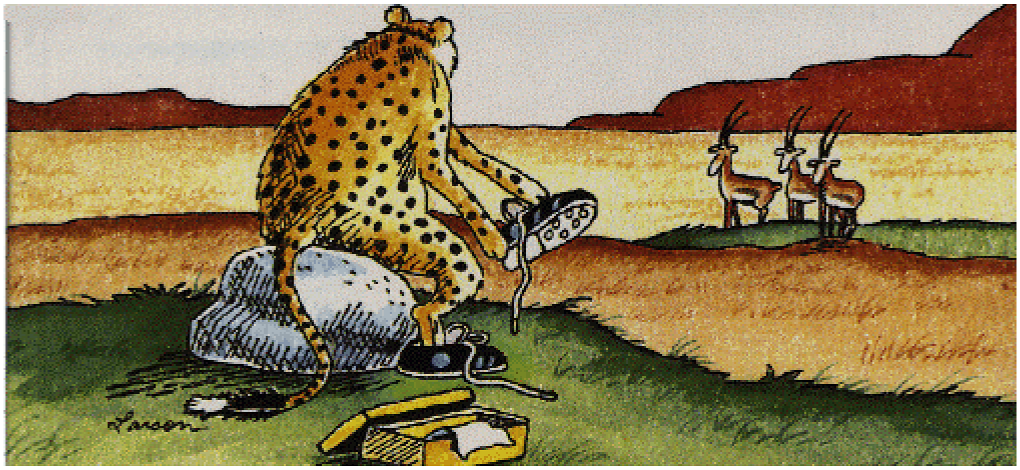
Moments around the ankle using elastic strain energy footwear



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Abstract

In walking and running the foot is subjected to high loads. Ideally, minimising these loads should maximise the protection to the foot and body, from these loads. Shock absorbing materials are used to achieve this in footwear. A problem with conventional shock absorbing materials is that most of the energy from the gait cycle applied during loading, is lost from the cycle. Elastic strain energy footwear (e-shoe) that aims to absorb and return the correct amount of energy, has been designed and built at **REHAB*Tech***.

However, studies covering the effects of an energy returning sole are divided on the benefits. It is believed that a runner's kinematics are altered to compensate for changes in footwear. This alteration in kinematics may also occur during normal walking. The aim of the present study was to determine the moments around the ankle during normal walking, when walking with a conventional shoe and when walking with the e-shoe. This to assess a possible change in the kinematics with the use of the e-shoe and to investigate if the e-shoe has the same properties in a practical use as in theory.

Data was taken from 11 subjects for both walking with a conventional shoe and walking with the e-shoe. Vertical force, anterior/posterior force, moment and power were calculated from the obtained data and a comparison between both shoes was made with the use of a t-test for paired samples.

The data showed no significant differences between a conventional shoe and the e-shoe. However the subjects reported more comfortable walking with the e-shoe. Therefore a subjective effect of the e-shoe must be accounted for. A more homogenous group and more trials per subject might give a clearer view on the effect of the e-shoe on walking kinematics.

Introduction

In walking and running the foot is subjected to high loads. Ideally, minimising these loads should maximise the protection to the foot and body, from these loads. Most conventional approaches rely on shock absorbing materials, such as EVA foams and rubbers to do this. A problem with this approach is that most of the energy from the gait cycle, applied during loading, is dissipated due to the visco-elastic properties of these materials (similar to walking on sand). Elastic strain energy footwear (e-shoe) that aims to absorb and return the correct amount of energy has been designed and built at **REHAB*Tech*** (final report: e-shoe, elastic strain energy footwear; 1995)[1].

If a higher proportion of energy is returned it should in theory increase running efficiency and therefore performance. A clinical use of the e-shoe is not yet investigated, but it is likely that the e-shoe can be of importance in rehabilitation, for example as a preventative and assistive device. A higher energy return could compensate for disrupted walking patterns caused by certain pathologies and result in less fatigue when walking long distances. When walking causes less fatigue, people are more likely to walk or jog on a regular basis, therefore maintaining a higher activity level. A higher activity level is believed to reduce the risk of certain chronic diseases, eg. coronary heart disease, hypercholesterolaemia and obesity.

However, studies covering the effects of an energy return sole are divided on the benefits. Most studies using ground reaction forces from force plates have found little differences in the shock absorbing properties. These studies used subjects running with different shoes. It is believed that the runner's kinematics are altered to compensate for the changes in footwear (Snel, 1985)[2]. This alteration in kinematics may also occur during normal walking. Therefore to investigate the clinical use of the e-shoe, insight in the differences of walking kinematics between a conventional shoe and the e-shoe is necessary.

The aim of the present study is to determine the moments around the ankle, as well as the power generated around the ankle during walking, for both a conventional shoe and the e-shoe. This to assess a possible change in the kinematics with the use of the e-shoe and to investigate if the e-shoe has the same properties in a practical use as in theory.

Methods

Shoes

Both shoes were of the same model, with identical uppers but with a different sole. A carbon-fibre insert placed in the sole is the basic construction of the e-shoe.

The conventional shoe was a standard orthopaedic shoe (Orthotics Australia Pty. Ltd.). The insert of the e-shoe was designed and made by **REHAB*Tech***, the placement of the insert in the shoe and the upper part of the shoe were manufactured by Orthotics Australia Pty. Ltd. (Table 1).

Table 1: *Weights of used shoes, testing rig and added masses.*

Weight conventional shoe	251 grams
Weight e-shoe	352 grams
Weight rig	2083 grams
Small extra mass	497 grams
Large extra mass	916 grams

Both shoes were tested for impact loading and energy return (picture 1). Two tests were conducted in which only the right shoe was tested. The first test looked at the initial impact, giving an indication of the shock absorption of the shoe. The other looked at the time and differences in magnitude between the first and second impact, giving the energy returned by the shoe. For these tests a L-shaped pendulum was used, which dropped the shoes, with added masses (table 1), through an arc onto a ground mounted force plate.

Picture 1: *Impact testing apparatus with the e-shoe in starting (left) and final (right) position*

This ensured all shoes travelled through the same path, originating from the same height. A solid foot was used to simulate a foot strike in running and walking. This allowed the shoes to land on the force plate in a typical geometry of a rear foot striker with an equivalent impact. Three drops were conducted for each shoe type. This was done to ensure repeatability of the tests. A Kistler force plate (9281B) and charge amplifier (9865B) were used together with the Bioware 2.0[3] software, for impact measurement. A sampling rate of 2016 Hz was used.

Subjects and protocol

To determine differences and changes in walking kinematics between a conventional shoe and the e-shoe, data was collected for 11 subjects (table 2).

Table 2: *Gender, age, height and weight of the subjects participating in this study.*

Subject	Gender	Age	Height (centimetres)	Weight (kilograms)
1	male	22	175.5	68
2	female	23	174.0	89
3	male	30	173.3	67
4	male	50	172.5	79
5	male	33	181.0	99
6	male	32	161.4	71
7	male	32	172.2	75
8	male	54	171.5	79
9	female	19	173.9	61
10	male	34	177.0	84
11	male	72	167.0	82

The subjects walked at normal pace on an elevated walkway and contacted a force plate to collect ground reaction force data (picture 2). Positions of ankle, lower leg and fifth metatarsal over time in space, were recorded by a one camera video imaging system (MacReflex, Qualisys)[4] with a standard error of five millimetres and a sample frequency of 50 Hz. The subjects were instructed not to alter their walking technique to contact the force plate. A good trial was one in which the subject contacted the force plate with the left foot without altering technique. Before each measurement the subjects were asked to try walking over the force plate without altering technique. This was done to get the subjects acquainted with walking over the force plate, as well as with the shoe condition. Three trials, ie. three times walking over the force plate, were conducted for each shoe condition on each subject. During these trials the ground reaction forces were sampled at 250 Hz. From these three trials one was randomly chosen for data processing. For both shoe conditions the same procedures were conducted on each subject.

Picture 2: *Subject walking over the force-plate, with the e-shoe*

Vertical force Fy

From the force plate data, obtained from each trial, six parameters were selected for analysis from the vertical force (F_y).

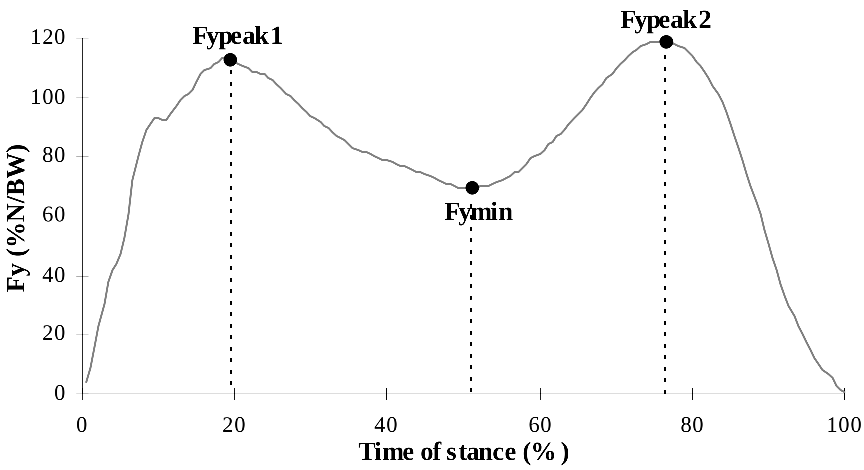

Figure 1: *Schematic representation of the Fy parameters. The parameters examined in this study and illustrated by this diagram are F_{ypeak1} = first peak of F_y and its time of occurrence after heal strike, F_{ymin} = F_y minimum and its time of occurrence after heal strike and F_{ypeak2} = second peak of F_y and its time of occurrence after heal strike.*

The F_y parameters selected for analysis and illustrated in fig. 1 were as follows: F_{ypeak1} = first peak of F_y and its time of occurrence after heal strike, F_{ymin} = F_y minimum and its time of occurrence after heal strike and F_{ypeak2} = second peak of F_y and its time of occurrence after heal strike.The F_y magnitudes were divided by the subjects body weight in Newtons (BW) to produce normalised values[5] (the body weight in Newtons is equal to the 'body weight in kilograms • 9.8').

Anterior/posterior force Fx

For F_x the following parameters selected for analysis were: F_{xmax} = F_x maximum and its time of occurrence after heal strike, F_{xmin} = F_x minimum and its time of occurrence after heal strike and F_{xcross} = the time of occurrence after heal strike of the shift from deceleration to acceleration; and illustrated in fig. 2. In this way a positive F_x is a deceleration and a negative F_x is an acceleration. The F_x magnitudes were divided by the subjects body weight in Newtons (BW) to produce normalised values[5] (the body weight in Newtons is equal to the 'body weight in kilograms • 9.8').

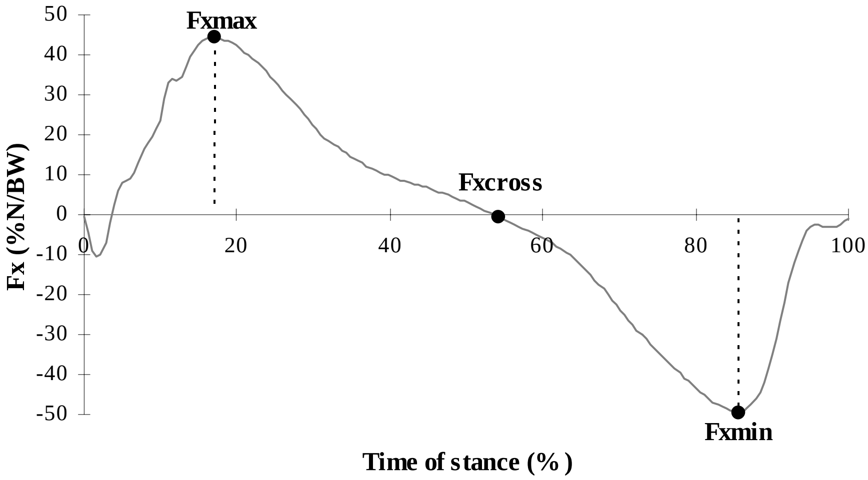

Figure 2: *Schematic representation of the F_x parameters. The parameters examined in this study and illustrated by this diagram are: F_{xmax} = F_x maximum and its time of occurrence after heal strike, F_{xmin} = F_x minimum and its time of and F_{xcross} = the time of occurrence after heal strike of the shift from deceleration to acceleration.*

Moment

The data from the force plate was combined with the data obtained from the video imaging system to calculate the moment around the ankle. To calculate the total internal moment (M_{tot}) around the ankle equation 1 was used[6,7]. F_x and F_y were obtained from the data of the force plate. Δ_{cop-a} and A_y were measured by the use of the video-imaging system.

In this way a positive value for M_{tot} represents a dorsiflexion, a negative value a plantarflexion. For M_{tot} the following parameters were selected for analysis (fig. 3): M_{max} = maximal internal moment (dorsiflexion) around the ankle and its time of occurrence after heal strike, M_{min} = minimal internal moment (plantarflexion) around the ankle and its time of occurrence after heal strike and $_{Mcross}$ = the time of occurrence after heal strike of the shift from dorsi- to plantarflexion.

Equation 1: *the equations used to determine the total internal moment around the ankle during normal walking.*

$$M_x + M_y = M_{tot}$$

M_x = Moment around ankle generated by F_x

M_y = Moment around ankle generated by F_y

M_{tot} = Total internal moment

M_x is calculated as $F_x \bullet \Delta_{cop-a}$

F_x = Force in direction of x

Δ_{cop-a} = distance between centre of pressure and position of the ankle in direction of x

M_y is calculated as $F_y \bullet A_y$

F_y = Force in direction of y

A_y = position of the ankle in direction of y

M_{tot} was standardised as a percentage of the maximal ‘plantarflexing moment’, as measured in the trial of the conventional shoe.

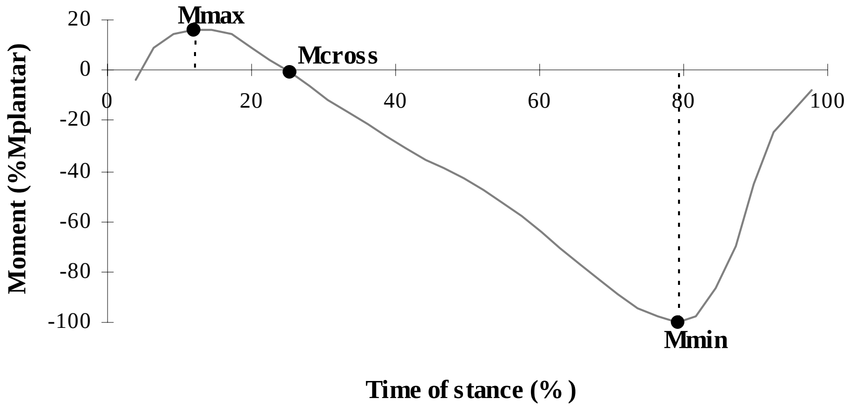

Figure 3: *Schematic representation of the M_{tot} parameters. The parameters examined in this study and illustrated by this diagram are*: *M_{max} = maximal internal moment around the ankle and its time of occurrence after heal strike, M_{min} = minimal internal moment around the ankle and its time of occurrence after heal strike and M_{cross} = the time of occurrence after heal strike of the shift from dorsi- to plantarflexion.*

Power

In order to calculate the power (P) generated around the ankle during stance, equation 2 was used[6,7]. Angular velocity was derived from the data of the video imaging system. Total internal was measured as explained in equation 1. Power was standardised as a percentage of BW[5]. A positive P represents energy absorption in the ankle, a negative P represents energy generation.

Equation 2: *the equation used to determine the total power around the ankle during normal walking.*

$$M_{tot} \bullet \omega = P$$

M_{tot} = total internal moment

ω = angular velocity

P = Power generated around ankle

For P the following parameters were analysed and shown in fig. 4: P_{max} = maximal power around the ankle and its time of occurrence after heal strike, P_{min} = minimal power around the ankle and its time of occurrence after heal strike and P_{cross} = the time of occurrence after heal strike of the shift from energy absorption to energy generation.

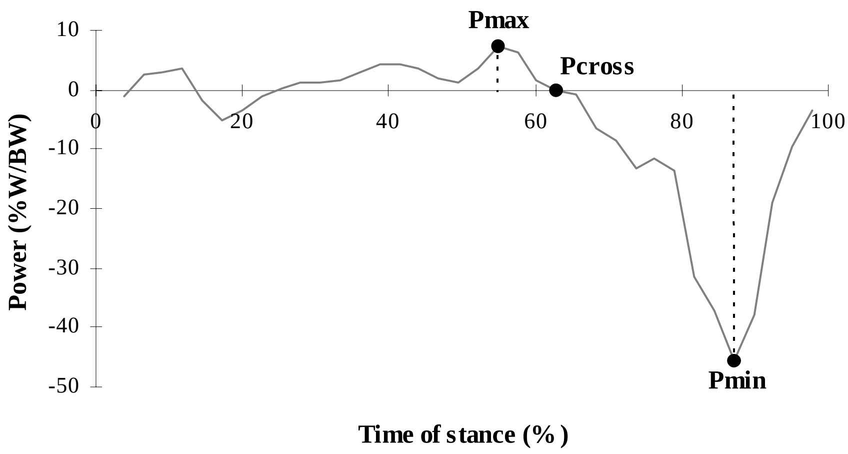

Figure 4: *Schematic representation of the P parameters. The parameters examined in this study and illustrated by this diagram are*: P_{max} *= maximal power and its time of occurrence after heal strike,* P_{min} *= minimal power and its time of occurrence after heal strike and* P_{cross} *= the time of occurrence after heal strike of the shift from energy absorption to energy generation.*

Data-analysis

Statistical comparisons were made between the conventional and the e-shoe for each parameter. A paired sample *t*-test was employed with a level of significance of 0.05, to determine significant differences between the parameters found for both shoes. All statistical analysis were done with the use of S-plus 4.0 (Mathsoft)[8].

Results

Shoes

The results of the impact loading and energy return test for both shoes are presented in table 3. The conventional shoe showed a higher initial impact and a lower energy return than the e-shoe. During the second test, simulating a higher impact energy, the two ends of the insert contacted at impact, effectively eliminating the function of the e-shoe.

Table 3: *Values found for initial impact and % energy return, for both the conventional and the e-shoe. Total weight is the sum of weights of the shoe and the rig.*

	Conventional shoe		**E-shoe**	
	Test 1	**Test 2**	**Test 1**	**Test 2***
Total weight (grams)	2831	3250	2945	3373
Impact (N)	1615	1985	1411	2012*
% Energy return	43%		63%	

***** *The two ends of the insert contacted at impact.***

These found values are in agreement with the tests conducted in the original research of the e-shoe (final report: e-shoe, elastic strain energy footwear; 1995)[1].

Vertical force Fy

The values for each of the magnitudes of the vertical force F_y parameters are presented for both the conventional and the e-shoe in table 4, as well as the mean and standard deviations (SD) of each of these parameters. No significant differences were found between the trials in the conventional and the e-shoe for each of the parameters measured. A graphical representation of the F_y data for each of the subjects can be found in Appendix B.

Table 5 shows values for the occurrence time after heal strike for both shoe trials, corresponding to respectively F_{ypeak1}, F_{ymin} and F_{ypeak2}. For time also, no significant differences were found between both shoe trials.

Table 4: *The values of the magnitudes of the vertical force F_y, obtained from both the conventional shoe and the e-shoe. Vertical force is expressed as a percentage of the subject's bodyweight (BW).*

	Fypeak1 (%N/BW)		Fymin (%N/BW)		Fypeak2 (%N/BW)	
Subject	**Conv**	**Es**	**Conv**	**Es**	**Conv**	**Es**
1	123.19	122.44	69.48	71.56	118.07	116.93
2	109.64	123.89	77.45	75.22	109.35	100.30
3	109.64	127.28	69.28	73.04	119.28	114.21
4	113.86	121.57	63.77	61.84	123.68	126.57
5	117.34	110.30	72.88	79.01	106.91	105.22
6	103.99	111.81	80.54	81.63	107.44	108.17
7	111.52	103.26	82.27	86.91	111.35	114.11
8	100.49	117.64	83.98	82.51	112.41	111.60
9	116.38	116.17	83.80	80.15	113.21	107.64
10	112.79	122.01	76.83	67.77	116.48	120.01
11	107.15	106.37	79.78	86.47	105.60	100.15
Means	111.46	116.61	76.37	76.92	113.07	111.36
SD	6.37	7.76	6.69	7.86	5.75	8.1

Despite the fact that no significant differences were found for the magnitude and time of occurrence of the F_y parameters it is interesting to note that the individual responses to both shoe trials were quite different. For the subjects 2, 3 and 8 a remarkable lower F_{ypeak1} was found when walking with the e-shoe, however for the subjects 5 and 7 a higher F_{ypeak1} was measured when walking with the e-shoe. As a further example of this variable response, figure 5 and figure 6 are a graphical representation of the F_y data for respectively subjects 1 and 3.

Table 5: *The time of occurrence after heal strike of respectively F_{ypeak1} F_{ymin} and F_{ypeak2} for both shoe trials.. Time is expressed as a percentage of the actual measured stance time.*

	time Fypeak1 (% Stance time)		time Fymin (% Stance time)		time Fypeak2 (% Stance time)	
Subject	**Conv**	**Es**	**Conv**	**Es**	**Conv**	**Es**
1	22.5	24.9	43.5	48.0	78.0	77.7
2	27.0	26.9	47.8	51.5	73.6	75.1
3	21.7	13.2	51.1	42.8	76.1	76.4
4	18.4	23.0	42.9	47.9	77.3	76.1
5	24.3	21.3	45.9	44.8	75.1	74.9
6	23.7	13.7	56.5	54.9	76.8	77.1
7	27.4	13.9	48.4	54.1	75.8	77.3
8	25.9	14.0	48.8	42.0	76.6	76.2
9	13.0	15.3	32.8	35.0	67.8	75.3
10	31.0	29.1	53.3	53.1	74.6	78.0
11	21.9	23.5	43.2	49.5	71.6	76.0
Means	23.3	19.9	46.7	47.6	74.9	76.4
SD	4.8	6.0	6.3	6.1	3.0	1.0

For subject 1 the same pattern for F_y was found, while subject 3 showed a lower F_{ypeak1} when walking with the e-shoe. It should also be noted that the between subjects variability found for F_y was high in both shoe trials, appendix C.

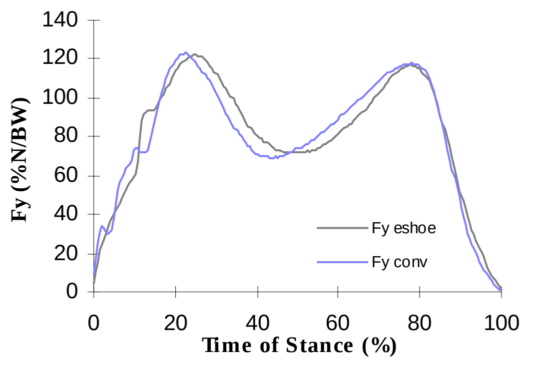

Fig 5: *Representation of vertical force F_y for subject 1, walking with the conventional shoe and the e-shoe. F_y is represented as a percentage of bodyweight.*

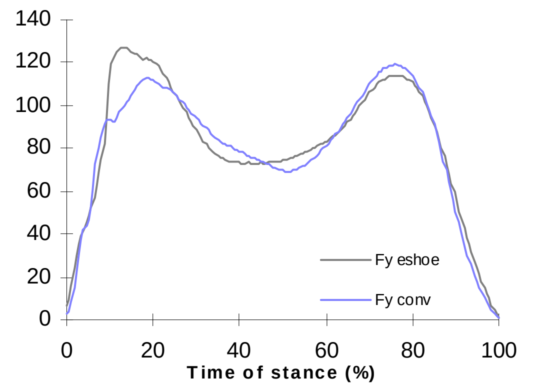

Fig 6: *Representation of vertical force F_y for subject 3, walking with the conventional shoe and the e-shoe. F_y is represented as a percentage of bodyweight.*

Anterior/posterior force F_x

In table 6 the values, means and standard deviations for the magnitudes of the anterior/posterior force F_x parameters are presented for both the conventional and the e-shoe. Significant lower values ($P = 0.0394$) were found for F_{xmin} when walking with the e-shoe. See Appendix B for a graphical representation of the F_x data for each of the subjects. Also the time of occurrence of F_{xmin} was shifted significantly ($P = 0.0472$) to a later point in stance time for the e-shoe, as seen in table 7. No significant differences were found for F_{xmax} and the time of occurrence of F_{xmax}.

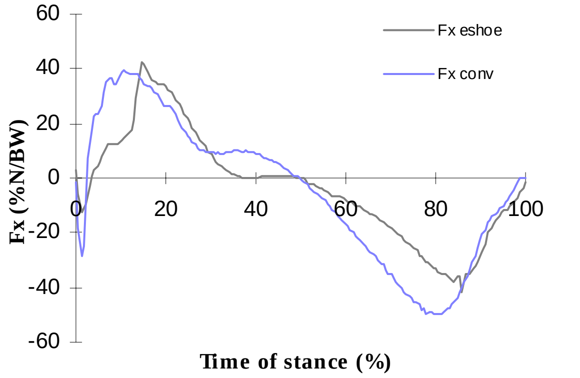

Fig 7: *Representation of anterior/posterior force F_x for subject 9, walking with the conventional shoe and the e-shoe. F_x is represented as a percentage of bodyweight.*

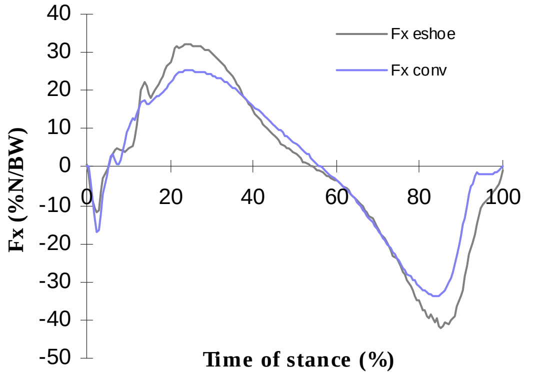

Fig 8: *Representation of anterior/posterior force F_x for subject 10, walking with the conventional shoe and the e-shoe. F_x is represented as a percentage of bodyweight.*

As for the F_y parameters different individual responses were found for the F_x parameters. The individual responses are shown in figure 7 and figure 8. Subject 9 shows a higher value for F_{xmin} when walking with the e-shoe than subject 10, while both subjects show the same later occurrence in stance time of F_{xmin} in the e-shoe trial. The between subjects variability, appendix D, also had a wide range. Especially during the first part of stance when F_x represents a deceleration, this variability was high.

Table 6: *The values of the magnitudes of the anterior/posterior force F_x parameters, obtained from both the conventional shoe and the e-shoe. F_x is expressed as a percentage of the subject's bodyweight (BW).*

	Fxmax (%N/BW)		Fxmin* (%N/BW)	
Subject	**Conv**	**Es**	**Conv**	**Es**
1	48.53	36.21	-53.80	-48.06
2	38.52	48.08	-45.27	-40.51
3	42.42	60.88	-56.19	-51.25
4	45.15	51.74	-57.95	-48.49
5	44.54	36.31	-49.36	-40.06
6	32.79	48.38	-46.93	-42.79
7	36.67	40.17	-49.63	-52.11
8	31.58	51.65	-43.96	-43.31
9	39.32	42.30	-49.91	-41.37
10	25.43	32.13	-33.88	-42.26
11	21.58	21.73	-28.90	-23.12
Means	36.95	42.69	-46.89	-43.03
SD	8.43	10.93	8.85	7.88

**** significant differences were found (P<0.05)***

Table 7: *The time of occurrence after heal strike of respectively F_{xmax} and F_{xmin} for both shoe trials.. Time is expressed as a percentage of the actual measured stance time.*

time Fxmax (% Stance time)		time Fxmin* (% Stance time)		time Fxcross (% Stance time)	
Conv	**Es**	**Conv**	**Es**	**Conv**	**Es**
19.4	20.1	83.0	83.8	54.5	56.1
16.3	16.6	83.1	83.4	55.4	55.1
13.9	11.5	83.3	83.9	51.7	51.6
16.9	11.7	84.7	84.7	53.5	55.7
16.6	17.1	85.6	85.0	53.5	56.0
12.4	12.0	84.2	84.0	54.5	58.6
16.7	11.9	82.8	84.0	54.7	53.2
17.9	13.5	83.6	84.5	52.1	51.5
10.7	14.7	81.4	85.9	49.5	49.2
23.9	24.3	84.5	85.1	56.4	54.3
19.7	17.9	83.1	85.7	55.3	55.7
16.8	15.6	83.6	84.6	53.8	54.3
3.6	4.1	1.1	0.8	2.0	2.7

**** significant differences were found (P<0.05)***

Moment

Table 8 shows the values, means and standard deviations for the parameters measured regarding the moments around the ankle. These parameters are presented for both the conventional and the e-shoe (see also appendix E). No significant differences were found between the trials in the conventional and the e-shoe for each of the parameters measured.

Table 9 shows values for the occurrence time after heal strike for both shoe trials, corresponding to respectively M_{max}, M_{min} and M_{cross}. For these times also, no significant differences were found between both shoe trials.

Table 8: *The values of the magnitudes of the parameters measured for moments around the ankle obtained from both the conventional shoe and the e-shoe. Moment is expressed as a percentage of the maximal plantarflexing moment as calculated from the trial with the conventional shoe.*

	M*max* (%Mplantar)		M*min* (%Mplantar)	
Subject	**Conv**	**Es**	**Conv**	**Es**
1	11.06	11.51	-100.00	-92.68
2	10.53	18.37	-100.00	-87.52
3	15.20	29.40	-100.00	-97.43
4	11.36	13.69	-100.00	-98.49
5	7.81	9.83	-100.00	-90.90
6	9.61	18.33	-100.00	-95.16
7	15.90	11.44	-100.00	-106.83
8	12.76	27.97	-100.00	-98.30
9	30.12	16.45	-100.00	-102.50
10	-1.72	8.12	-100.00	-106.65
11	8.98	3.84	-100.00	-101.95
Means	11.96	15.36	-100.00	-98.04
SD	7.61	7.90	0.00	6.21

As found for F_y and F_x also for the moments around the ankle, different individual responses were found between the subjects. An example of the individual responses regarding the moments around the ankle is given in figure 9 and 10. In these figures contrary values for each parameter found for the moments around the ankle can be seen between the subjects 6 and 7. For subject 6 a lower dorsiflexing moment and a higher plantarflexing moment as calculated from the conventional shoe trial, when compared to the e-shoe trial.

Table 9: *The time of occurrence after heal strike of respectively M_{max}, M_{min} and M_{cross} for both shoe trials. Time is expressed as a percentage of the actual measured stance time.*

	time of M*max* (%Stance time)		time of M*min* (%Stance time)		M*cross* (%Stance time)	
Subject	**Conv**	**Es**	**Conv**	**Es**	**Conv**	**Es**
1	8.4	8.9	79.1	78.8	13.3	20.9
2	14.6	11.8	79.2	76.9	17.0	22.1
3	11.1	12.1	80.6	81.0	14.6	24.4
4	12.9	12.3	80.4	76.7	15.7	23.3
5	11.6	13.8	80.7	80.1	13.7	21.8
6	9.0	12.6	79.7	78.3	10.3	18.6
7	11.8	8.2	79.0	80.4	18.5	21.4
8	14.9	13.5	79.6	80.8	19.6	28.9
9	11.3	15.3	73.4	77.1	18.0	25.4
10	5.6	9.1	79.2	80.6	***	18.9
11	5.5	7.7	76.5	79.1	14.4	12.8
Means	10.6	11.4	78.8	79.1	20.8	20.8
SD	3.2	2.5	2.1	1.6	4.3	4.3

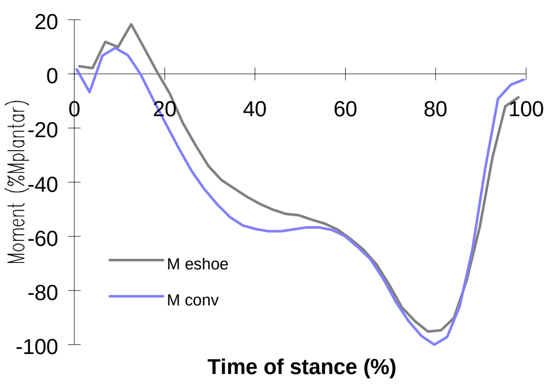

Fig 9: *Representation of moments around the ankle for subject 6, walking with the conventional shoe and the e-shoe. Moment is represented as a percentage of maximal plantarflexing moment as calculated from the trial with the conventional shoe.*

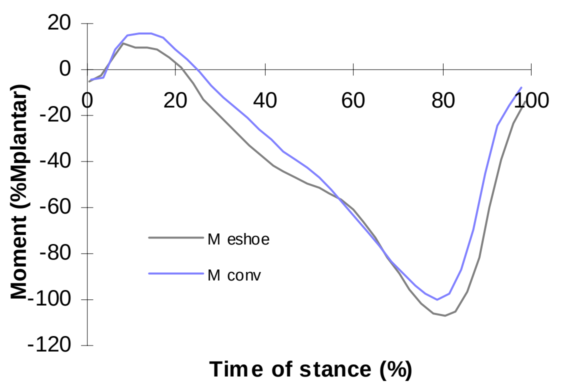

Fig 10: *Representation of moments around the ankle for subject 7, walking with the conventional shoe and the e-shoe. Moment is represented as a percentage of maximal plantarflexing moment as calculated from the trial with the conventional shoe.*

Subject 7 had a higher dorsiflexing moment and a lower plantarflexing moment for walking with the conventional shoe, when compared to walking with the e-shoe. Also for subject 6 an earlier occurrence of the shift from dorsi- to plantarflexion was found when walking with the conventional shoe, while this shift occurred at a later time in stance for subject 7. For the between subjects variability see appendix F.

Power

The values, mean values and standard deviations for each power parameter are presented for both trials in table 10. No significant differences were found between the trials conducted for the conventional shoe and the e-shoe for the power magnitudes. For a graphical representation of the data see appendix G and H.

Table 10: *The values of the magnitudes of the parameters measured power absorbed and generated by the subjects when walking with both the conventional shoe and the e-shoe. Power is expressed as a percentage of the subject's bodyweight (BW).*

	P*max* (%W/BW)		**P*min* (%W/BW)**	
Subject	**Conv**	**Es**	**Conv**	**Es**
1	12.30	7.35	-54.86	-35.31
2	5.98	-0.24	-59.07	-45.63
3	12.91	7.23	-63.42	-45.10
4	6.97	15.74	-63.25	-46.16
5	3.25	-0.63	-50.75	-37.68
6	7.29	3.18	-42.13	-54.39
7	7.27	4.76	-45.52	-46.31
8	1.73	7.29	-39.41	-47.46
9	10.01	12.36	-43.81	-48.96
10	9.39	7.84	-11.01	-41.76
11	3.62	11.74	-31.95	-26.13
Means	6.75	6.97	-45.93	-43.17
SD	3.99	5.09	15.35	7.69

When looking at the times of occurrence after heal strike of P_{max}, P_{min} and P_{cross} also no significant differences were found. The values, means and standard deviations of these time parameters are shown in table 11. The individual differences in the generation of power can be seen in figure 11 and 12. Subject 3 generates more power using the conventional shoe, while subject 6 generates more power using the e-shoe in the last phase of the stance time.

Table 11: *The time of occurrence after heal strike of respectively P_{max}, P_{min} and P_{cross} for both shoe trials. Time is expressed as a percentage of the actual measured stance time.*

	time of P*max* (%Stance time)		time of P*min* (%Stance time)		P*cross* (%Stance time)	
Subject	**Conv**	**Es**	**Conv**	**Es**	**Conv**	**Es**
1	73.8	67.6	84.3	84.4	76.9	72.5
2	70.8	68.0	87.6	85.8	73.3	***
3	66.7	66.7	88.9	86.8	76.2	71.1
4	68.1	64.4	86.5	85.9	72.9	74.6
5	55.8	71.8	89.0	82.9	66.8	***
6	68.4	69.7	88.1	84.0	69.6	70.9
7	54.8	75.3	87.1	88.1	62.6	77.4
8	74.6	73.1	89.6	86.0	77.3	75.9
9	45.2	59.4	79.1	88.8	54.4	54.4
10	76.7	74.9	89.3	83.4	81.2	76.0
11	71.0	66.3	87.4	86.7	73.0	73.3
Means	66.0	68.8	87.0	85.7	71.3	72.7
SD	9.8	4.8	3.0	1.9	7.6	2.9

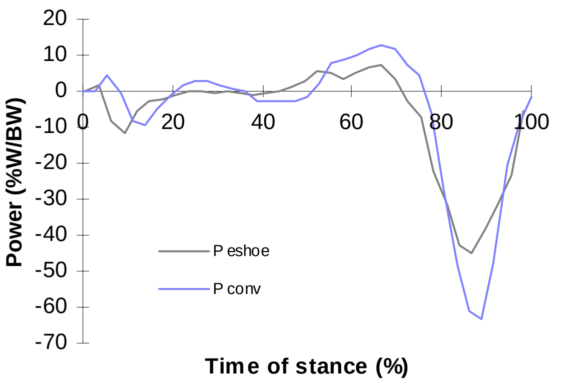

Fig 11: *Representation of the power absorbed/generated by subject 3, when walking with the conventional shoe and the e-shoe. Power is expressed as a percentage of subject's bodyweight (BW).*

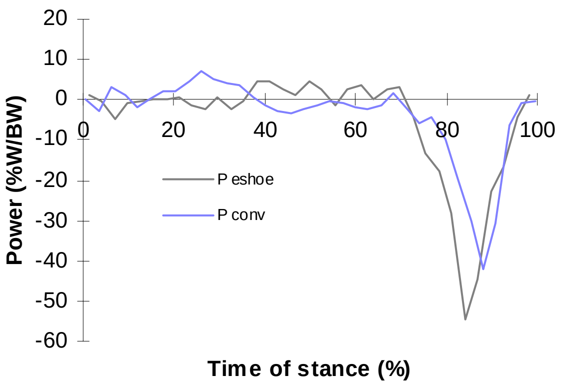

Fig 12: *Representation of the power absorbed/generated by subject 6, when walking with the conventional shoe and the e-shoe. Power is expressed as a percentage of subject's bodyweight (BW).*

Standard error

Figure 13 represents data found for one subjects. In this figure it can be seen that the range of the standard error of the e-shoe covered the error range of the conventional shoe.

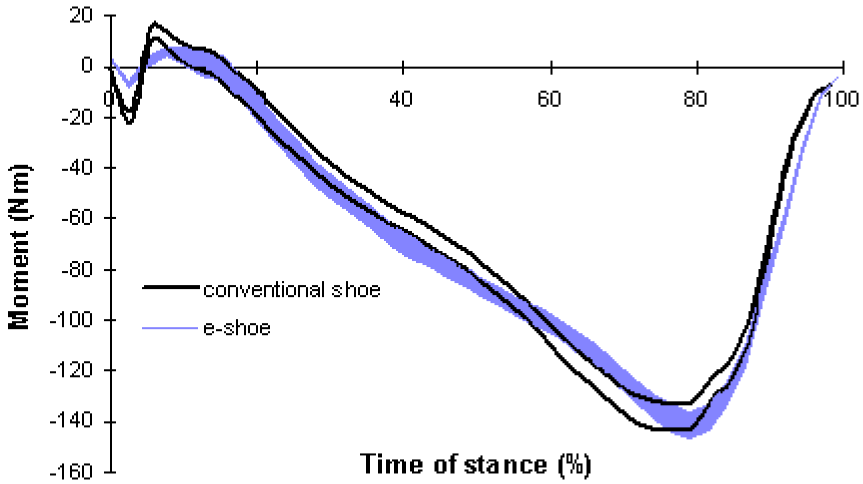

Figure 13: *Error range for both the conventional shoe and the e-shoe, for a subject whose error ranges covered each other.*

It can be seen in figure 14 that the same is not the case for another subject. Here the results found for the e-shoe falls outside the error range of the conventional shoe.

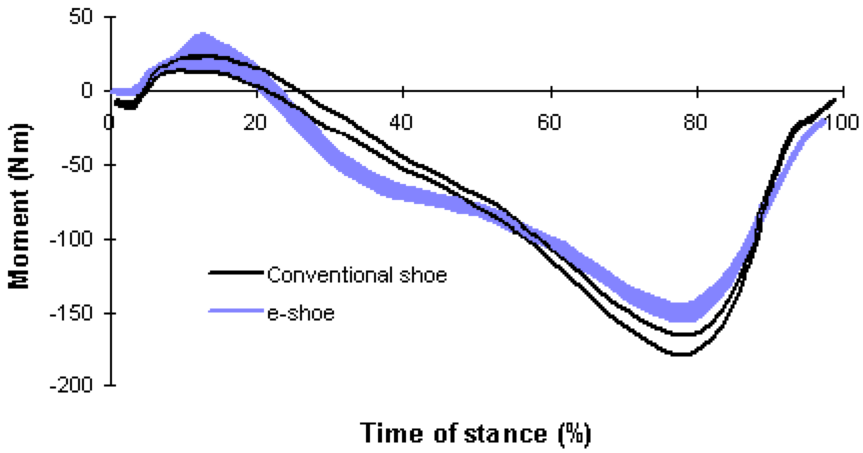

Figure 14: *Error range for both the conventional shoe and the e-shoe, for a subject with different error ranges for both shoes.*

The above mentioned results were found throughout the whole population and in a random order.

Discussion

The tests regarding the impact absorption and energy return properties of the shoes incorporated in this study indicated that the e-shoe used, had the same properties as the previously manufactured prototype. In prior research regarding the e-shoe (final report: e-shoe, elastic strain energy footwear, 1995)[1] it was found that the e-shoe had a higher shock absorption and a higher energy return when running, compared to a conventional shoe.

The results found in the present study are in comparison with kinematic data obtained by Winter (1990)[7]. The results only showed a significant difference between the conventional shoe and the e-shoe for F_{xmin} and the time of occurrence of F_{xmin}. For F_{xmin} significant lower values were found for the e-shoe trial, which implies a lower acceleration in the second part of stance. Also in the e-shoe trial F_{xmin} occurred significantly later during stance time. For the other parameters no significant differences were found.

Small differences in the construction of both shoes can have an effect on walking kinematics. The outer sole of the e-shoe was slightly deformed by the process of adding the insert. This resulted in a rocker in the middle of the outer sole. The found differences in F_x could be caused by this rocker. F_x is used to initiate and bring to an end the periods of locomotion (acceleration and deceleration). Once a constant speed has been obtained F_x should theoretically no longer be necessary to maintain speed (Rose and Gamble, 1994)[5]. However F_x is still required to maintain body balance during gait. When walking this rocker could act as a lever under the middle of the foot, pushing the centre of pressure forward. Because the foot is earlier in the position to toe off, the needed F_x for forward progression can be lower and shifted to a later point in stance time.

For the different subjects a high variability of the differences in walking kinematics between both shoes was found. As mentioned in the results, the e-shoe had an effect on some subjects, while for others an opposite or no effect was found. The insert of the e-shoe was designed for a person of 70 kilograms. The subjects used in this study ranged in weight from 61 kilograms to 99 kilograms. However the effect of the e-shoe was not depended on the weight of the subject, since the effects of the e-shoe seem to be random across the population.

As mentioned above, the tests regarding the impact absorption and energy return properties of the used shoes indicated higher energy return and shock absorption properties in the e-shoe. Therefore it can be assumed that the subjects altered their walking kinematics. Walking kinematics could be altered by the fitting of the shoe. In the present study only one pair of conventional shoes was available and only one similar pair of the e-shoe. Both were in a men's size 8. For some subjects the shoes were slightly to big and an extra inner sole had to be added to make the fitting better. Therefore not all the subjects were walking comfortably and might have altered their walking kinematics, next to the possible effect of the above mentioned rocker.

Part of the results can be explained by the alterations in walking kinematics to compensate for the differences in footwear. Not everybody alters his walking kinematics at the same rate and over the same time span. Since in this research the subjects had only five minutes to adapt to the shoe and a high variability was found between the subjects, it is reasonable to assume that the adaptation time has a large effect on the results. A longer adaptation time may result in a lower variability between the subjects.

When looking at the standard errors, for some subjects it was found that the results from the e-shoe covered the range of the results found for the conventional shoe. For other subjects this was not found, which implies an actual difference between both shoes. However Clarke et al. (1983)[9] reported a step to step coefficient of variation of 9.5 % in the vertical force impact peak during jogging. Next to this coefficient variation, it should be commented that a rather small variability in moment patterns was found for jogging (Winter, 1983)[10], compared to a high variability reported in the same patterns during normal walking (Winter, 1980)[11]. Therefore a higher step to step variation than this 9.5% should be accounted for. When adding this step to step variation to the standard error, a bigger range for both shoes will be found and the results for both shoes will possibly cover each other. Better results would have been found if data was averaged over more trials, which reduces the effect of the step to step variation on the standard error.

Comments made by the subjects showed more comfortable walking when walking on the e-shoe. The subjects could feel the higher shock absorption properties of the e-shoe. The energy return properties were not commented on by the subjects. One of the subjects even reported less pain in his painful achilles tendon when walking with the e-shoe. Since the subjects were not asked for a subjective response and all the responses were spontaneous, these responses show an actual difference between the shoes. Therefore, although no significant objective results were found, it cannot be said that the shoe has no effect.

Recommendation

More research should be conducted with a more homogenous group and more trials. Also the effect of the adaptation should be studied, to get a clearer view on the effect of the e-shoe on walking kinematics. To achieve a more comprehensive conclusion, the subjective responses on the e-shoe should also be measured and taken into account.

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3) **Kistler** *Bioware®: Biomechanical Software Analysis system.* Kistler instrumente AG Winterthur, Winterthur Switzerland 1993

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8) **Mathsoft** *Statistical analysis in S-Plus.* Mathsoft international, Surrey United Kingdom 1997.

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Appendix A

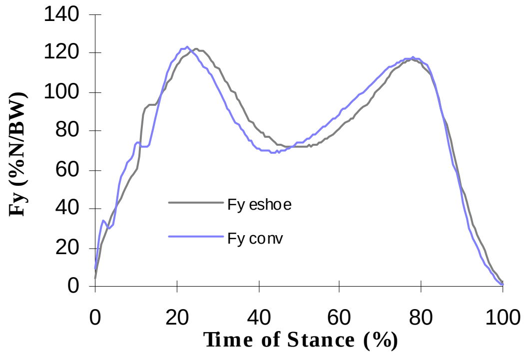
Weight conventional shoe	251 g
Weight e-shoe	374 g (- 22 g for inner sole)
Small extra mass	497 g
Large extra mass	916g
Weight rig	2083 g
Length to center of mass	0.43 m

Shoe	**Conv. 1**	**Conv. 2**	**Conv. 3**	**Conv. 4**	**Conv. 5**	**Conv. 6**
Mass	3250	3250	3250	2831	2831	2831
Time 1st peak, sec, t1	0.2044	0.2058	0.2053	0.2048	0.2055	0.2058
Time 2nd peak, sec, t2	0.6121	0.6165	0.6150	0.5595	0.5778	0.5813
Change time, t2-t1	0.4077	0.4107	0.4097	0.3547	0.3723	0.3755
Velocity, ms	1.9998	2.0145	2.0096	1.7398	1.8261	1.8418
Mass shoe, g	3.2500	3.2500	3.2500	2.8310	2.8310	2.8310
Return energy, Joules	6.4985	6.5945	6.5624	4.2846	4.7203	4.8018
Potential energy, Joules	13.7095	13.7095	13.7095	11.9420	11.9420	11.9420
Percentage energy return	47%	48%	48%	36%	40%	40%
Average	**43%**					
Impact	1959	2001	1994	1511	1673	1662
Average	**1985**			**1615**		

Shoe	**e-shoe 1**	**e-shoe 2**	**e-shoe 3**	**e-shoe 4**	**e-shoe 5**	**e-shoe 6**
Mass	3373	3373	3373	2954	2954	2954
Time 1st peak, sec, t1	0.2098	0.2073	0.2073	0.2073	0.2073	0.2073
Time 2nd peak, sec, t2	0.6875	0.6979	0.6979	0.6746	0.6279	0.6775
Change time, t2-t1	0.4777	0.4906	0.4906	0.4673	0.4206	0.4702
Velocity, ms	2.3431	2.4064	2.4064	2.2921	2.0630	2.3063
Mass shoe, g	3.3730	3.3730	3.3730	2.9540	2.9540	2.9540
Return energy, Joules	9.2592	9.7661	9.7661	7.7598	6.2863	7.8564
Potential energy, Joules	14.2283	14.2283	14.2283	12.4609	12.4609	12.4609
Percentage energy return	65%	69%	69%	62%	50%	63%
Average	**63%**					
Impact	1945	2045	2047	1395	1467	1371
Average	**2012**			**1411**		

Appendix B

The vertical force Fy over time for each subject. The e-shoe and the conventional shoe are plotted in one figure. Fy is expressed as a percentage of the subjects bodyweight. Time of stance is expressed as a percentage of the actual measured stance time.



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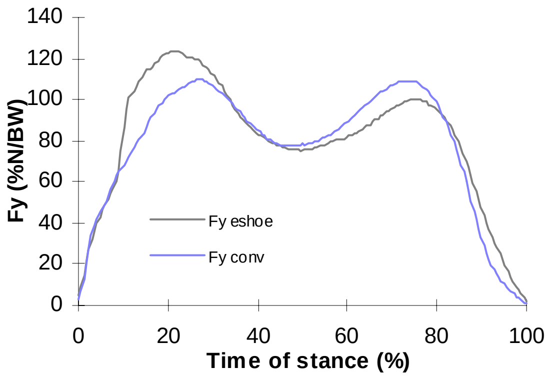

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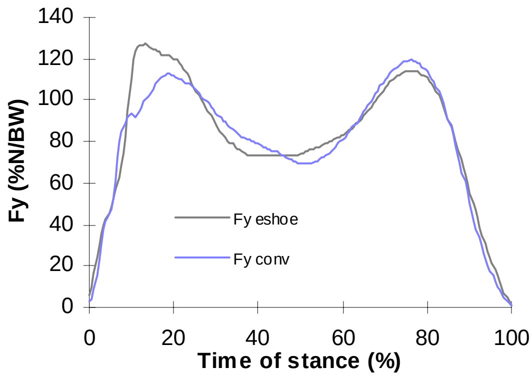

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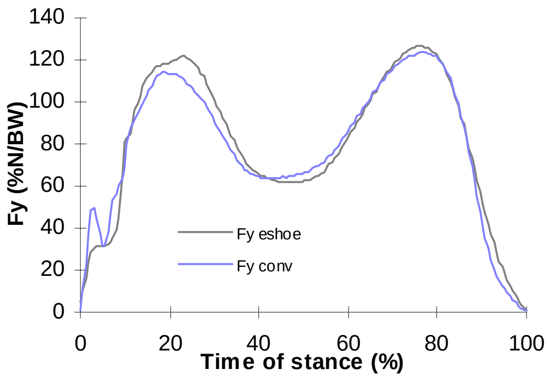

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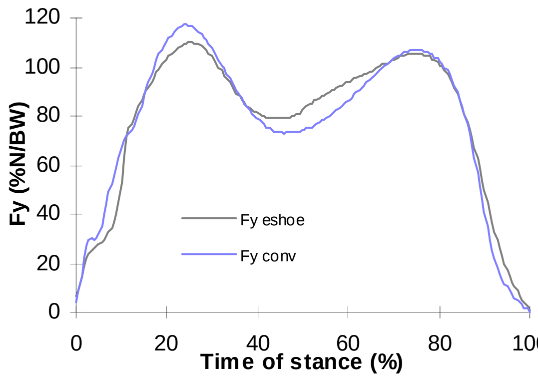

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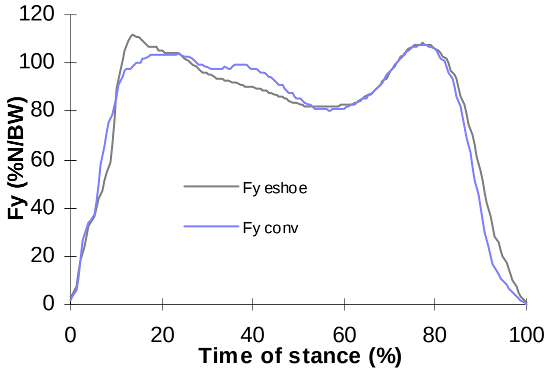

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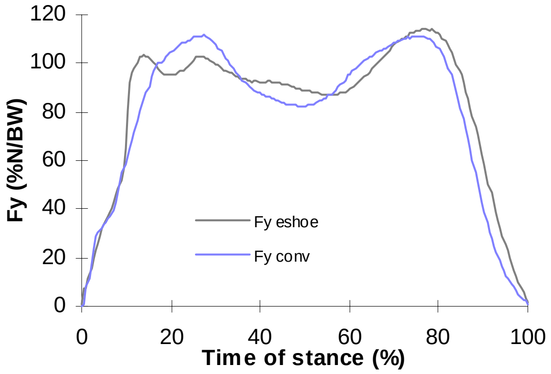

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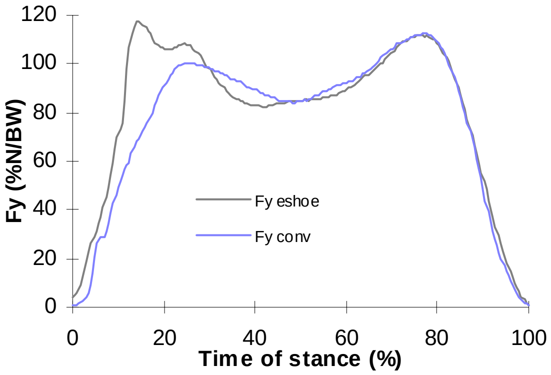

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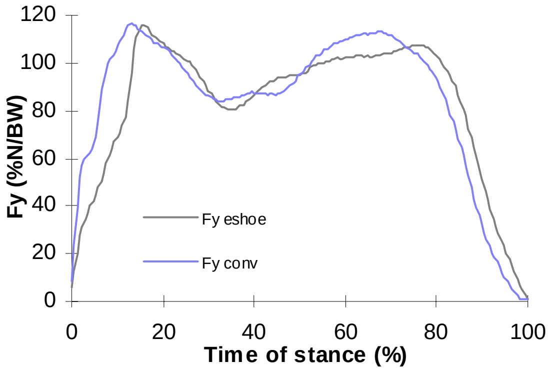

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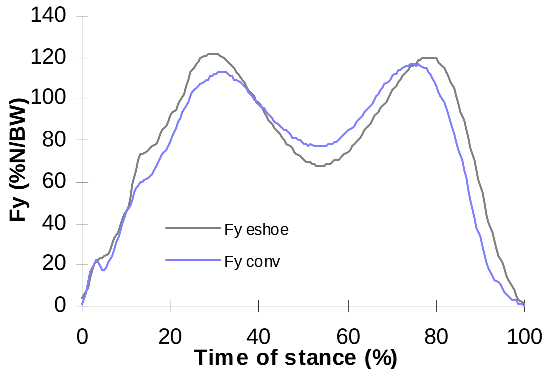

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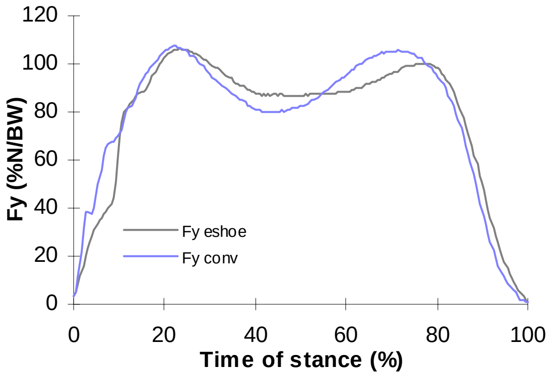

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Appendix C

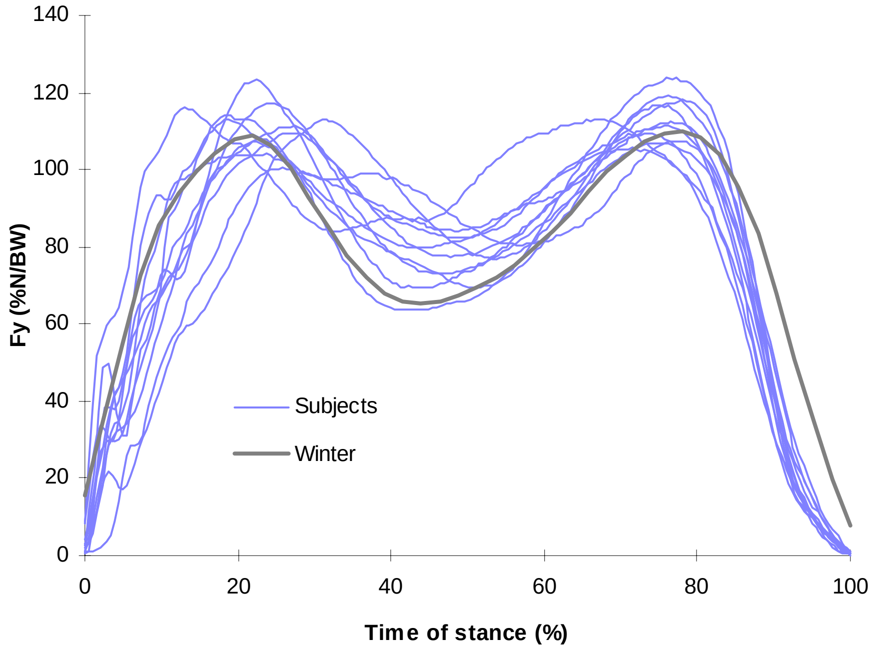


Figure 1: The F_y values found for each separate subject, when walking with the conventional shoe. The grey line represents mean data as found by Winter (1990).

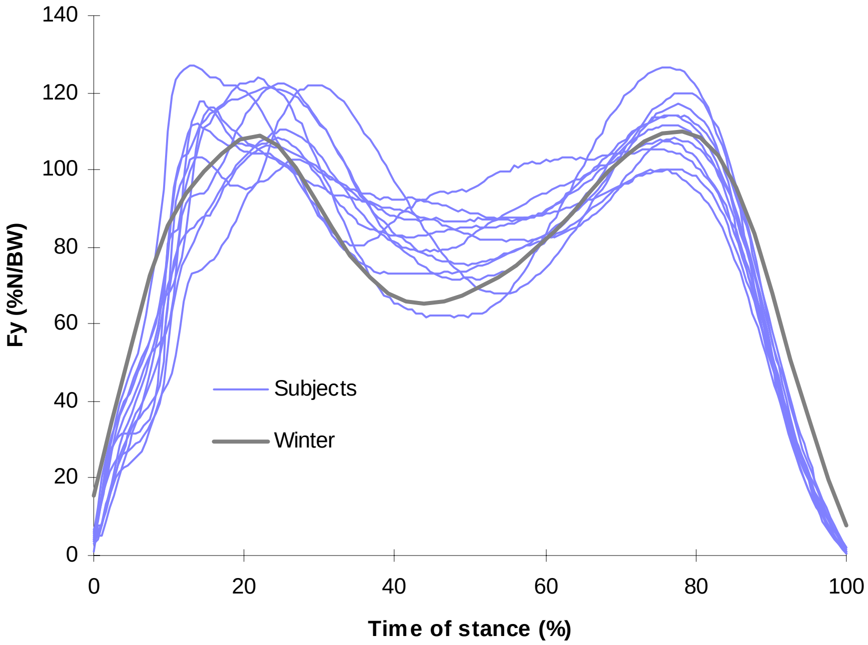
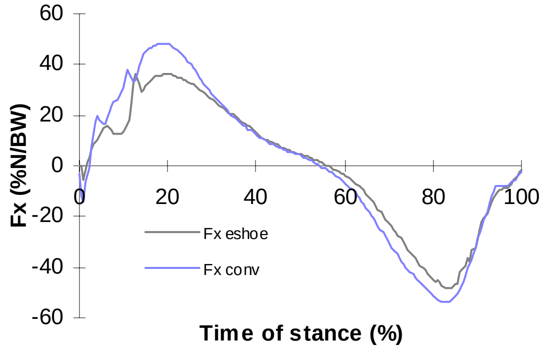


Figure 2: The F_y values found for each separate subject, when walking with the e-shoe. The grey line represents mean data as found by Winter (1990).

Appendix D

The anterior/posterior force over time for each subject. The e-shoe and the conventional shoe are plotted in one figure. Forces are expressed as a percentage of the subjects bodyweight. Time of stance is expressed as a percentage of the actual measured stance time.



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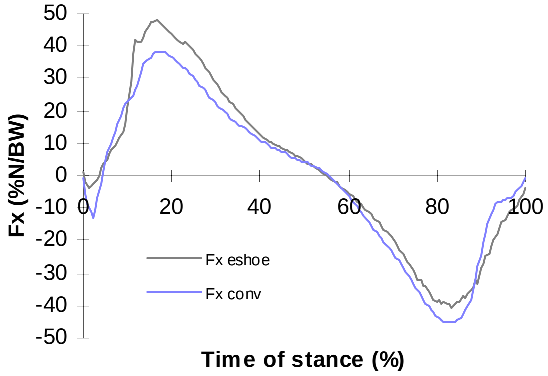

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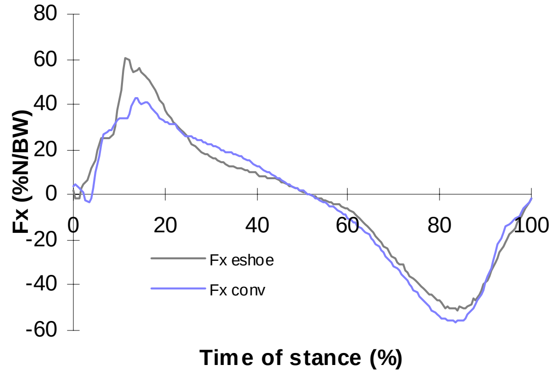

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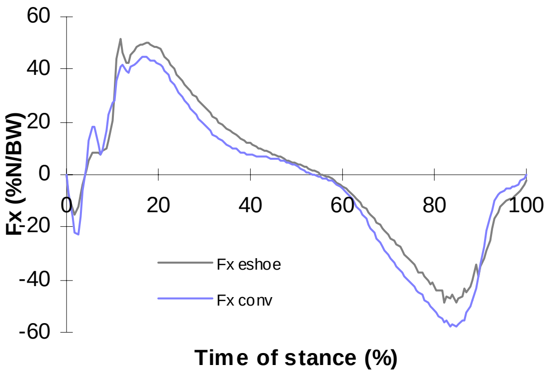

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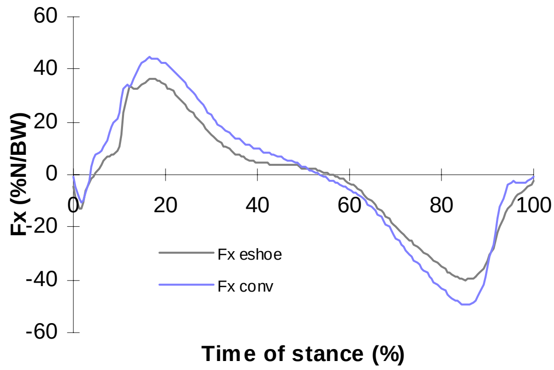

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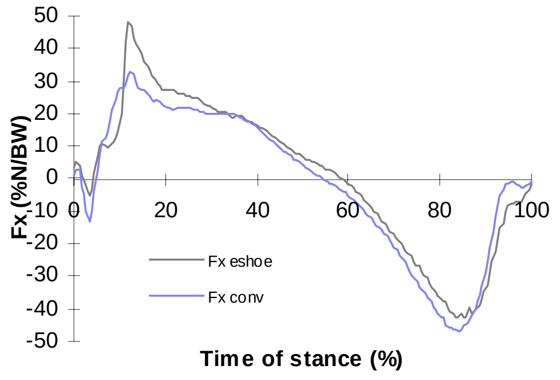

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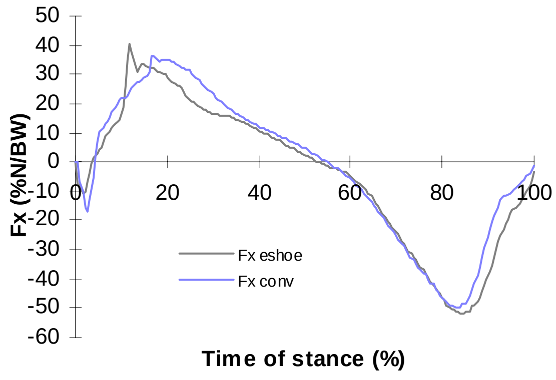

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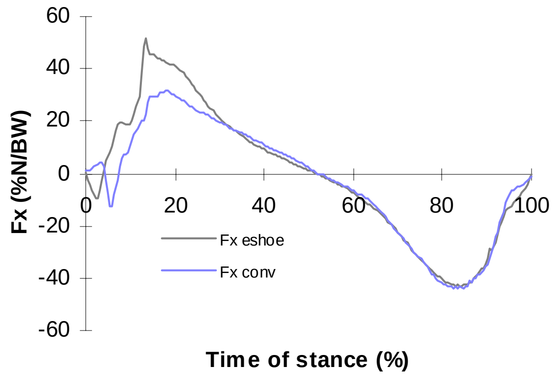

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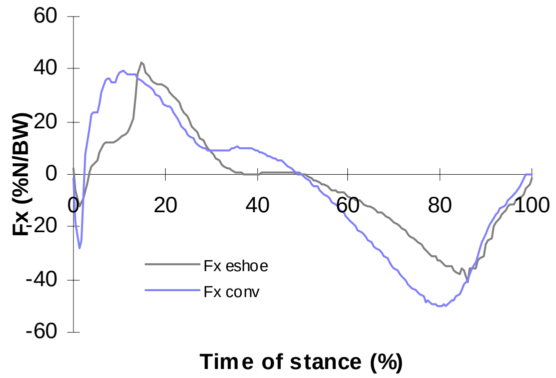

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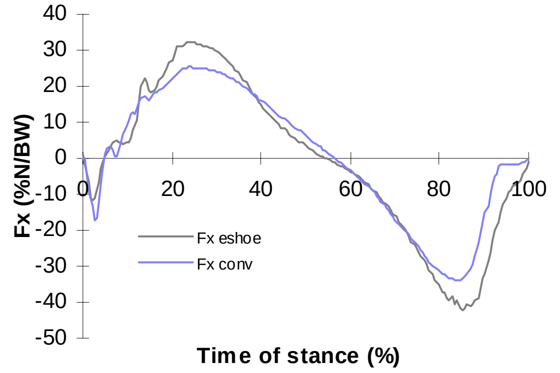

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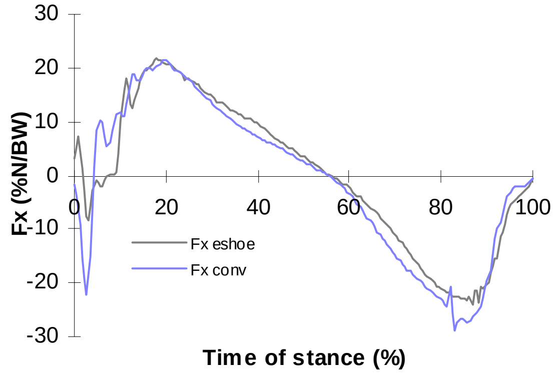


Subject 11

Appendix E

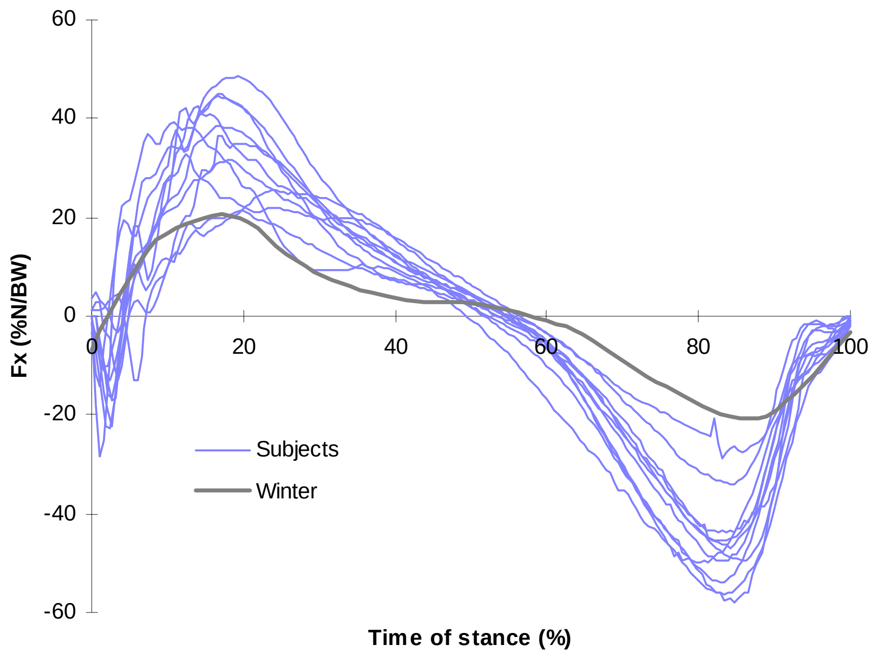


Figure 1: The F_x values found for each separate subject, when walking with the conventional shoe. The grey line represents mean data as found by Winter (1990).

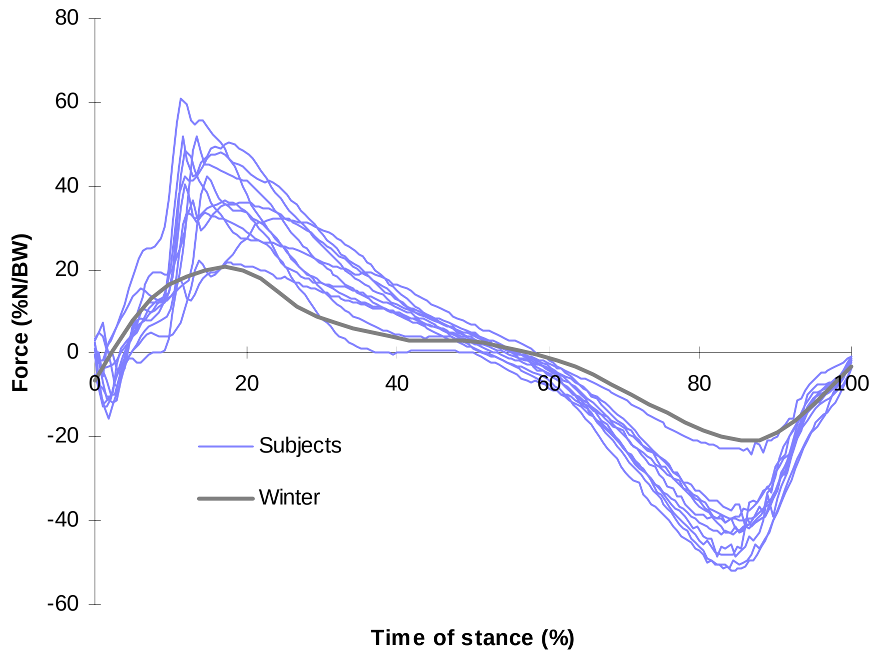
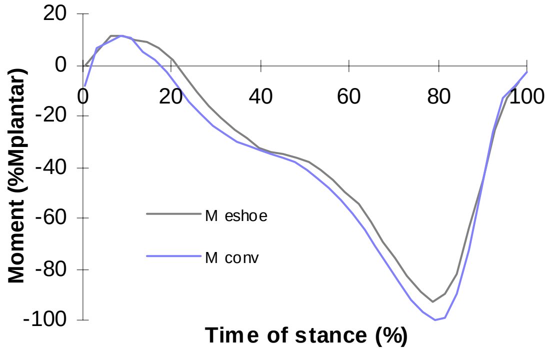


Figure 2: The F_x values found for each separate subject, when walking with the e-shoe. The grey line represents mean data as found by Winter (1990).

Appendix F

The moments around the ankle over time for each subject. The e-shoe and the conventional shoe are plotted in one figure. Moments are expressed as a percentage of the maximal plantarflexing moment, as measured when walking with the conventional shoe. Time of stance is expressed as a percentage of the actual measured stance time.



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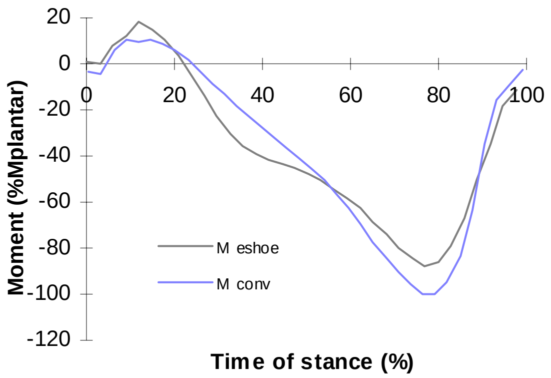

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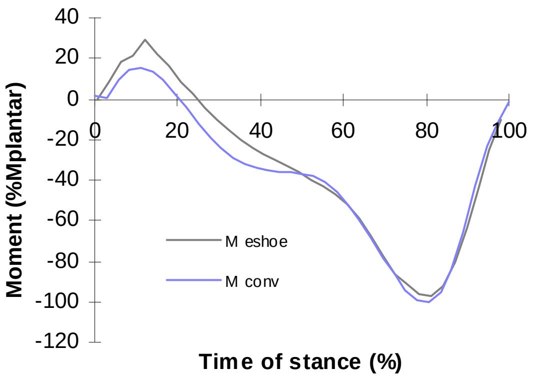

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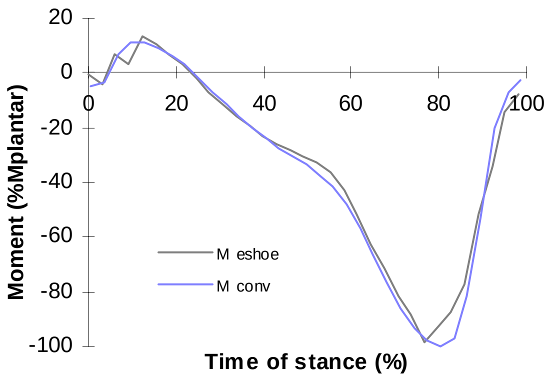

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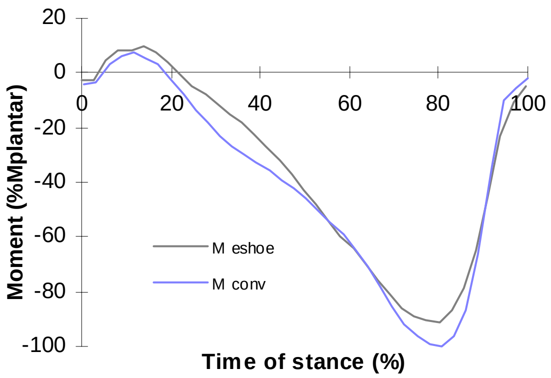

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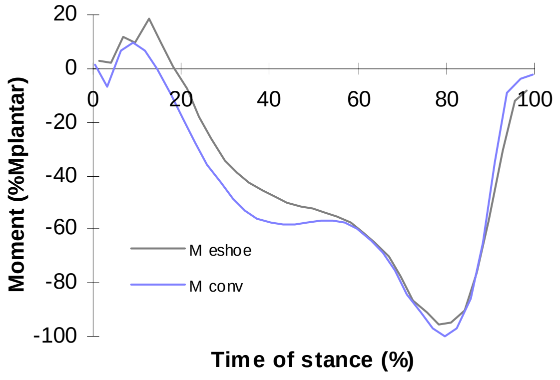

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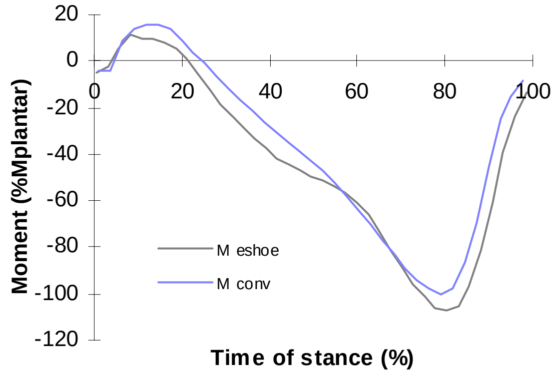

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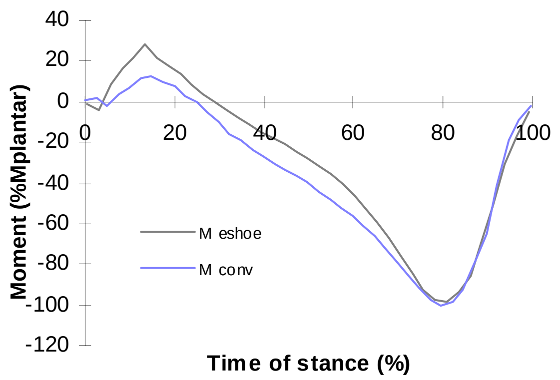

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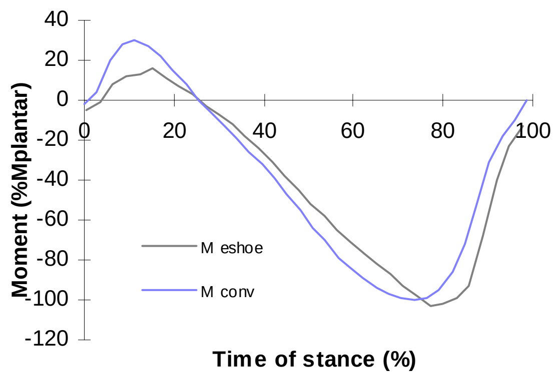

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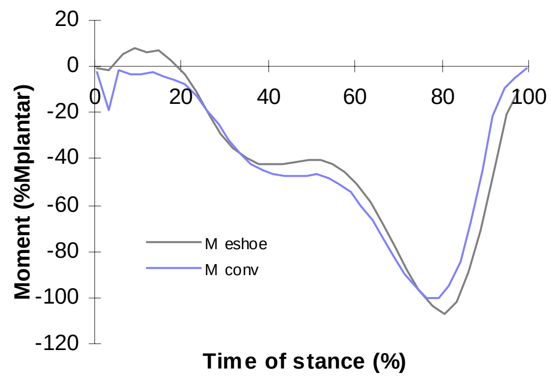

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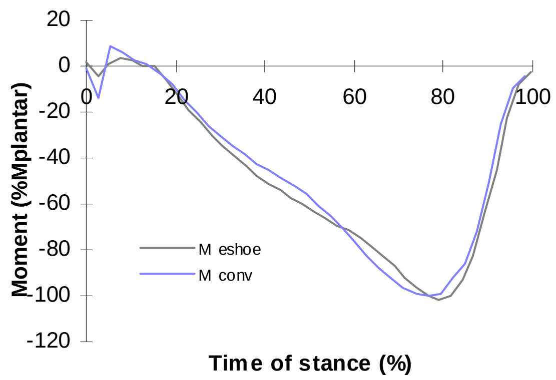


Subject 11

Appendix G

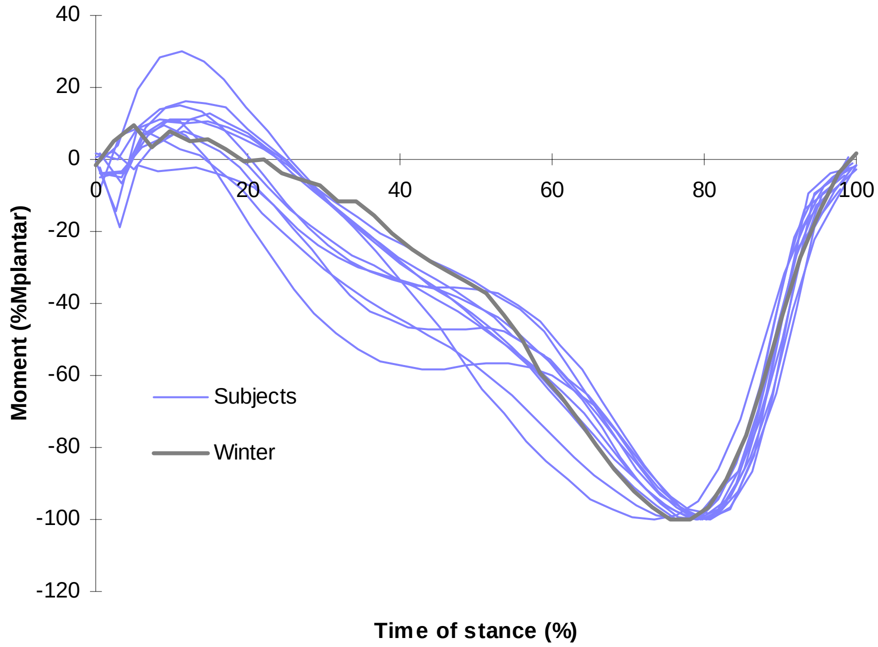


Figure 1: The moment magnitudes calculated for each separate subject, when walking with the conventional shoe. The grey line represents mean data as found by Winter (1990).

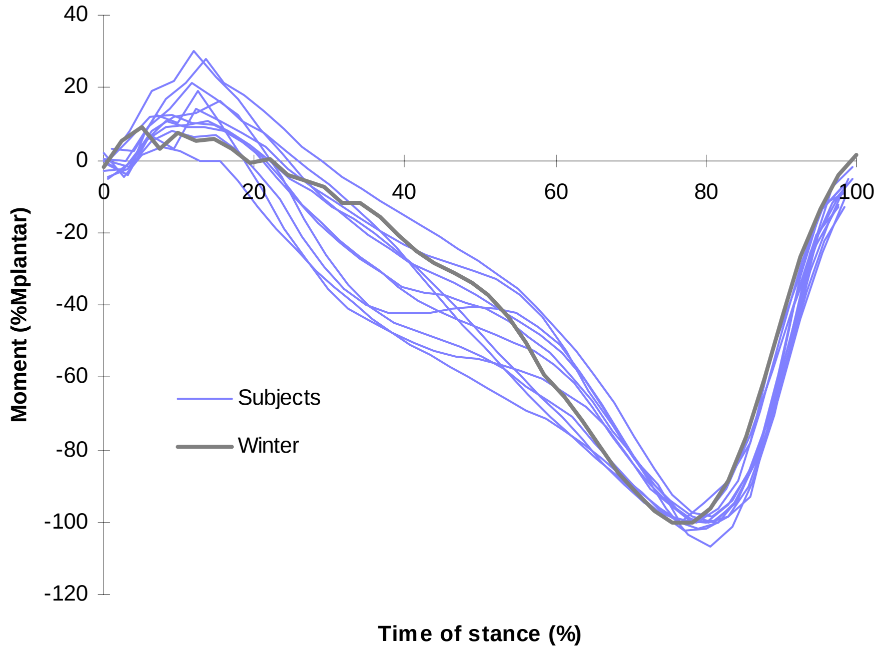
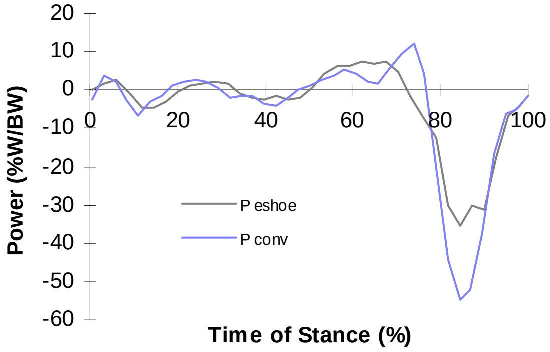


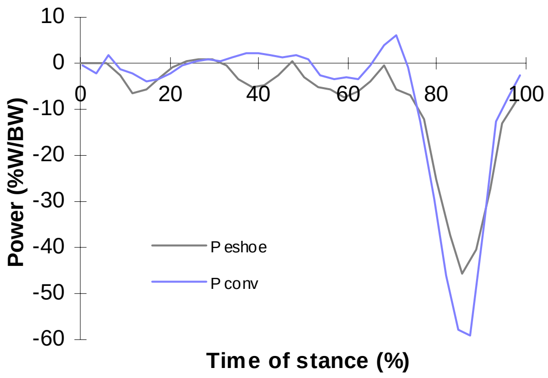
Figure 2: The moments magnitudes calculated for each separate subject, when walking with the e-shoe. The grey line represents mean data as found by Winter (1990).

Appendix H

The power generated around the ankle over time for each subject. The e-shoe and the conventional shoe are plotted in one figure. Powers are expressed as a percentage of the subjects bodyweight. Time of stance is expressed as a percentage of the actual measured stance time.



Subject 1



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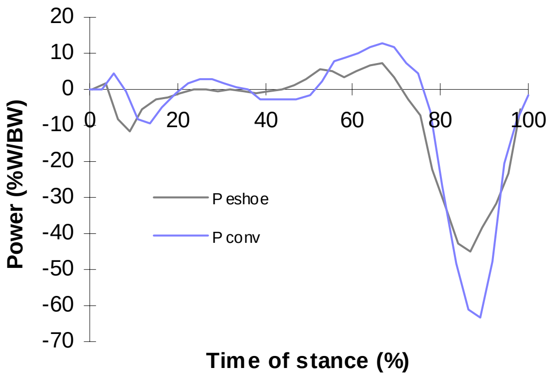

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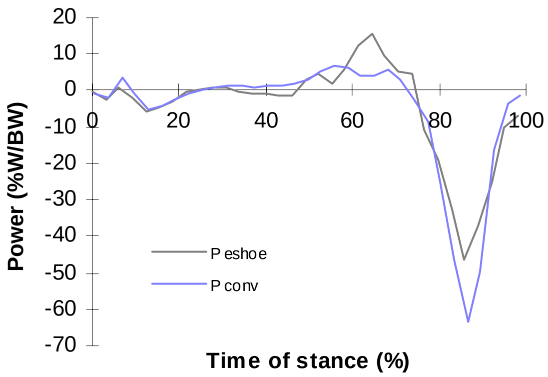

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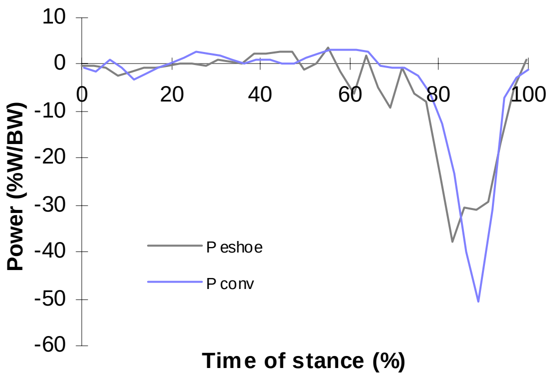

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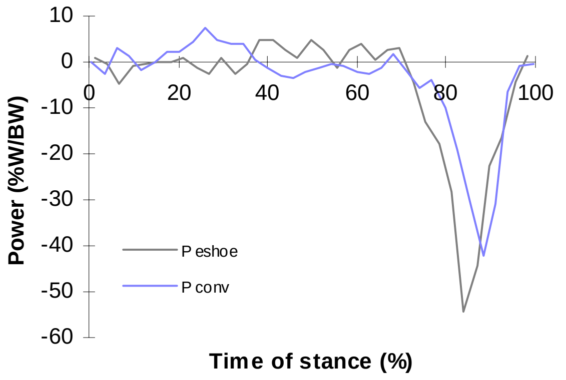

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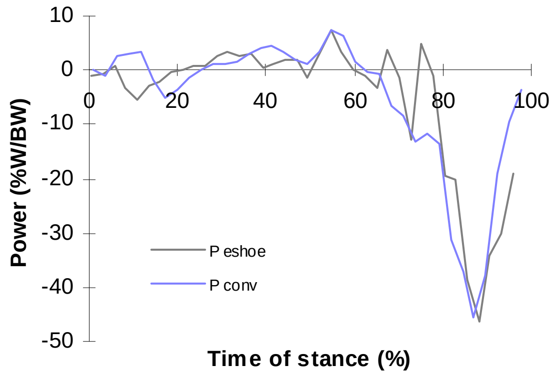

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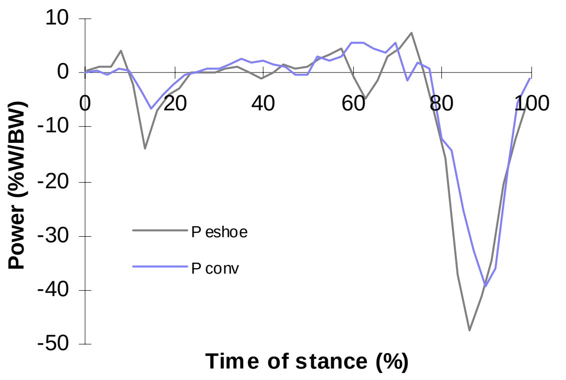

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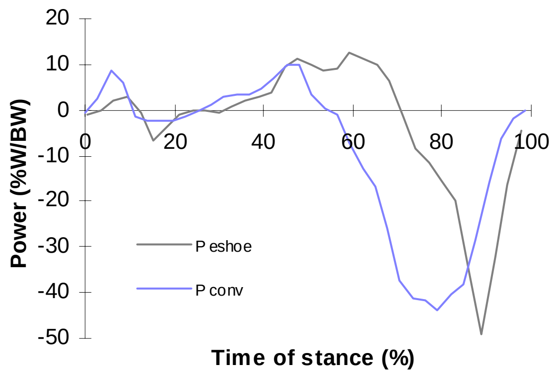

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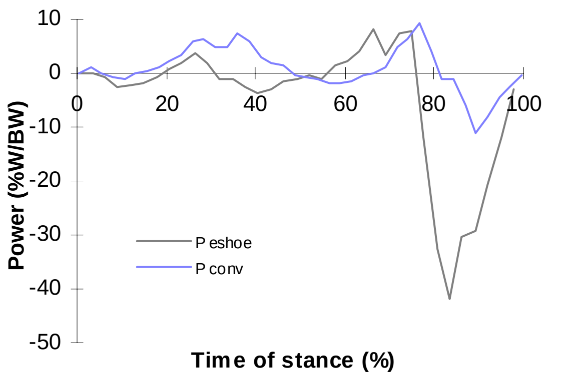

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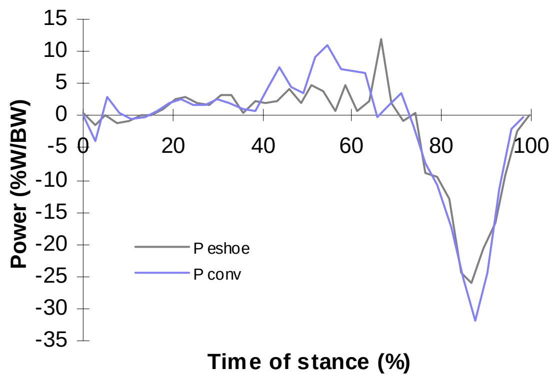

Subject 11

Appendix I

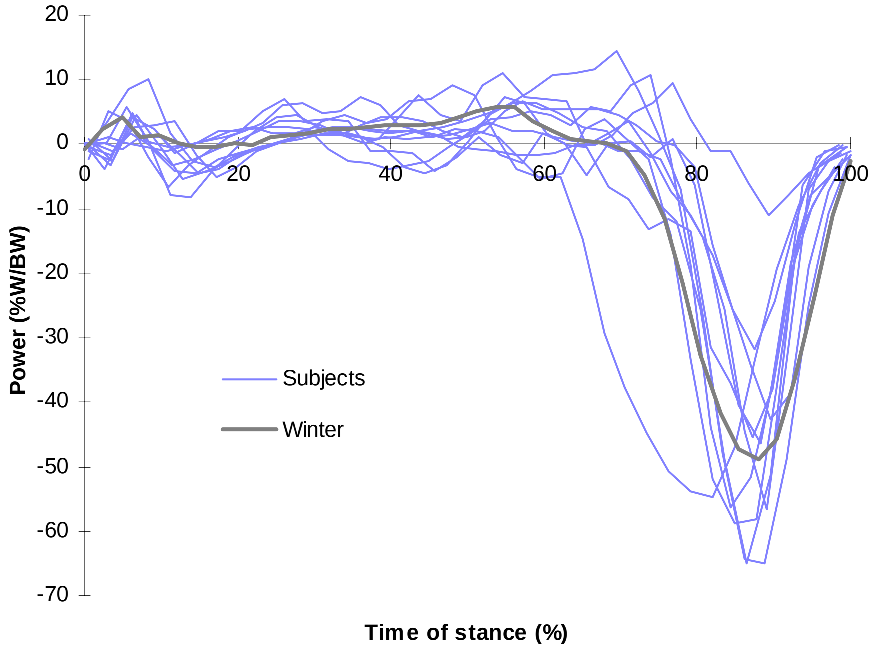

Figure 1: The power magnitudes calculated for each separate subject, when walking with the conventional shoe. The grey line represents mean data as found by Winter (1990).

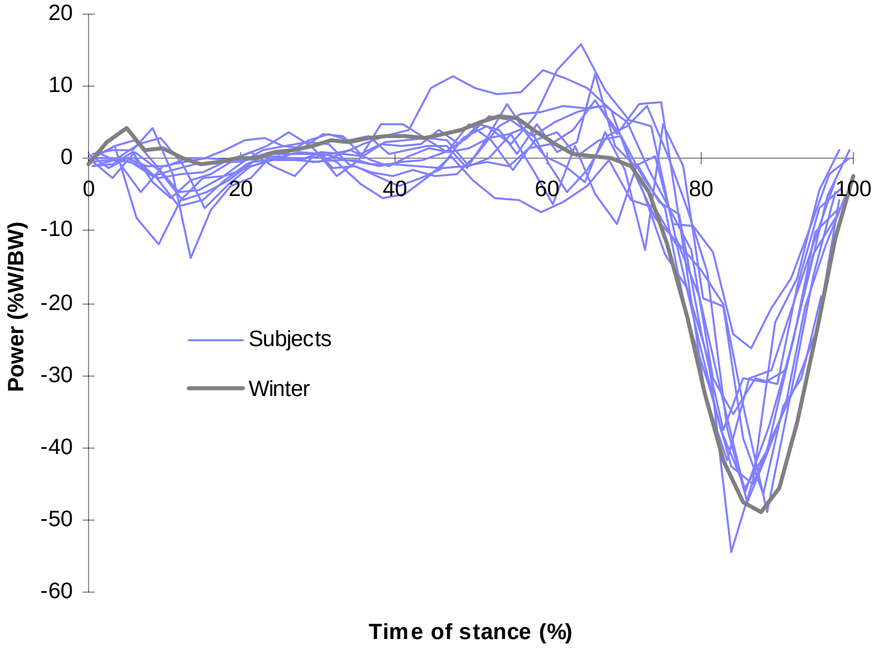

Figure 2: The power magnitudes calculated for each separate subject, when walking with the e-shoe. The grey line represents mean data as found by Winter (1990).