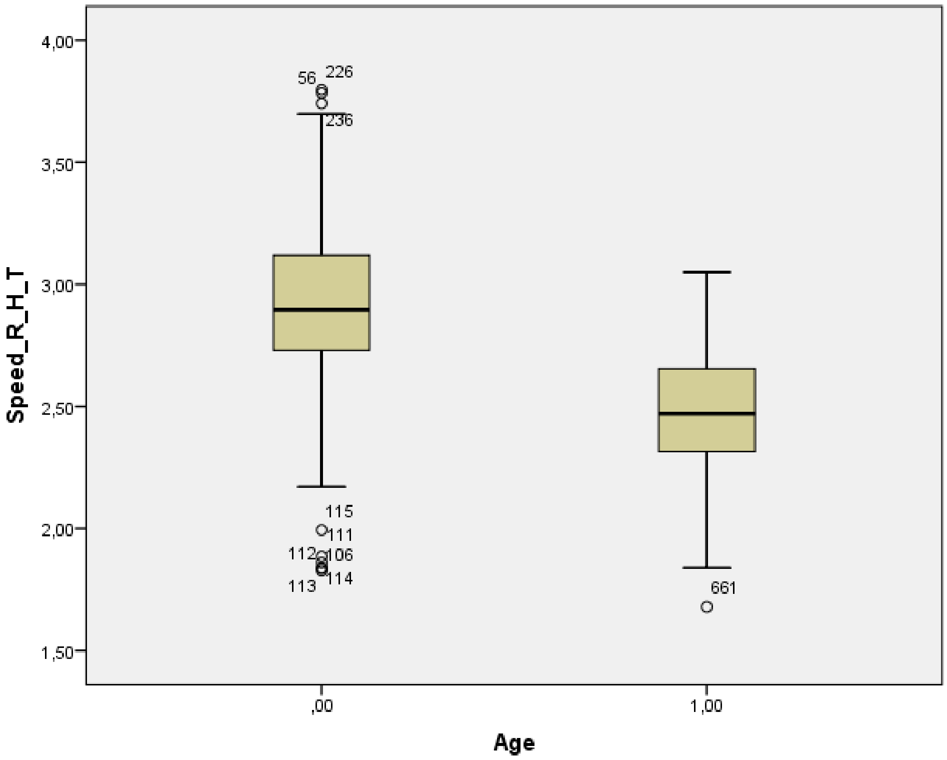



Normal Q-Q Plot of Speed_L_H_T
Expected Normal
Observed Value
4
2
0
-2
1,5
2,0
2,5
3,0
3,5
4,0


Detrended Normal Q-Q Plot of Speed_L_H_T
Dev from Normal
Observed Value
0,4
0,3
0,2
0,1
0,0000
-0,1
-0,2
1,5
2,0
2,5
3,0
3,5
4,0


4,00
3,50
3,00
2,50
2,00
1,50
Speed_L_H_T

Right circle



Mean_young: 2,9069
Mean_old: 2,4911

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Speed_R_H_T	731	96,9%	23	3,1%	754	100,0%

Descriptives

			Statistic	Std. Error
Speed_R_H_T	Mean		2,6583	,01316
	95% Confidence Interval for Mean	Lower Bound	2,6325	
		Upper Bound	2,6841	
	5% Trimmed Mean		2,6473	
	Median		2,6379	
	Variance		,127	
	Std. Deviation		,35573	
	Minimum		1,68	
	Maximum		3,80	
	Range		2,12	
	Interquartile Range		,48	
	Skewness		,429	,090
	Kurtosis		,201	,181

Extreme Values

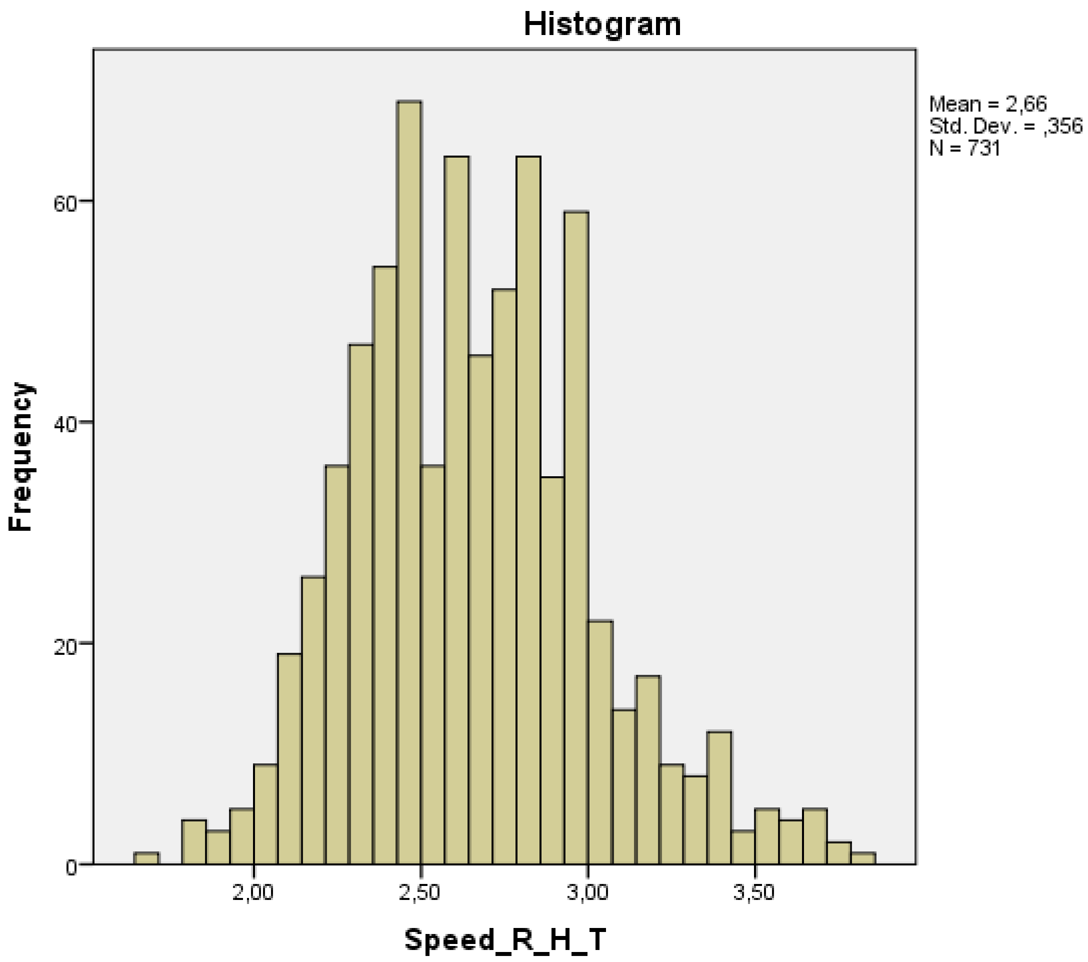
			Case Number	Value
Speed_R_H_T	Highest	1	226	3,80
		2	56	3,78
		3	236	3,74
		4	62	3,70
		5	57	3,68
	Lowest	1	661	1,68
		2	113	1,83
		3	112	1,84
		4	106	1,84
		5	460	1,84

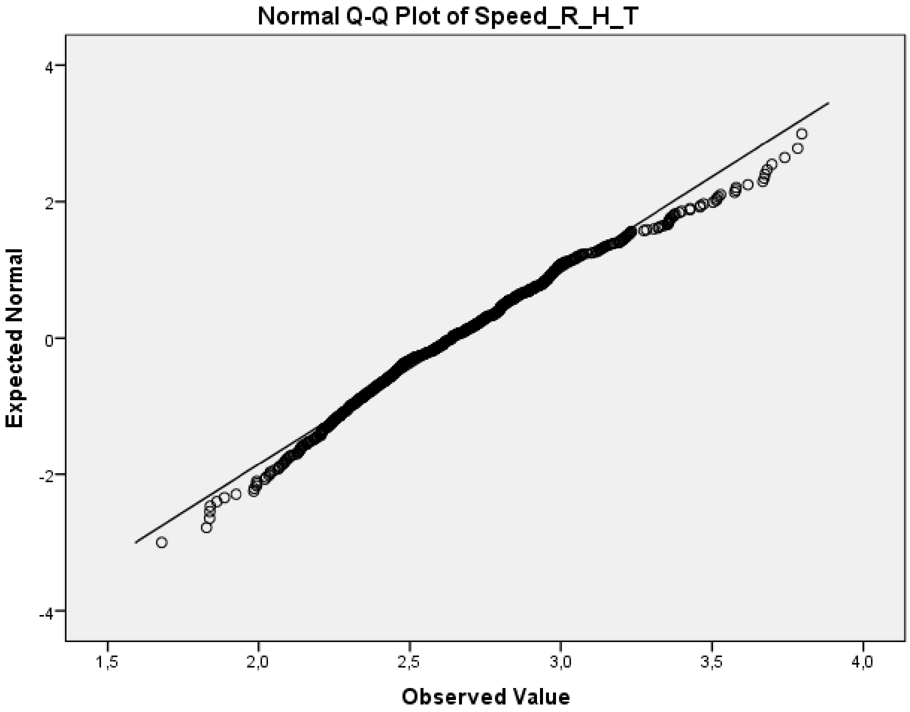
Tests of Normality

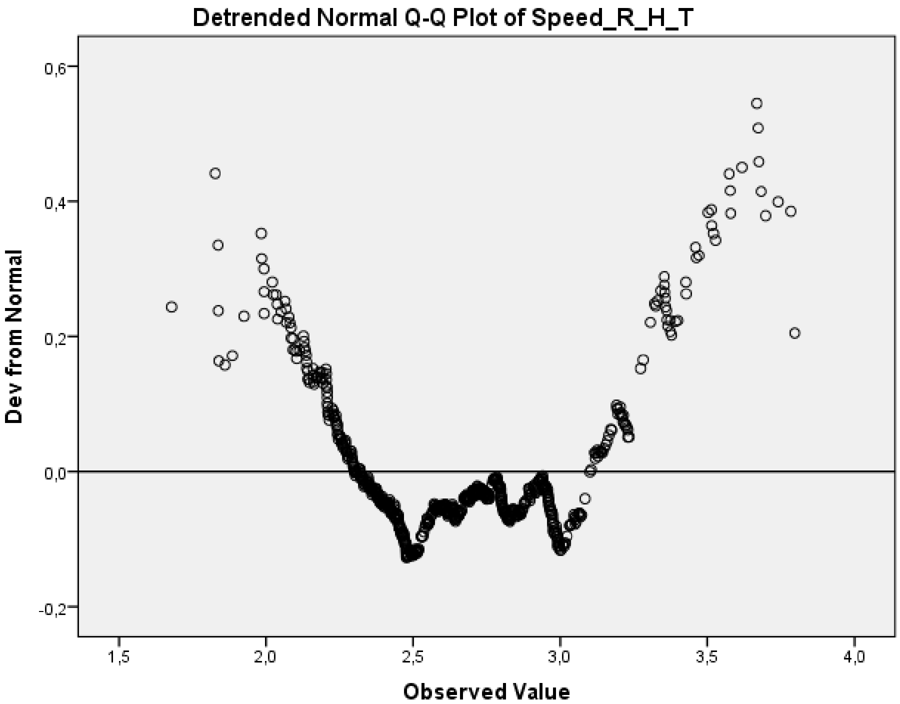
	Kolmogorov-Smirnov[a]	Shapiro-Wilk

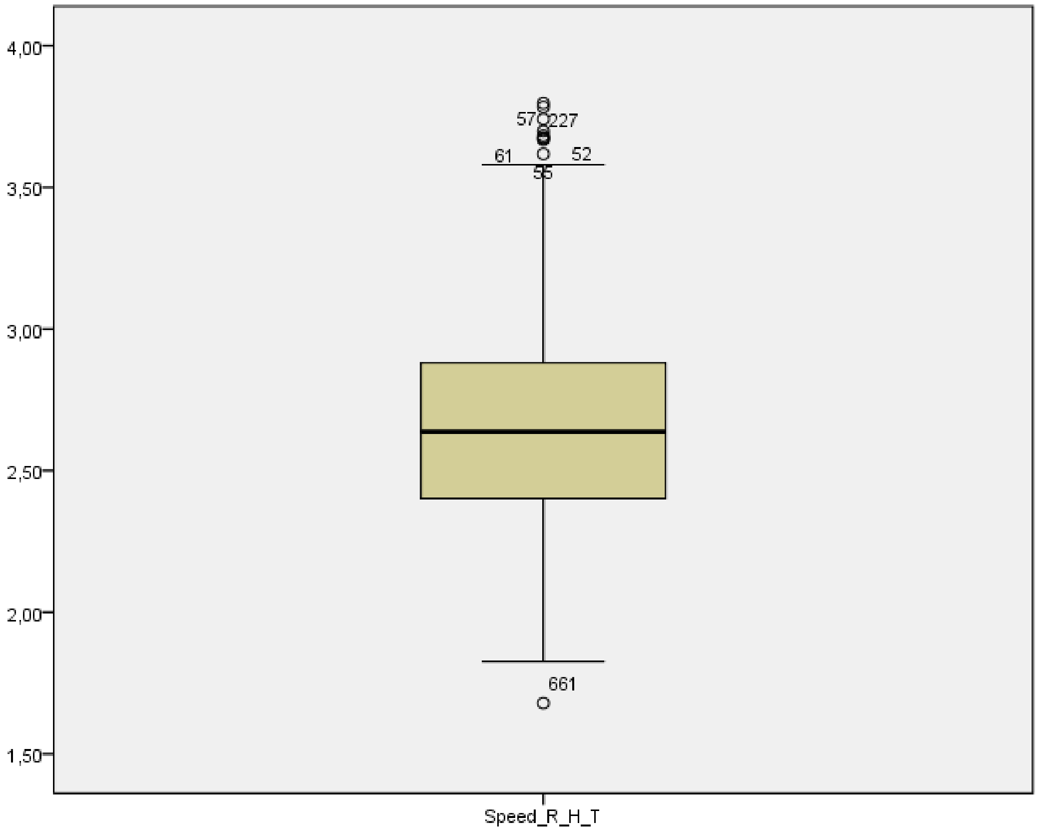
	Statistic	df	Sig.	Statistic	df	Sig.
Speed_R_H_T	,047	731	,001	,987	731	,000

a. Lilliefors Significance Correction




Normal Q-Q Plot of Speed_R_H_T
Expected Normal
Observed Value
4
2
0
-2
-4
1,5
2,0
2,5
3,0
3,5
4,0


Detrended Normal Q-Q Plot of Speed_R_H_T
Dev from Normal
Observed Value
0,6
0,4
0,2
0,0
-0,2
1,5
2,0
2,5
3,0
3,5
4,0


4,00
3,50
3,00
2,50
2,00
1,50
57
227
61
52
55
661
Speed_R_H_T