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The effect of direction and fatigue while running on an athletic track on kinematic inter-limb difference

Master Thesis

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Abstract

Running is a popular sport with little need of equipment, however running also correlates with a lot of injuries in the lower limbs. Running technique can be an important factor in injuries. To improve running technique, it is important to receive appropriate feedback. Symmetry between the lower limbs movements is particularly important. Differences between the left and right lower limb are found during measurements outside standardized and controlled environments. These differences were found during a marathon, but also during sprinting in a curve (anti-clockwise). However, it is not known yet if there are inter-limb differences during distance running on an athletic track with curves. Furthermore, the mutual relation between fatigue and inter-limb difference is not clear yet.

The aim of this study was to examine whether the running direction (straight, clockwise (CW) or anti-clockwise (ACW)) has an effect on the inter-limb difference in kinematics. Furthermore, the effect of fatigue and leg dominance on the inter-limb difference was investigated. An inter-limb difference in straight, CW and ACW running was expected. In addition to this, it was assumed that the outer leg had a larger step length and a shorter ground contact time than the inner leg, which results in larger inter-limb differences in the curves in comparison with the straight direction.

Twelve trained runners performed a 4 km, non-fatigued run (i.e. performed at a speed bearable for the subjects) followed by a fatiguing protocol, where each subject ran between 4 and 12 times 100 m series with an increasing velocity. Subsequently, subjects ran a 1.2 km, fatigued run, on an athletic track. In order to collect data for both CW and ACW curves, the subjects switched running direction once during the non-fatigued run and once during the fatigued run. Inertial Measurement Units (IMUs) were used to calculate joint kinematics and spatiotemporal parameters. The inter-limb difference values (left side - right side) and the symmetry angle values were calculated to find inter-limb differences in the kinematic and spatiotemporal parameters.

The results showed that during the fatigued run, in the sagittal plane, there was a significantly higher inter-limb difference value in CW direction for knee at initial contact (IC) and midstance (MS), hip at IC and midswing (MSW) and ankle at MS. In the frontal plane, there was a significantly higher inter-limb difference value in the hip at IC for the CW direction for both the non-fatigued and the fatigued run. Due to fatigue, the knee at IC showed a significantly increased inter-limb difference value in the CW direction. Regarding symmetry angles, during the CW direction there was a significantly higher value in the knee at MS. Due to fatigue, a higher symmetry angle was found for the ankle at MS in the sagittal plane.

In conclusion, an effect of running direction is shown on the inter-limb difference. In particular, the CW direction showed the highest inter-limb differences. Furthermore, inter-limb differences increased in kinematic parameters in all directions due to fatigue and the increase was the highest for the CW direction. Lastly, no conclusions could be drawn if there is an effect of leg dominance.

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Acronyms

AIC	Akaike's Information Criterion
ACW	Anti-clockwise
AR1	Autoregressive
CS	Compound Symmetry
CW	Clockwise
IC	Initial contact
IMU	Inertial Measurement Units
MS	Midstance
MSW	Midswing
SA	Symmetry Angle
TO	Toe-off
UN	Unstructured

Contents

1 Introduction

Running is a popular sport with little need of equipment [1]. However, running also correlates with a lot of injuries in the lower limbs [2]. Improvements in running techniques can influence the running economy and lead to improvements in running performance [3][4]. Receiving appropriate feedback can help to improve the runners' technique [5][6] as well as preventing injuries [7]. It has been found that fatigue alters the running kinematics, which increases the risk of injuries [8]. Feedback can be provided by measuring and interpreting running parameters, such as kinematics, kinetics, shock attenuation and spatiotemporal parameters of the lower limbs.

The identification of kinematic, kinetic, shock attenuation and spatiotemporal parameters of the running technique is often done in a standardized and controlled environment, using a three-dimensional optical motion capture system and force plates [9][10][11]. Measurements in these studies have been performed on short walkways or on an instrumented treadmill. Short walkways only allow measurements over a short period of time, while treadmills only allow measurements at a fixed velocity, which results in a cyclical pattern. For example, Hanley et al. analyzed changes in gait variability and symmetry in distance runners [9]. Athletes ran on an instrumented treadmill for 10.000 meters. They found asymmetries in a few variables such as flight time and impact force. None of the athletes ran asymmetrically for more than four of the seven variables and therefore there was no clear asymmetry shown in the results. In contrast, Radzak et al. investigated the effect of fatigue with an exhaustive protocol on an 18-m runway [11]. Fatigue is used to denote a transient decrease in the capacity to perform physical actions [12]. They found significant differences in kinematic and kinetic parameters between lower limbs in a healthy population, which was done in a controlled environment [11]. The differences were observed both in rested and fatigued states. Furthermore, some authors have hypothesized that the dominant and non-dominant legs fatigue at different rates [13][14], but this was not supported in the results of Ali et al. [15], Brown et al. [13] and Girard et al.'s research [16]. These previous studies were done in a controlled environment but a controlled environment differs from a real-world running environment and could result in different kinematics and kinetics. A treadmill facilitates a more repeatable pattern of movement in comparison with a real-world running environment [17]. Therefore, it is expected that a larger running asymmetry will occur in real-world running.

Measuring kinematic parameters in 'real world' running is possible with Inertial Measurement Units (IMUs). IMUs are capable to collect a large amount of data. Reenalda et al. (2016) used IMUs to investigate the effect of fatigue during a marathon. It was observed that on a group level there were differences in kinematics between the left and right leg [18]. This study also found increased peak knee flexion at midstance and midswing and increased ankle angle at initial contact due to fatigue. These differences were not supported by the controlled environment studies of Hanley et al. and Radzak et al. [9][11]. Strohrmann et al. (2012) also used IMUs to investigate kinematic changes in fatigue running [19]. They found that runners on a treadmill had a lower step frequency as they fatigued and that, during the outside run, runners rotated their leg slower forward. No clear evidence was demonstrated about whether kinematic asymmetries arise, increase or decrease due to fatigue.

A fundamental difference in the running environment between treadmill and overground running is the absence of curves in treadmill running. Many studies already assessed the difference between curves and straight running. However, these studies focused on sprinting and found that 3D changes are present in the joint angles in the frontal and transverse plane of the lower limb during curve sprints [5][20][21][22]. Alt et al. (2015), also found higher maximum values for hip adduction and hip external rotation during contact time of the inner leg when running in a curve. The inner leg was stabilized in the movements in the frontal plane (adduction-eversion), while the outer leg seemed to control the motions in the horizontal plane (rotation) [5]. Furthermore, kinematic differences between curve and straight sprinting were found during running around an athletic track. It is shown that the left ground contact time tends to be longer than the right one [21][23][24][25]. The radius of the curve during running also influences the sprinting performance [26]. Churchill et al. (2019) investigated curve sprinting in one direction around an athletic track. Since the left and right legs are presumably not identical, it is important to take both directions into account [27]. The effect of running in curve versus straight line running on the kinematics in the lower limbs is not known for long runs under the influence of fatigue.

Leg dominance could also be a factor that influences running parameters. Seeley et al. [14] found increased dominant limb impulses during the propulsive phase of fast-speed walking. Therefore, Brown et al. [13] assumed that there would be a difference between the dominant and non-dominant leg during running. However, during running, there was no significant difference found between the dominant and non-dominant lower limb [13][16]. This suggests that kinematic or kinetic inter-limb differences seen during overground running are not affected by lower limb dominance. These findings were only for linear running and anti-clockwise running. The effect of leg dominance in clockwise curve running is not yet known.

2 Scientific background

2.1 Gait cycle

The running gait cycle can be divided into three primary phases, the contact time (0% to 45%), float phase (45% to 50% and 95% to 100%) and swing phase (50% to 95%), which alternates for each lower limb [28]. During the contact time, one foot is on the ground, for the entire time. During the float phase, both feet are in the air and in the swing phase, one foot is for the entire time, in the air. In this study, contact time, initial contact (IC), midstance (MS), midswing (MSW), step length and step frequency are parameters of interest and will be described more in detail below. The running gait cycle is shown in Figure 2.1, which represents the left foot.

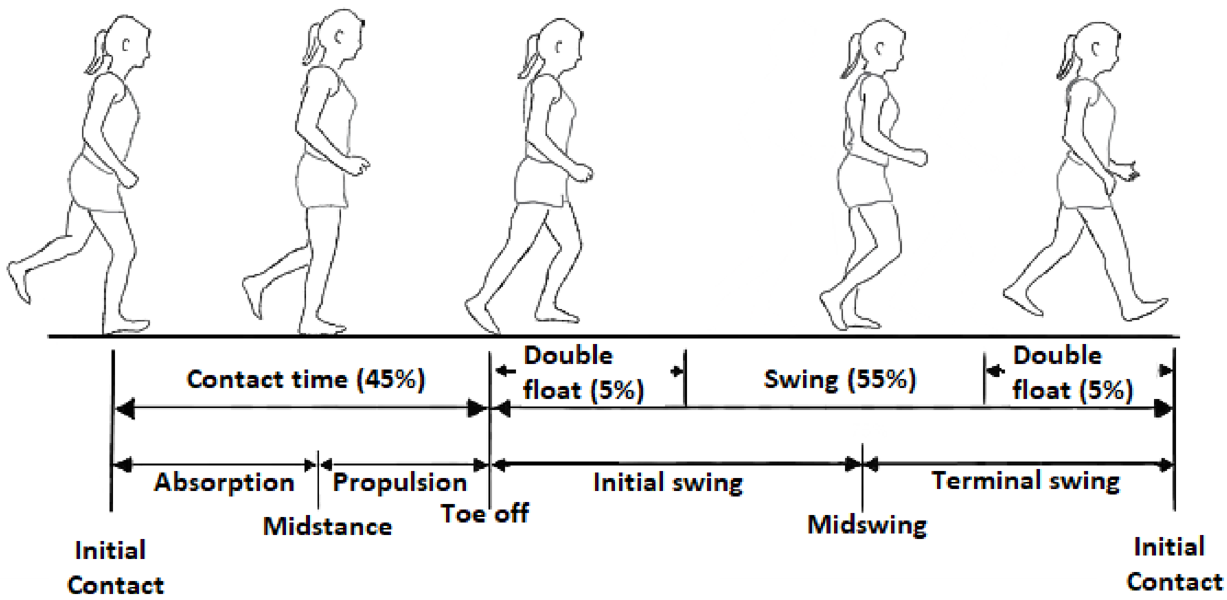

Figure 2.1: Gait cycle during running (redraw from Coughlin et al. [28]).

- Contact time (stance phase) (0% - 45%)
  The contact time consists of 4 phases, which are described below. Contact time is one of the parameters that is used in the analysis of this study. During this phase, one foot is for the entire time, on the ground.
  - Initial Contact (IC)
    Initial contact is the start of the gait cycle. IC refers to the moment at which the foot hits the ground. This moment is, called IC, independently of the position of the contact (heel, midfoot or forefoot). When the left foot is at IC, the right foot is off the ground and in swing phase. At this moment, muscles, tendons and joints function to absorb the impact of the landing [29]. The hip and knee at IC are used as parameters in this research.
  - Absorption
    Once the left foot makes contact with the ground, the body is performing a controlled landing, managed via deceleration and braking. For this reason, the knee and ankle flex angles and the foot rolls to absorb impact forces.
  - Midstance (MS)
    The absorption phase continues until the left leg is directly under the hip as the body weight passes over it. At this moment, the left ankle is at maximum dorsiflexion and the knee at maximum flexion angle. The ankle and knee at MS are used as parameters in this study.
  - Propulsion
    After the leg made a controlled landing and absorbed energy, the left ankle, knee and hip all start extending to push the body up and forwards. This phase ends when the toe of the left foot leaves the ground. This is called Toe-off (TO). TO is used to determine the contact time of the feet.

- Swing phase (50% - 95%)
  The swing phase consists of 3 phases. However, only the midswing is of interest in this work and is therefore described below.
  - Midswing (MSW)
    The swinging leg is passing the contact time leg, and the thigh reached its peak advancement. During this phase, the hip and knee are flexed. At MSW the knee has the highest peak flexion. The hip, knee and ankle angles during MSW are used as parameters in this study.

  Below important spatiotemporal parameters are described, which were used in this study.

- Step length
  The step length is the distance between the point of IC of one foot and the point of IC of the opposite foot.
- Step frequency
  The step frequency is how many steps per leg is done per minute.

2.2 Inertial Measurement Units

An Inertial Measurement Unit (IMU) is an electronic device that has 9 sensors, 3 accelerometers, 3 gyroscopes and 3 magnetometers. The accelerometer measures the linear acceleration in the three axes (X, Y and Z). It is assumed that the Z-axis is aligned with gravity. The X and Y axes provide orientation measurements and give the orientations in these axes. During active movement, the estimated orientation of the sensors is biased. Movement artifacts are added to the acceleration signal. Therefore, raw data from the sensor needs to be filtered [30].

While accelerometers can measure linear acceleration, gyroscopes measure angular velocity around three axes; pitch (X-axis), roll (Y-axis) and yaw (Z-axis). A gyroscope can be used to determine an object's orientation within 3D space. However, a gyroscope has no initial frame of reference (like gravity), but it can be combined with an accelerometer to measure the angular position. The magnetometer measures the magnetic fields. Combining with accelerometer and gyroscope data, the absolute heading is determined.

After the sensor to segment calibration, each sensor unit provides an estimation of the orientation of the body segment relative to a global reference. Each sensor provides biased information. To overcome this bias, a combination of these sensors is used to provide more accurate sensor orientation. This is used to calculate 3D joint angular kinematics.

3 Objective

The inter-limb difference between straight line and curve running for long runs and the effect of fatigue is not yet known. Therefore, the aim of this study was to examine whether the running direction (straight, clockwise (CW) and anti-clockwise (ACW)) on an athletic track affects inter-limb difference. Furthermore, this study investigated the effect of fatigue and leg dominance on the inter-limb difference in kinematics and also in spatiotemporal parameters.

The inter-limb difference during straight, CW and ACW running has been studied. A series of hypotheses were formulated and tested:

- It was hypothesized that an inter-limb difference during straight, CW and ACW would exist.
- During curved running, it was expected that the outer leg has a kinematic difference in comparison with the inner leg; meaning that the inter-limb difference is larger during CW and ACW running.
- During curved running, the outer leg is expected to have a larger step length and a shorter ground contact time than the inner leg. This would affect the inter-limb difference and a larger inter-limb difference during curved running (CW and ACW running) is expected.
- It was expected, that fatigue would increase the inter-limb differences expressed in joint angles and spatiotemporal parameters.

4 Methods

4.1 Experiment design

12 healthy runners (6 male, 6 female, mean ± SD: age 29.8 ± 11.2 years (age range 21-55), height 177 ± 9.5 cm, weight 72.3 ± 11.9 kg, an average velocity of the subjects' personal best 10 km of 12 ± 2.9 km/h and running experience of 6 ± 4.3 years (experience range 1.5 - 16 years)) who ran at least 15 km per week in the previous six months were recruited from the University of Twente and surrounding community (Table 4.1). They reported no history of injuries in the previous year. The experimental protocol was approved by the local Medical Ethical Committee and all participants signed an informed consent form prior to participation.

Prior to the running protocol, subjects physical parameters were noted, foot strike pattern was captured with a JVC HD camera, IMU sensors were attached to the runner and static and dynamic calibrations were performed to obtain sensor to segment calibration.

Table 4.1: Characteristics of runners

PP	Age (years)	Height (cm)	Mass (kg)	Speed 10k (km/h)	Running experience (years)
1	25	182	69	13.5	5
2	23	164	55	10.9	3
3	24	167	69	9.4	9
4	45	167	58	10.9	16
5	43	185	75	17.1	9
6	55	188	100	10.3	10
7	21	184	65.5	18.2	5
8	24	168	63.5	10	7.5
9	25	174	78	9.7	2
10	26	187	77	12	1.5
11	23	169	75	10.2	1.5
12	24	188	82	12	6
Mean	29.8	176.9	72.3	12.0	6.3
SD	11.2	9.5	11.9	2.9	4.3

After a self-chosen warm-up of five to ten minutes, the runners performed three different runs on the athletic track at the University of Twente. Each subject ran during the first run a distance of 4 km, non-fatigued run, at a constant velocity. The constant velocity was determined based on a maximal 10 km performance run that the subject ran in the last year. Before the run, the subject was asked when the run was performed and if they were still able to run that speed. If this was not the case, the velocity was reduced to a more recent 10 km performance run. 100% of the average velocity during that run was used as constant velocity during the experiment. Runners followed a cyclist who cycled in front of the runner at the calculated velocity. The first run was categorized into two sessions (CW and ACW running), which was randomized. The subject switched direction of rotation of the track once, after 2 km, during the run. After the non-fatigued run, the subject performed a second run, which was a fatiguing protocol and was performed directly after the non-fatigued run. The subject ran sessions of 100 meter without stopping. These sessions had a minimum of 4 times and a maximum of 12 times. The velocity of the first 100 meter was 100% of the average velocity of the maximal performance run of 10 km. After every 100 meter, the velocity was increased by 0.2 km/h. A Borg Scale (Figure 4.1) was used after each 100 meter [31]. Each number of the Borg Scale indicated the subjects rate of perceived exertion. Number 16 indicated between "heavy" and "very heavy". This number was used to stop the fatiguing protocol. Number 16 was chosen, since it was important that subjects were able to finish the protocol and were not too fatigued. Once this number was reached, the subject continued to the last run. The subject ran an additional 1.2 km, fatigued run, with the same constant velocity as the non-fatigued run, where the subject switched direction of rotation of the track once after 0.6 km, which was the same order as non-fatigued run.

Load	Borgscore
	6
Very very light	7
	8
Very light	9
	10
Fairly light	11
	12
Fairly heavy	13
	14
Heavy	15
	16
Verry heavy	17
	18
Very very heavy	19
Maximum	20

Figure 4.1: Borg Scale from 6 to 20 which was used to indicate the subjects rate of perceived exertion during the fatiguing protocol [31]

4.2 Measurement device

Runners were equipped with eight Xsens IMUs (MTx, Xsens Technologies B.V., Enschede, the Netherlands). Each IMU weighed 30 gram and included 3D accelerometer (range $\pm 160 m/s^2$), 3D angular velocity (range $\pm 1200 degrees/s$) and 3D magnetometer (range $\pm 750 mGauss$). The IMUs were placed on the foot (under the shoe laces), tibia (on the anterior side, diagonally below the tibial tuberosity to the medial side), thigh (well above the knee on the lateral side of the upper leg), pelvis (attached at the back in between the left and right posterior superior iliac spine, close to the sacro-iliac joint) and trunk (on the superior side of the sternum) (Figure 4.2). To securely attach sensors to the skin, they were fixed with tensospray and kinesiotape. Running velocity and distance were recorded during the three runs using a GPS enabled watch (Garmin Forerunner 210, Garmin, Wichita USA). The bicycle velocity was controlled with a bicycle computer (Sigma Rox 12.0, Sigma, Germany).

Figure 4.2: IMUs that were placed at the feet (green arrow), tibia (blue arrow) and thigh (yellow arrow).

4.3 Data acquisition

Xsens software (Xsens MVN analyse 2019.2.1, Xsens, the Netherlands) was used for signal acquisition, while for data processing and analysis MATLAB R2018b (The MathWorks Inc., MA, USA) was used. To estimate the orientation of each sensor, a Kalman filter was used to fuse the data of each accelerometer, gyroscope and magnetometer. Static and dynamic calibrations were used to determine the time-invariant relation between each sensor frame and the corresponding anatomical segment frame. For this calibration, the subject was asked to stand still in upright position (N-pose) for four seconds and then walk for five meters turn and walk back to the start position and stand still for four more seconds.

4.4 Data analysis

For data analysis, the UTrack was divided into four parts of 75 meters and 4 parts of 25 meters. The parts of 25 meters were not used for data analysis. The four parts of 75 meters covered the straight and curve parts of the athletic track, as shown in Figure 4.3. Three phases of the non-fatigued run and fatigued run were defined. These stages were straight running, CW running and ACW running.

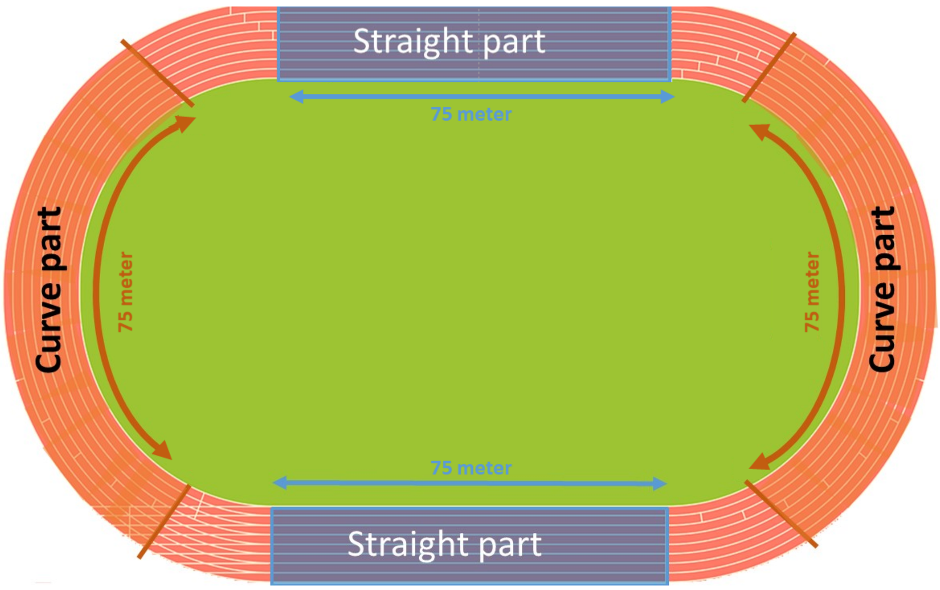

Figure 4.3: Top view of athletic track, where the parts for straight running (blue) and the parts for curve running (orange) are shown.

Detection of the straight and curve parts was performed in MATLAB. For each straight and curve part a length of 75 meter was used, which was calculated by means of the running velocity of each subject. Both, the straight and curve parts were detected based on the sideways velocity of the pelvis sensor. The straight parts were defined when the sideways velocity of the pelvis was constant. Based on the constant running velocity of the subject, the center of each straight part was defined. The peaks of the sideways velocity of the pelvis were identified as the center of the curves.

Next, event detection was based on inertial data acquired from the pelvis sensor. Peak downward velocity of the pelvis was used to identify the IC of the left and right foot. The TO of the left and right foot were detected based on the accelerometer data of the foot sensor. The data is cut into gait cycles starting with IC. The maximum value of knee flexion during the contact time was used to identify the MS of the gait cycle. The maximum value of the knee flexion during the swing phase was used to detect the MSW. For each stride, the hip, knee and ankle angles were obtained in the sagittal plane and the hip in the frontal plane.

The number of samples per step were obtained during step detection. Step duration was calculated by dividing samples per step by the sampling frequency of 240 Hz. Step frequency was calculated as the inverse of step duration. Step frequency and average running velocity were used to compute the step length. Contact time was calculated as the time between the IC of one leg to the TO of the same leg.

In this study, contact time, step length and step frequency were highlighted. These parameters were chosen because it was expected that these parameters would differ between the left and right leg during running in the curves [5][26]. Furthermore, data collected from the IMUs were used for the joint kinematics. Kinematic parameters were obtained in the sagittal and frontal plane for the hip, knee and ankle. Because running is largely a sagittal plane movement, kinematic values can be obtained with greater reliability than frontal plane or transverse plane motions [32]. Therefore, most parameters were obtained in the sagittal plane. More specific, in the sagittal plane, knee flexion at IC, max knee flexion at MS and max knee flexion at MSW [5][18], max ankle dorsiflexion at MS and ankle plantarflexion at MSW, hip flexion at IC and MSW were highlighted [13]. Alt et al. found inter-limb differences in hip adduction at IC in the frontal plane. Therefore, the hip at IC in the frontal plane was also obtained in this study [5]. For the mentioned parameters, the inter-limb difference was investigated. The inter-limb difference value was calculated as left side - right side.

Symmetry Angles (SA) were calculated for the kinematic and spatiotemporal parameters [33].

The SA is a measure of the relationship between discrete values obtained from the left and right side, in this case, the left and right leg. The SA is calculated as follows [33][34].

$$SymmetryAngle(SA) = \frac{|45^\circ - tan^{-1}[\frac{left}{right}]|}{90} \cdot 100$$

But if

$$(45^\circ - tan^{-1}[\frac{left}{right}]) > 90$$

then

$$\frac{(45^\circ - tan^{-1}[\frac{left}{right}]) - 180}{90} \cdot 100$$

The SA results in an absolute score between 0 and 100%, that describes the deviation of the observed relationship between the two legs from a theoretically perfect relationship. 0% is associated with a perfect symmetry and 100% is associated with perfect asymmetry.

4.5 Statistical analysis

Statistical analysis was performed with the software program IBM SPSS Statistics. Normal distribution was checked for all outcome measures. This was done by plotting a histogram of the output values. Data was presented by calculation of the mean ± standard deviation (SD). For the statistical analysis, the significance level was set at $\alpha = 0.05$. At first linear mixed model was used to detect the significant difference for the inter-limb difference between each direction (straight, CW and ACW), where the repeated covariance type alternated between three different kinds. Repeated covariance is a way to setting up the values for the repeated measures.

- Unstructured (UN)
  For the UN method it is assumed that the variance at each time point is different and the correlation between measurement times is different for each pairing.
- Compound Symmetry (CS)
  For the CS method it is assumed that the variance at each time point is constant, which means that it is expected that the different methods have the same variance (the same degree of spread). Furthermore, it is expected that the correlation stays the same for all the time points.
- Autoregressive (AR1)
  For the AR1 method, it is assumed that the variance at each time point is constant and the correlation between measurement times reduces as time points get further apart.

The method that has been used for the linear mixed model changed based on the Akaike's Information Criterion value (AIC). The AIC is an estimator of in-sample prediction error and thereby relative quality of statistical models for a given data set. Therefore, the method with the lowest AIC value was used per parameter. For the inter-limb difference between the fatigued and non-fatigued state, a paired T-test was performed. A paired t-test is a statistical procedure that compares the means and SDs of two related groups (in this case non-fatigue and fatigue) to determine if there is a significant difference between these groups. All tests were done for hip, knee and ankle angles, spatiotemporal parameters and the SA values.

5 Results

Firstly, the effect of running direction on the inter-limb difference between the inner and outer leg was analyzed. It was expected that the inner leg would act the same in CW and ACW running. Next, instead of the inter-limb difference between inner and outer leg, the inter-limb difference between left and right leg was analyzed. Subsequently, the effect of fatigue on the inter-limb difference was studied. Furthermore, the SA method was used to investigate inter-limb differences (left side - right side) between straight, CW and ACW running.

5.1 The effect of running direction on the inter-limb difference between the inner and outer leg

The inter-limb difference (inner leg - outer leg) in the hip, knee and ankle angles was observed. It is shown that the inter-limb difference between the inner and outer leg during ACW running behaved in the inverse direction than during CW running (Figure 5.1. Therefore, the inter-limb difference between left and right leg was used to find the effect of running direction on the inter-limb difference.

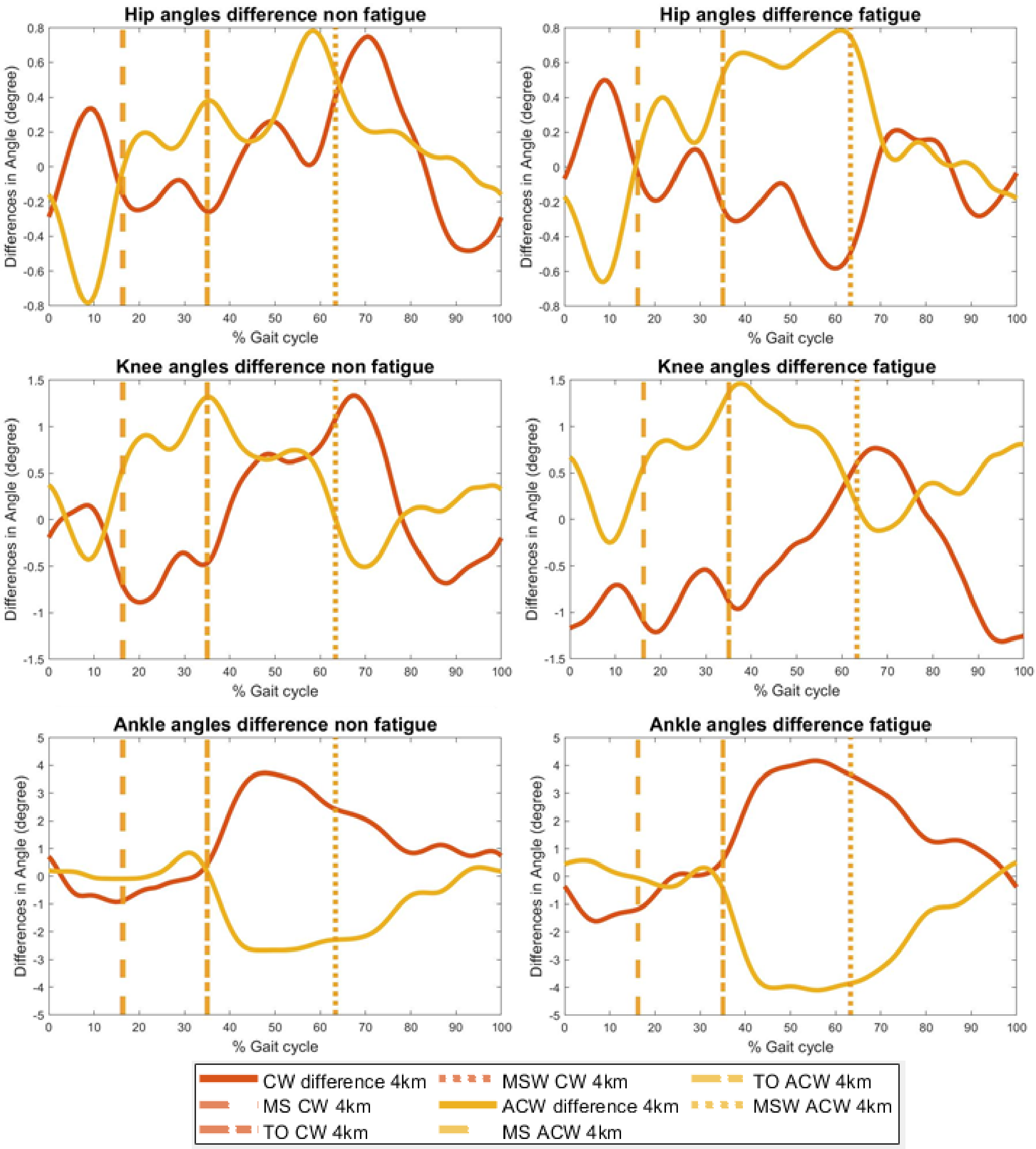

Figure 5.1: The average differences in hip, knee and ankle angles during the gait cycle for all subjects. This is done for the clockwise (CW) (red) and anti-clockwise (ACW) (yellow) direction. The difference was calculated as the inner leg minus the outer leg. The MS, MSW and TO are shown for both the CW and ACW direction. MS means midstance, MSW means midswing and TO means Toe-off. These are not identical to each other but are almost the same, that is why it is hard to distinguish them.

5.2 The effect of running direction on the inter-limb difference between the left and right leg

An inter-limb difference (left side - right side) was assessed in all directions for the hip, knee and ankle angles (Figure 5.2). For the non-fatigued state, in the hip and knee, a larger inter-limb difference was shown while running CW and ACW when compared to running straight. Comparing the CW and ACW direction, the inter-limb difference varied during the gait cycle. At IC, a higher inter-limb difference was shown in the ACW direction, while during the MSW a higher inter-limb difference was observed in the CW direction. In the ankle, at IC and at MSW, a higher inter-limb difference was shown in the CW direction. In Appendix A, the overall average of the hip, knee and ankle angles during the gait cycle are shown.

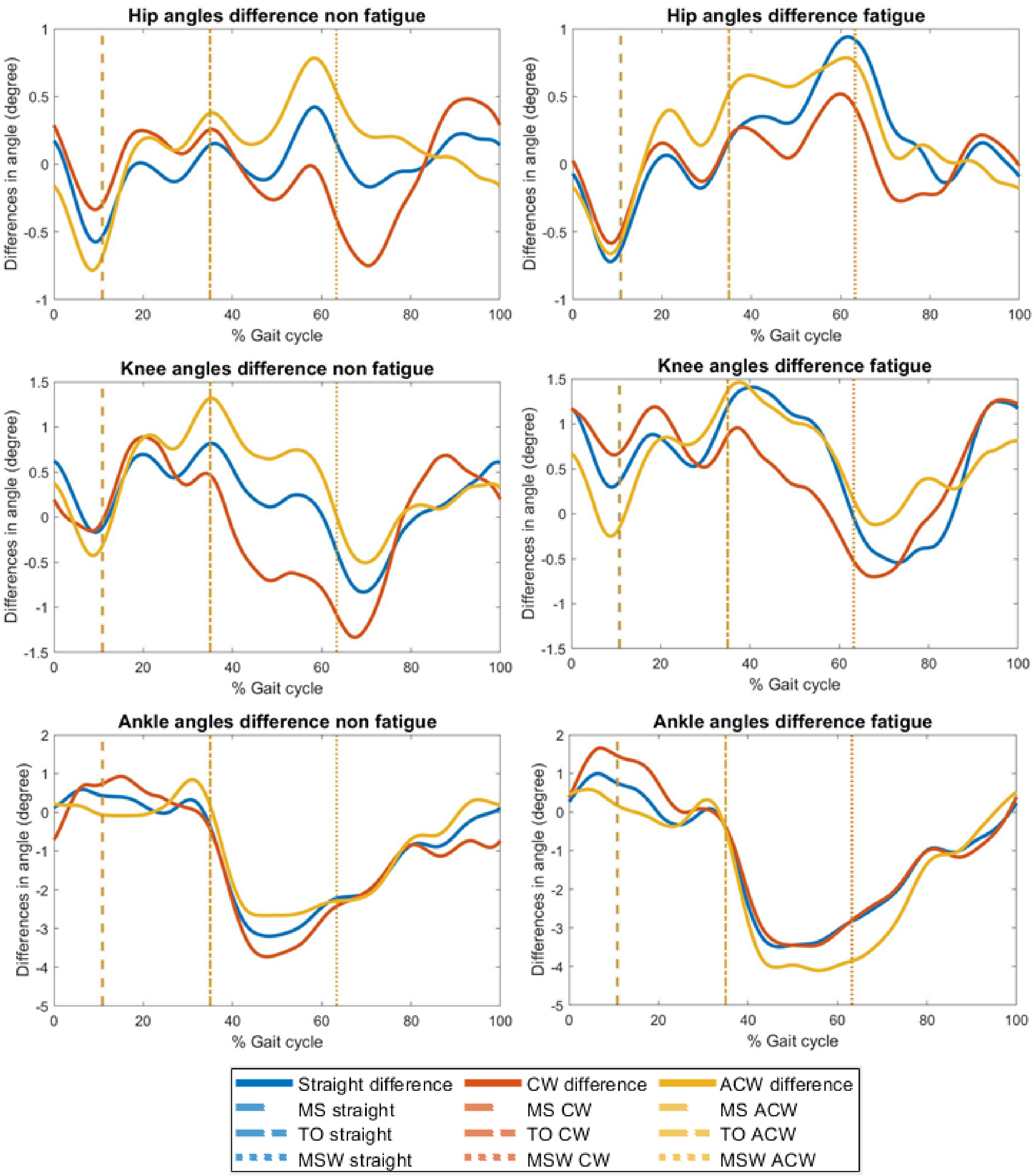

Figure 5.2: The average differences in hip, knee and ankle angles during the gait cycle for all subjects. This is done for the straight (blue), clockwise (CW) (red) and anti-clockwise (ACW) (yellow) direction. The difference is calculated as the left leg minus the right leg. The MS, MSW and TO are shown for all directions. MS means midstance, MSW means midswing and TO means toe-off. These are not identical to each other but are almost the same, that is why it is hard to distinguish them.

Significant changes in running kinematic were observed between all directions in the fatigued run for knee at IC ($p<0.02$) and MS ($p<0.001$). The knee angle inter-limb difference value was the highest for CW direction for the knee at IC (inter-limb difference of 0.50 degrees) and knee at MS (inter-limb difference of 2.01 degrees). A significant higher hip angle inter-limb difference value at IC ($p<0.04$) and at MSW ($p<0.03$) was found for CW direction (inter-limb difference of 0.12 degrees for hip at IC and 3.25 degrees for hip at MSW). The ankle inter-limb difference value at MS was significantly higher ($p<0.006$) in CW direction (inter-limb difference of 1.55 degrees) in comparison with ACW (inter-limb difference of 0.32 degrees) and straight direction (inter-limb difference of 1.10 degrees). In the frontal plane, significant higher inter-limb difference values were observed for hip at IC, for both non-fatigued run ($p<0.02$) and fatigued run ($p<0.04$) in CW direction (inter-limb difference of 0.97 degrees for non-fatigued run and 1.08 degrees for fatigued run). Table 5.1 shows results about the kinematic parameters in the sagittal plane, peak knee flexion at MS and MSW, knee angle IC, ankle angle at MS and MSW and hip angle at IC and MSW (average ± SD) and in the frontal plane, hip angle at IC. The left and right values for the defined kinematic parameters can be found in Appendix B.1.

Table 5.1: Average inter-limb difference value for the defined kinematic parameters for each direction (straight, clockwise and anti-clockwise) during the non-fatigued and fatigued state. A * denotes a significant difference with $p < 0.05$ while NS indicates the inter-limb difference was not significant between all directions. IC means initial contact, MS means midstance and MSW means midswing.

Parameter	Non fatigue (4 km)							Fatigue (1.2 km)						
	Straight		Clockwise		Anti Clockwise			Straight		Clockwise		Anti Clockwise		
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD	
Sagittal plane														
Hip @ IC (degrees)	0.13	1.78	0.12	2.01	-0.14	1.94	NS	-0.07	2.41	0.12	2.18	-0.11	2.24	*
Hip @ MSW (degrees)	-0.66	5.98	0.59	3.13	0.87	3.78	NS	0.60	3.17	3.25	9.38	-0.44	2.37	*
Knee @ IC (degrees)	0.82	3.94	0.37	4.68	0.46	4.05	NS	1.10	4.16	1.47	4.13	0.98	4.43	*
Knee @ MS (degrees)	-0.057	3.54	-0.052	3.70	-0.33	3.85	NS	0.17	3.36	0.50	3.35	-0.21	3.55	*
Knee @ MSW (degrees)	0.65	5.84	0.80	5.13	-0.20	3.89	NS	1.08	4.72	2.01	4.92	0.29	3.64	NS
Ankle @ MS (degrees)	0.58	2.13	0.67	1.94	0.19	2.81	NS	1.10	2.96	1.55	2.68	0.32	3.58	*
Ankle @ MSW (degrees)	0.84	9.55	1.38	7.98	-2.28	5.04	NS	1.19	9.89	3.21	9.53	-4.26	5.64	NS
Frontal plane														
Hip @ IC (degrees)	0.89	5.82	0.97	6.07	0.03	5.47	*	0.88	5.31	1.08	5.30	0.72	5.29	*

The results showed that the inter-limb difference value in the step frequency decreased in the non-fatigued run for both curves, CW and ACW, in comparison with the straight direction (inter-limb difference of 1.10 steps/minute), where CW and ACW had a difference (smaller than 0.2 steps/minute). The inter-limb difference value in step length was in the non-fatigued state the highest for ACW direction (inter-limb difference of 0.10 meters) and in the fatigued state the highest for CW direction (0.16 meters). The inter-limb difference value in the contact time did not show a large inter-limb difference for all directions (differences smaller than 0.04 seconds).

No significant difference for the inter-limb difference was observed. Inter-limb difference values are presented in Table 5.2 for mentioned spatiotemporal parameters (average ± SD) for all three directions in the non-fatigued and fatigued state and in Appendix B.2, the left and right leg values are shown for these parameters. It was expected that the outer leg (left leg for CW and right leg for ACW running) had a larger step length and a shorter ground contact time than the inner leg. It was shown that there was a step difference between the left and right leg during curve running. However, it was not shown that the outer leg had a larger step length. Furthermore, no large difference was found in the contact time between the outer and inner leg during curve running (smaller than 0.04 seconds).

Table 5.2: Average inter-limb difference values for the defined spatiotemporal parameters for each direction (straight, clockwise and anti-clockwise) during the non-fatigued and fatigued state. A * denotes a significant difference with $p < 0.05$ while NS indicates the inter-limb difference was not significant between all directions.

Parameter	Non fatigue (4 km)							Fatigue (1.2 km)						
	Straight		Clockwise		Anti Clockwise			Straight		Clockwise		Anti Clockwise		
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD	
Step length (m)	0.075	0.19	-0.062	0.19	-0.10	0.34	NS	0.046	0.15	0.16	0.54	0.015	0.049	NS
Step frequency (steps/minute)	1.10	6.01	-0.18	5.05	-0.14	4.93	NS	0.49	4.56	0.37	4.40	0.24	4.37	NS
Contact Time (s)	-0.005	0.02	-0.01	0.03	-0.006	0.03	NS	0.006	0.03	-0.0001	0.03	0.0009	0.04	NS

5.3 The effect of fatigue on the inter-limb difference between the left and right leg

The inter-limb difference values in the kinematic parameters were found to change due to fatigue. In the CW direction, all kinematic parameters, except for the hip at IC in the sagittal plane increased. The straight and ACW direction showed an increase due to fatigue for 5 kinematic parameters. The knee at IC and at MSW, the ankle at MS and MSW showed a fatigue-induced increase for all directions (Table 5.1).

Significant changes were observed in the CW direction in the knee at IC ($p < 0.007$) and ankle at MS ($p<0.006$), where the knee at IC increased from an inter-limb difference of 0.37 degrees to 1.47 degrees. Comparing all directions, the inter-limb difference value increased the most in the CW direction due to fatigue. Furthermore, the inter-limb difference value also increased the highest in the CW direction for the hip at MSW (inter-limb difference increase of 1.10 degrees), knee at MSW (increase of 2.66 degrees) and ankle at MS (increase of 0.88 degrees) due to fatigue.

The inter-limb difference value increased for the step length and step frequency for the CW direction (increase of 0.01 meter and 0.19 steps/minute) and the step frequency increased in the ACW direction (increase of 0.10 steps/minute) (Table 5.2). There was no significant difference found between the non-fatigued and fatigued state for the spatiotemporal parameters for each direction. Furthermore, no clear observational differences were found in the contact time.

5.4 Symmetry angle (SA)

An inter-limb difference was found based on the calculated SA values in all directions. It was shown that the CW direction in comparison with straight and ACW direction had the highest SA value for most parameters. The knee at MS showed a significant difference ($p < 0.049$) in the fatigued state between the directions, CW direction showed the highest SA of 4.2 %. Furthermore, the inter-limb difference was high for all directions for the ankle at MSW (SA > 20%) and hip at IC (SA > 30%) in the front plane (Table 5.3).
The effect of fatigue was also analyzed on the SA. The SA of the ankle at MS increased significantly ($p < 0.03$) due to fatigue in the ACW direction (increase of 1.09%). The inter-limb difference did not change significantly for all spatiotemporal parameters (Table 5.4).

Table 5.3: The average SA values are shown for the kinematic parameters inter-limb difference and in the right for each direction. A * denotes a significant difference with $p < 0.05$ while NS indicates the inter-limb difference was not significant between all directions.

Parameter	Non fatigue (4 km)							Fatigue (1.2 km)						
	Straight		Clockwise		Anti Clockwise			Straight		Clockwise		Anti Clockwise		
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD	
Sagittal plane														
Hip @ IC	1.58	1.19	1.73	1.36	1.58	1.43	NS	2.05	1.56	1.95	1.54	2.01	1.39	NS
Hip @ MSW	4.47	7.75	2.95	2.13	4.55	2.84	NS	3.80	2.72	9.51	20.72	3.10	2.12	NS
Knee @ IC	6.07	4.25	6.72	3.70	6.12	4.62	NS	6.33	6.81	6.45	6.93	6.81	6.84	NS
Knee @ MS	1.73	0.91	2.32	1.87	2.31	2.06	NS	1.68	0.88	2.26	1.47	2.31	1.70	*
Knee @ MSW	2.30	4.20	1.18	0.89	1.06	1.00	NS	0.92	0.80	2.05	3.79	0.94	0.97	NS
Ankle @ MS	2.50	1.44	2.35	1.76	3.00	2.55	NS	2.79	1.54	3.67	2.38	4.09	2.87	NS
Ankle @ MSW	22.74	25.88	24.10	28.36	25.31	27.85	NS	21.08	23.78	22.91	34.50	19.54	24.32	NS
Frontal plane														
Hip @ IC	39.20	24.35	39.90	24.58	36.47	20.95	NS	33.58	21.30	32.42	22.71	31.73	22.02	NS

Table 5.4: The average SA values are shown for the spatiotemporal parameters inter-limb difference and in the right for each direction. A * denotes a significant difference with $p < 0.05$ while NS indicates the inter-limb difference was not significant between all directions.

Parameter	Non fatigue (4 km)							Fatigue (1.2 km)						
	Straight		Clockwise		Anti Clockwise			Straight		Clockwise		Anti Clockwise		
	Average	SD	Average	SD	Average	SD		Average	SD	Average	SD	Average	SD	
Step length	2.86	5.91	2.51	6.01	2.57	10.12	NS	1.89	4.74	4.74	14.4	0.98	1.31	NS
Step frequency	0.97	0.70	0.86	0.50	0.75	0.62	NS	0.68	0.68	0.69	0.79	0.67	0.50	NS
Contact Time	1.47	1.21	1.26	1.17	0.93	0.87	NS	1.43	1.45	0.96	0.89	0.88	1.01	NS

6 Discussion

The aim of this study was to examine whether the running direction (straight, CW or ACW) affects the inter-limb difference. First of all, it was expected that in curve running the inner leg had kinematic differences in comparison with the outer leg, which would result in a larger inter-limb difference. Furthermore, it was hypothesized that the outer leg would have a larger step length and the inner leg would have a longer ground contact time due to the curve pattern in which the subject was running. Therefore it was expected that, in curved directions, the ground contact time and step length had a larger inter-limb difference. Furthermore, this study investigated the effect of fatigue and leg dominance on inter-limb differences. It was hypothesized that the inter-limb difference in joint angles was increased due to fatigue.

The inter-limb difference values in the curve directions, were higher for some kinematic parameters. Focusing on the inter-limb difference values, a significant inter-limb difference between the directions was found in the fatigue state in the sagittal plane for the knee at IC, knee at MS, hip at IC, hip at MSW and in the frontal plane, hip at IC. In these parameters, the highest inter-limb difference was found in the CW direction. Using the SA method, the inter-limb difference was found in the knee at MS, where ACW direction had the highest SA value. Inter-limb difference in the step length was found, however, it was not shown that the outer leg showed a higher step length. Furthermore, no observational difference in the inter-limb difference was found in the contact time between the directions.

The effect of fatigue was only found significant in the knee at IC and ankle at MS, where the knee and ankle showed a higher inter-limb difference value in the CW direction due to fatigue. Furthermore, the inter-limb difference values also increased for the knee at MSW and ankle at MS due to fatigue in all directions, where the increase in the inter-limb difference value was the highest in the CW direction. The inter-limb difference value also increased for the ankle at MSW, where the increase in the value was the highest in ACW direction. Using the SA method, the inter-limb difference of the ankle at MS increased significantly due to fatigue in the ACW direction. The inter-limb difference in the step length increased in the CW direction due to fatigue. The inter-limb difference in the contact time did not show an increase due to fatigue.

In the following sections, the findings of this study are summarized and discussed.

6.1 The effect of running direction on inter-limb difference

Two methods (inter-limb difference (left side − right side) and the SA) were used to analyze the kinematic parameters in the hip, knee and ankle in the sagittal plane and hip in the frontal plane and for the spatiotemporal parameters. This study found significant kinematic changes in the fatigued state due to the direction.

At first, the inter-limb difference was calculated for the inner leg minus the outer leg. It was expected that the inner leg would present a similar pattern for the CW and ACW direction, meaning that the inter-limb difference patterns would present peaks and valleys at roughly the same time. However, the results showed that the inner leg did not behave the same for the CW and ACW direction (Figure 5.1). Reasons could be that the curves were not curved enough or the direction did not influence the left and right differences. Subsequently, the results were based on the inter-limb difference left side minus right side.

It was shown that the inter-limb difference is higher for most kinematic parameters in the CW direction. It is possible that the subjects were not used to the CW direction running and therefore had a higher inter-limb difference in the CW direction. A reason for this could be that the athletic track's original direction is ACW and not CW. However, it is also possible that subjects were not used at all to running on an athletic track. Since this information was not collected from the subjects, no final conclusions can be drawn.

A significant difference was found between the different directions during the knee at MS in the fatigued state for the SA values and the inter-limb difference (left side - right side). These values were higher for the curved directions in comparison with the straight direction. The SA value difference was between the 2 and 4 for the knee at MS and the inter-limb difference value was around 0.50 degrees. These differences were negligibly small. It is possible that these differences were due to measurement error and not due to the inter-limb difference in the body. Furthermore, the difference between the different directions for the left or right leg separately showed a higher knee flexion for the curved directions. Alt et al. compared linear and curved sprinting for the left and right leg but did not find significant kinematic modulations in the stance phase for the knee joint angles. The results of this study are not in line with those of Alt et al. [5]. A possible reason is that Alt et al. did not examine a fatigued state in their research, this is consistent with the fact that no significant kinematic changes were found for the non-fatigued state in the present study either.

A significant difference was found between the different directions during the knee at IC in the fatigued state. The inter-limb difference was the largest for the CW direction (1.47 degrees). The knee at IC was not larger than 24 degrees. Therefore the inter-limb difference is relatively small. There was no significant difference found for the SA values. The ACW direction showed the highest SA value (6.81%) in comparison with the CW (6.45%) and straight (6.33%) directions. However, the differences between the directions in the SA values are very small and could be due to a measurement error.

In the fatigued state, the CW direction had a significant difference with the ACW and straight directions in the ankle at MS. The CW direction showed the highest inter-limb difference (1.55 degrees) and the lowest for the ACW direction (0.32 degrees). The straight direction had an inter-limb difference of 1.10 degrees. It was expected that the straight direction would have the lowest inter-limb difference. However, there was no significant difference found for the SA values. The ACW direction showed the highest SA value (4.09%) and the straight direction showed the lowest SA value (2.79%). Alt et al. compared linear and curved sprinting for the left and right leg but did not find significant kinematic modulations in the stance phase for the ankle joint angle [5]. This study result is not in line with the study results of Alt et al. A possible reason is that Alt et al. did not examine this parameter while the subject was in a fatigued state, which is consistent with the fact that no significant kinematic changes were found in the non-fatigued state in this study. In addition to this, the SA values did not show any significant difference. Due to the different outcomes between the inter-limb difference and SA values, it is not possible to make any supported conclusions with this data.

The ankle at MSW did not show a significant inter-limb difference or a significant difference in the SA values. However, the SA values were quite high for the ankles at MSW, which were above 20 degrees. These high difference were not found for the inter-limb difference values in all directions. These differences were also higher than expected in the CW and ACW direction (higher than 3 degrees). It was expected that the inter-limb difference would increase in curved directions in comparison with the straight direction. However, these results are not significant and therefore no definite conclusions can be made.

The inter-limb difference changed significantly in the fatigued state for the hip in the sagittal plane at IC. A higher inter-limb difference value was shown for the curved directions, as it was expected. However, the inter-limb difference showed a difference below 0.2 degrees in the opposite direction as expected. Since the absolute value of this difference is fairly low, it can be attributed to a measurement error.

Hip at MSW showed a significant difference between directions in the fatigued state. The inter-limb difference value increased for the CW direction with around 2.5 degrees difference in comparison with the straight and ACW direction. This matches the hypothesis that curve running results in a higher inter-limb difference between the straight and CW direction. However, the difference between CW and ACW is unexpected. This could be explained by the fact that the usual direction of the athletic track is ACW and not CW. Furthermore, the inter-limb differences in the straight and ACW direction are negligibly small and could be attributed to a measurement error.

For both the non-fatigued and fatigued state, the inter-limb difference was significant between the different directions for the hip at IC in the frontal plane. Furthermore, these differences were not found significant for the SA values. In the non-fatigued state, CW showed more asymmetry while in the fatigued state, the straight direction showed more asymmetry. However, all SA values were quite high (SA $>$ 31%), meaning that the presence of an asymmetry was independent from the direction.

The inter-limb difference values and SA values were analyzed for the step length, step frequency and contact time. In this study, there was no significant inter-limb difference found for the contact time for both the non-fatigued and fatigued state and between the different directions. However, in previous studies significant differences were found during bend sprinting between the left and right steps [21][23][24][25]. Alt et al. [5] found a significantly higher contact time in the curve for the inner leg in comparison with the outer leg. This study found results based on bend sprinting while in this study, the participants ran at their average velocity of a 10 km. Furthermore, the cited studies did not investigate the inter-limb difference. However, Alt et al. supported the assumption that the inside and outside leg seemed to fulfill different tasks during curve sprinting. In this study, it was expected that the inter-limb difference was smaller for the straight direction than for the curve directions. The lower velocity compared to the sprinting studies could be a reason for the non-significant difference in the contact time. Furthermore, the inter-limb differences for contact time were negligibly small (smaller than 0.01 sec). Since the absolute value of this difference is fairly low, it can be attributed to a measurement error.

The inter-limb difference in step frequency and step length did not show a significant difference between the different directions. A decreased step frequency for the straight direction during this research in comparison with the curved directions was expected. Instead, the results showed that the step frequency increased for the straight direction in comparison with the CW and ACW direction, albeit without a statistically significant difference. Furthermore, these inter-limb differences in step length were negligibly small (smaller than 0.2 meters) and could be possible that these differences were due to measurement error. Churchill et al. [26] found a decreased step frequency for a decreased radius in the lanes around an athletic track. Alt et al. compared straight sprints with curved sprints [5], where the step length and step frequency were not affected by the bend. This study's results are in line with the results of Alt et al., no significant difference was found between straight and curved running. However, these same results do not match with those of Churchill et al. A reason for this in congruence could be that both studies [5][26] were based on sprint running while in this study an average 10 km speed was used. A reason that this studies findings are in line with Alt et al. and not with Churchill et al. could be that Churchill et al. compared the different lanes on an athletic track while Alt et al. compared straight and curved running around the track.

6.2 The effect of fatigue on inter-limb difference

In the CW direction, all kinematic parameters, except for the hip at IC in the sagittal plane increased due to fatigue. The straight and ACW direction showed an increase due to fatigue for 5 kinematic parameters. The knee at IC and MSW, the ankle at MS and MSW showed in all directions, an increase due to fatigue.

The inter-limb difference value increased significantly in the knee at IC and ankle at MS due to fatigue in the CW direction. This matched the hypothesis that the inter-limb difference increased due to fatigue in the knee at IC and ankle at MS. However, the SA values did not increase significantly for the knee at IC in all directions. The knee at IC showed more flexion in the fatigued state, which agreed with previous research [35]. The SA value increased significantly in the ankle at MS, however this was in the ACW direction.

No large significant difference (smaller than 2 degrees) was found in the fatigue-related comparison. This could indicate either that the subjects were already fatigued when running the non-fatigued run, or that they were not fatigued enough during the fatigued run. This might also indicate that the running pattern does not change due to fatigue, at least for trained subjects. A solution could be to analyze the data of the non-fatigued and fatigued run separating each round in each direction. This could be used to analyze if there is an effect shown of fatigue during the non-fatigued and fatigued run.

There is no significant difference found in the hip adduction due to fatigue. Brown et al. concluded that there was no significant difference between the left and right leg for the non-fatigued and fatigued state during a 10.000 m treadmill run [13]. Therefore, these study results agreed with previous study research findings.

The SA value and inter-limb difference value of the hip at IC in the sagittal plane increased due to fatigue. However, these differences are negligibly small and could be attributed to a measurement error. Furthermore, these inter-limb differences were not statistically significant. The hypothesis about an increased inter-limb difference due to fatigue could not be accepted for this parameter due to the small changes.

In comparing the non-fatigued state and fatigued state results in contact time, a decreased asymmetry in curved directions in the fatigued state was observed. This was unexpected as the prediction made was that the asymmetry would increase due to fatigue. However, these differences were negligibly small (inter-limb difference lower than 0.05), which could also be due to a measurement error.

6.3 Symmetry angle as a metric to assess inter-limb difference

The SA method was used to investigate the inter-limb difference during running. However, the SD of the SA values were high for all parameters, which means that the SA value for each person is measurably different from one another. This could be a reason why the SA significance differs from the inter-limb difference significance in the parameters. Hanley et al. also found a high SD in the spatiotemporal parameters [9]. They also investigated the inter-limb difference on the individual level where the subjects' inter-limb difference was considered asymmetrical if more than half of their SA values was greater than a certain value. Therefore, an improvement could be to investigate the SA values and inter-limb difference values for each subject and to examine if there was a significant difference in the parameters for each subject over multiple steps, instead of using the average for each subject. Furthermore, the inter-limb difference (left side – right side) had a high SD value for most parameters. A reason could be that the subjects were very diverse. This meant large differences in running behaviours between subjects and results in high SD's when calculating the average.

Radzak et al. investigated next to the SA values, also the comparison of the biomechanical variables between the left and right leg at the non-fatigued and fatigued states [11]. This was done with a statistical test to assess the differences between the left and right leg. An improvement in this study could be comparing the left and right leg with statistical tests to find a statistically significant relation.

Furthermore, it was remarkable that the comparison method plays an important role in finding inter-limb differences. As explained in Chapter 4.4, the SA is a positive value between 0 and 100, the result is not influenced by the direction of the difference (i.e. if the highest value is left or right). This is, contrary to the inter-limb difference, whose value's sign is given by the difference direction. In this method, it did not matter if the left or right value had a higher value, while in the inter-limb difference only left side – right side was compared and this could lead to the differences in the two methods. When comparing these results with other studies it could therefore be more reliable if the same statistical method is used. Further research could be based on the SA method alone to compare the inter-limb difference to see if the outcome changes. Furthermore, individual symmetry angles could be compared over multiple gait cycle to find inter-limb differences in between subjects.

6.4 Limitations

This study was not without limitations. The variety of significant differences could be partly due to the selection of variables utilized for comparison. Kinematic outcome measures were based on discrete values, such as IC and MS. The inter-limb difference may occur within the range of these discrete values, therefore the inter-limb difference may not had been lost in this analysis. In Appendix A, it is shown that, during the swing phase, a difference between the left and right ankle in the gait cycle is shown. However, these difference decreased at the chosen midswing point. Another method for analyzing the data, such as statistical parametric mapping, could be used to find other or more inter-limb differences throughout the gait cycle. Statistical parametric mapping gives the opportunity of avoiding abstraction of the originally sampled time series before performing the statistical analysis. Since kinematic time series can be complex, it is difficult to objectively specify an a-priori method (in this case looking at IC, MS and MSW) for analysis [36]. Therefore, statistical parametric mapping could improve the statistical analysis.

Another limitation can be found in the statistical analysis used to analyze the effect of running direction. The statistical test mixed model was used to find the relationship between all directions. It was expected that the three directions would give another inter-limb difference result since a comparison between the left and right side was made. The use of this statistical analysis method implies that an indication of significant difference is found only when all three directions are different from each other. This means that the difference between two specific directions was not analyzed in this study. In further research, paired t-test could be done to find significant difference between straight and CW/ACW direction and between CW and ACW direction.

An additional limitation was represented by the subjectivity of the concept of fatigue. In this study, a Borg Scale was used to indicate how fatigued the subject was and to decide whether the subject was fatigued enough to continue to the last part of the protocol. However, some subjects showed a decreased Borg Scale after the fatiguing protocol, once they started running in their average velocity of the 10 km again. The Borg Scale is based on a subjective feeling in the moment so there is the possibility that a psycho-physiological effect played a role at the end of the research, reducing the Borg Scale. In further research, the protocol needs to be adjusted in such a way that subjects stay fatigued after the fatiguing protocol. Another solution would be use in addition to the Borg Scale, direct feedback on the heart rate and VO2 consumption.

Another limitation was the influence of leg dominance. The average of the gait cycle in the hip, knee and ankle would not change that much for the leg dominance in comparison with the left and right leg, since only two subjects had a leg dominance in the left leg. The differences between the left and right leg for the hip and knee have shown to be small and not statistically significant (smaller than 3 degrees) (Appendix A). The difference between the left and right leg for the ankle angles showed a difference in the swing phase, however, it is not known if this difference is due to leg dominance or not. Given the low number of left-dominant subjects (2), it was not possible to draw any conclusions about the influence of leg dominance. In further research, more subjects with left leg dominance need to be included, in order to investigate the influence of the leg dominance on inter-limb difference.

Next, the characteristics of the runners were very diverse. Due to the low number of participants in this study, it was not possible to categorize the participants into subgroups. This could explain the large SDs in the results. The velocity of the subjects was very diverse. In contrast, Girard et al [16] showed that running velocity does not influence lower limb mechanical asymmetry. However, the subjects were shortly observed on individual level in this study. In this study, it was shown that the kinematic parameters did not differ due to the characteristics. In contrast, the step length and step frequency showed a higher value for the fast runners, which could lead to higher SDs. Next, it is also known that female recreational runners exhibit significantly different lower limb mechanics in the frontal and transverse plane at the hip and knee during running [37]. For further research, the characteristics of the runners (gender, age, height, foot pattern, velocity and running experience) could be similar to each other to eliminate as many mediator variables as possible. Furthermore, more individual analysis on each subject needs to be done to find inter-limb differences on an individual level.

Lastly, the amount of studies on this topic is limited and the previous research is based on different set ups. This makes a comparison between experimental results extremely difficult and would explain why this study seems to contradict the previous ones in some aspects.

7 Conclusion

The aim of this study was to find whether the effect of running direction (straight, clockwise or anti-clockwise) on an athletic track had an effect on inter-limb kinematics. Furthermore, the effect of fatigue on the inter-limb difference were investigated.

Overall, during non-fatigued running, the running direction only showed a significant effect on the inter-limb difference in the frontal plane for the hip at IC. In the fatigued state, the running direction effected inter-limb difference as measured by several mechanical parameters.

Inter-limb difference changed significantly due to fatigue for a few parameters. Finally, using the SA method instead of the inter-limb difference between left and right, significant differences were found. In conclusion, running direction had an influence on the inter-limb difference. In particular, the CW direction showed the highest inter-limb differences. Furthermore, fatigue amplified the effect of the running direction on inter-limb difference. The CW direction again showed the highest inter-limb differences. Lastly, no conclusions could be drawn if there is an effect of leg dominance.

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A Hip, knee and ankle angles in the sagittal plane during the gait cycle

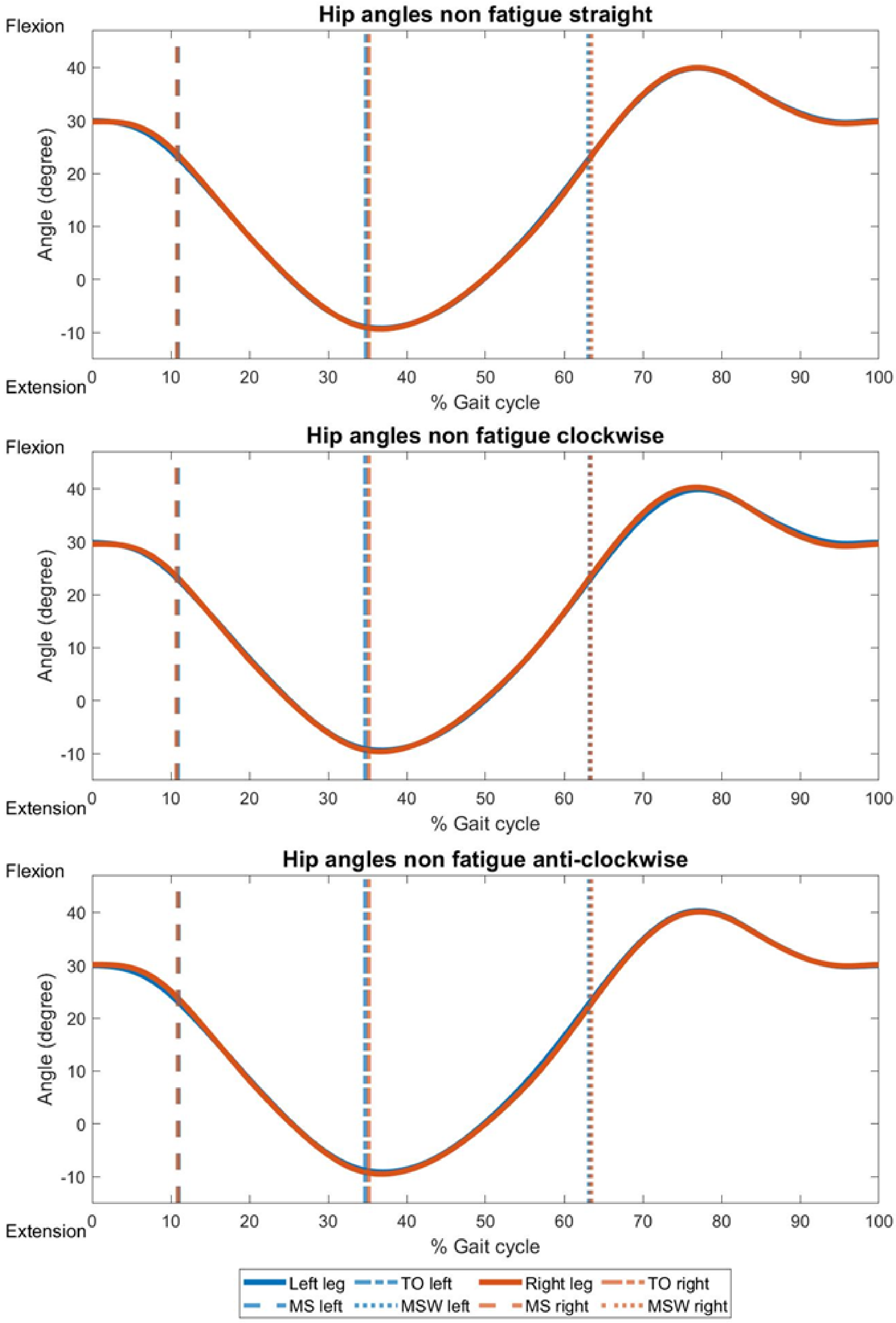

Figure A.1: Gait cycle of the hip joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the non-fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

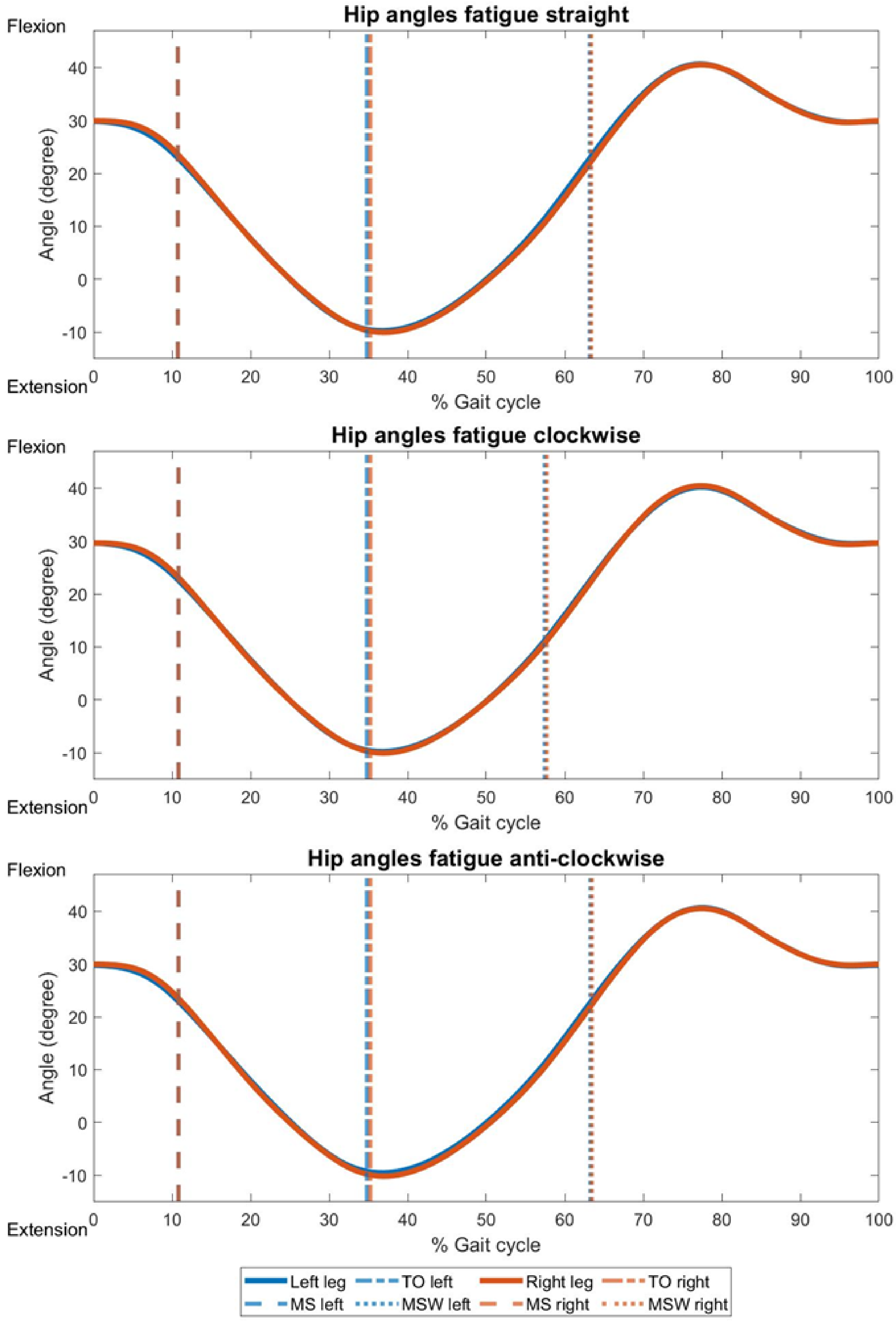

Figure A.2: Gait cycle of the hip joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

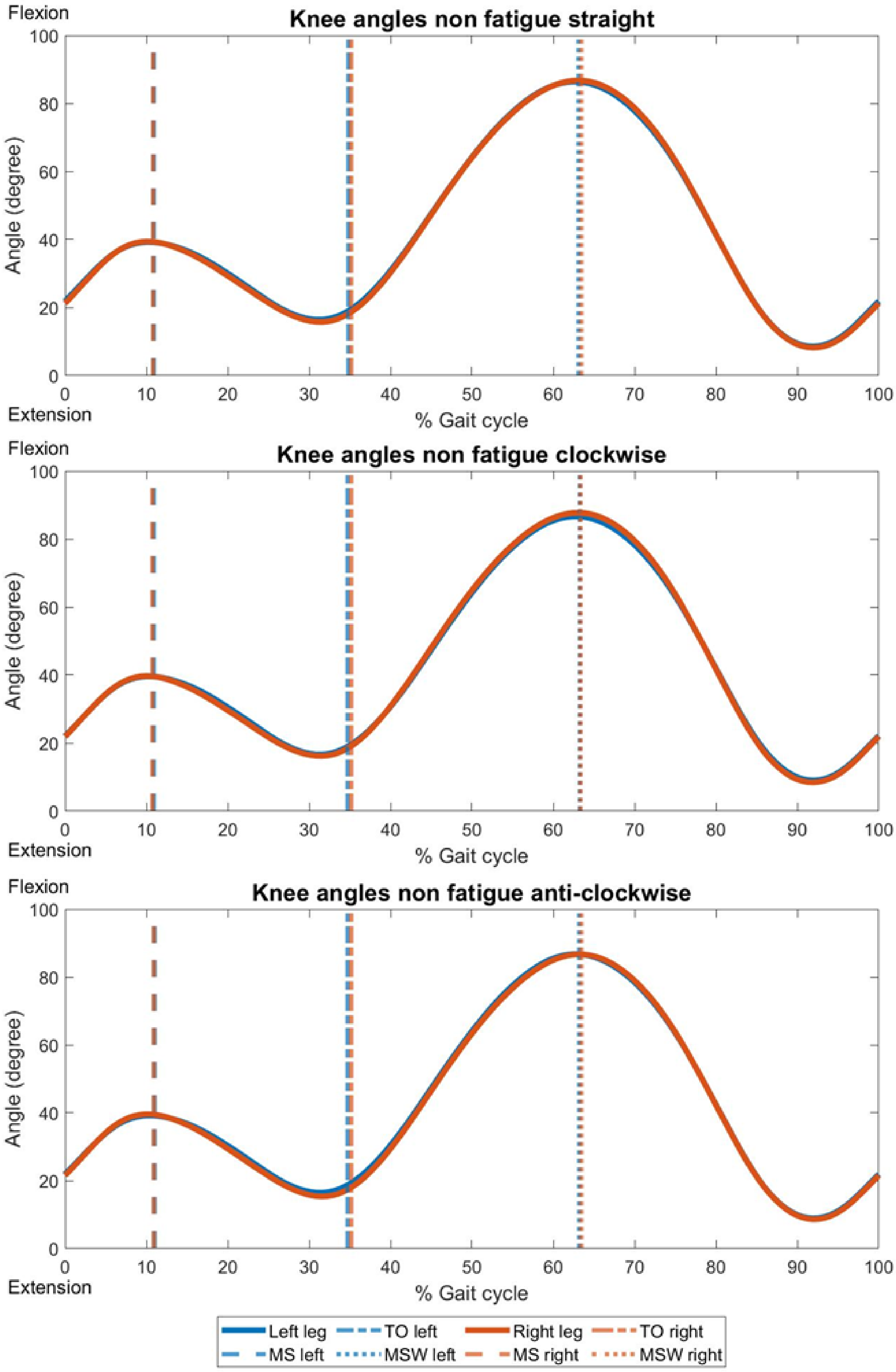

Figure A.3: Gait cycle of the knee joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the non-fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

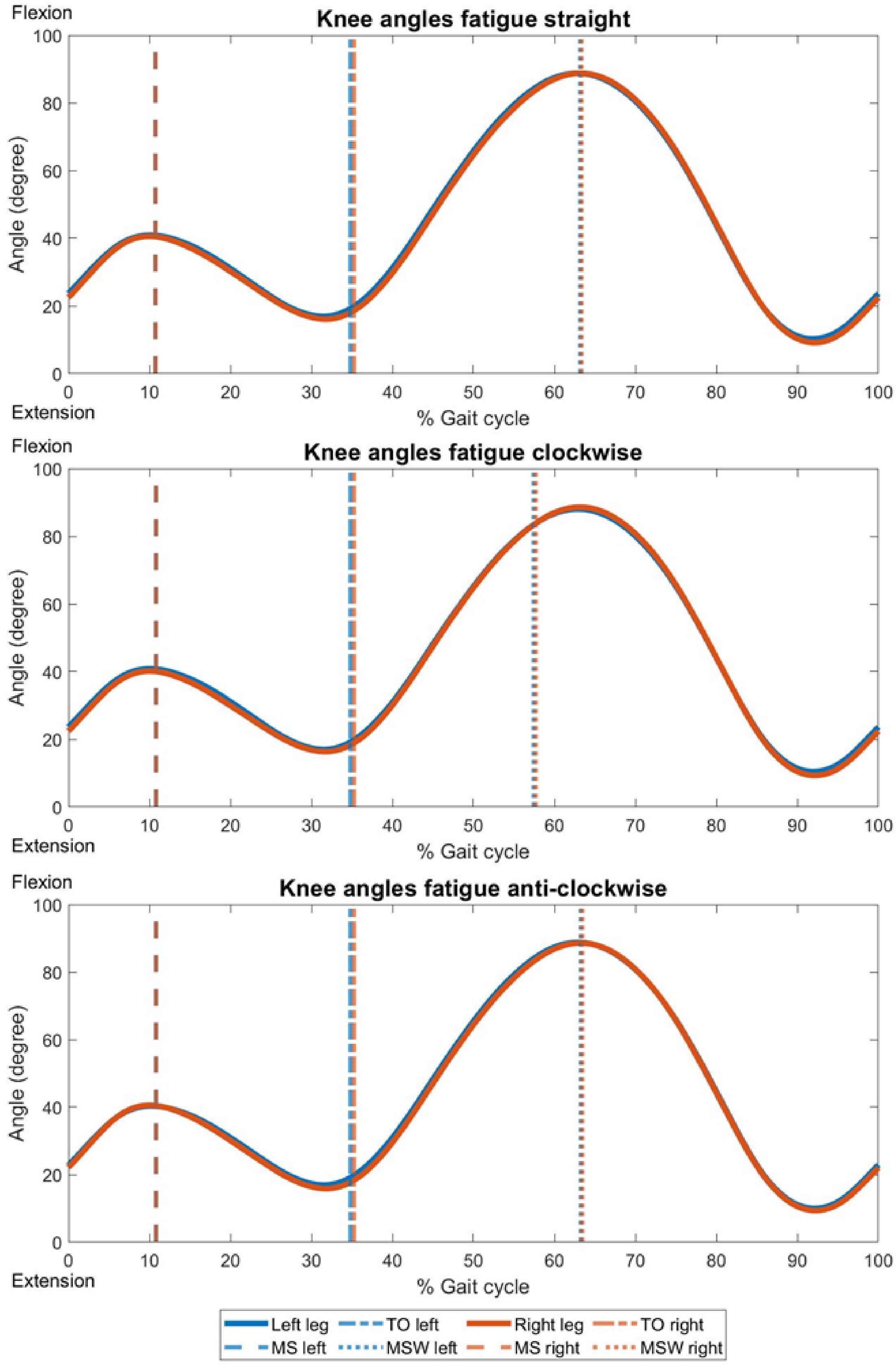

Figure A.4: Gait cycle of the knee joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

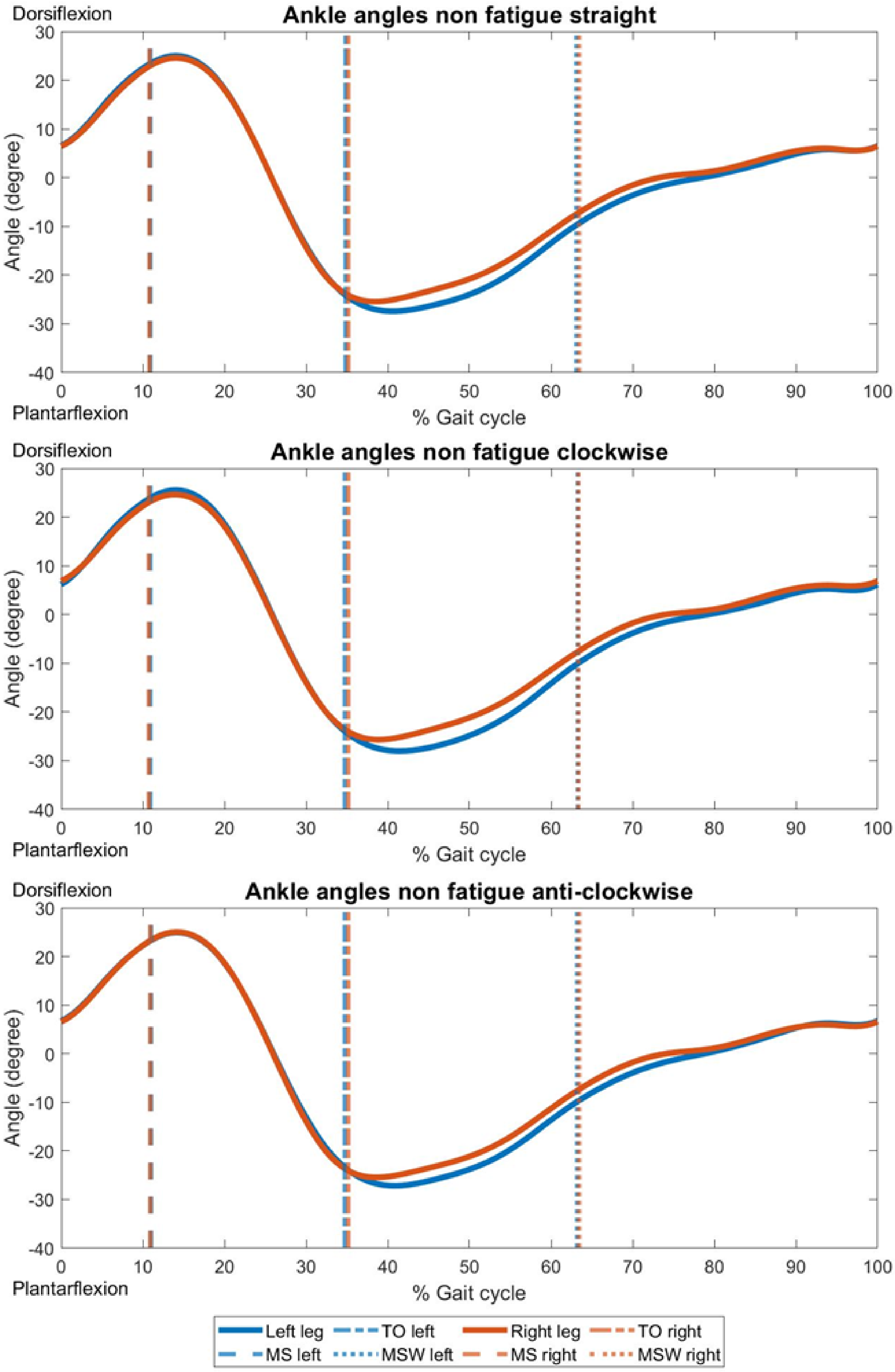

Figure A.5: Gait cycle of the ankle joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the non-fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

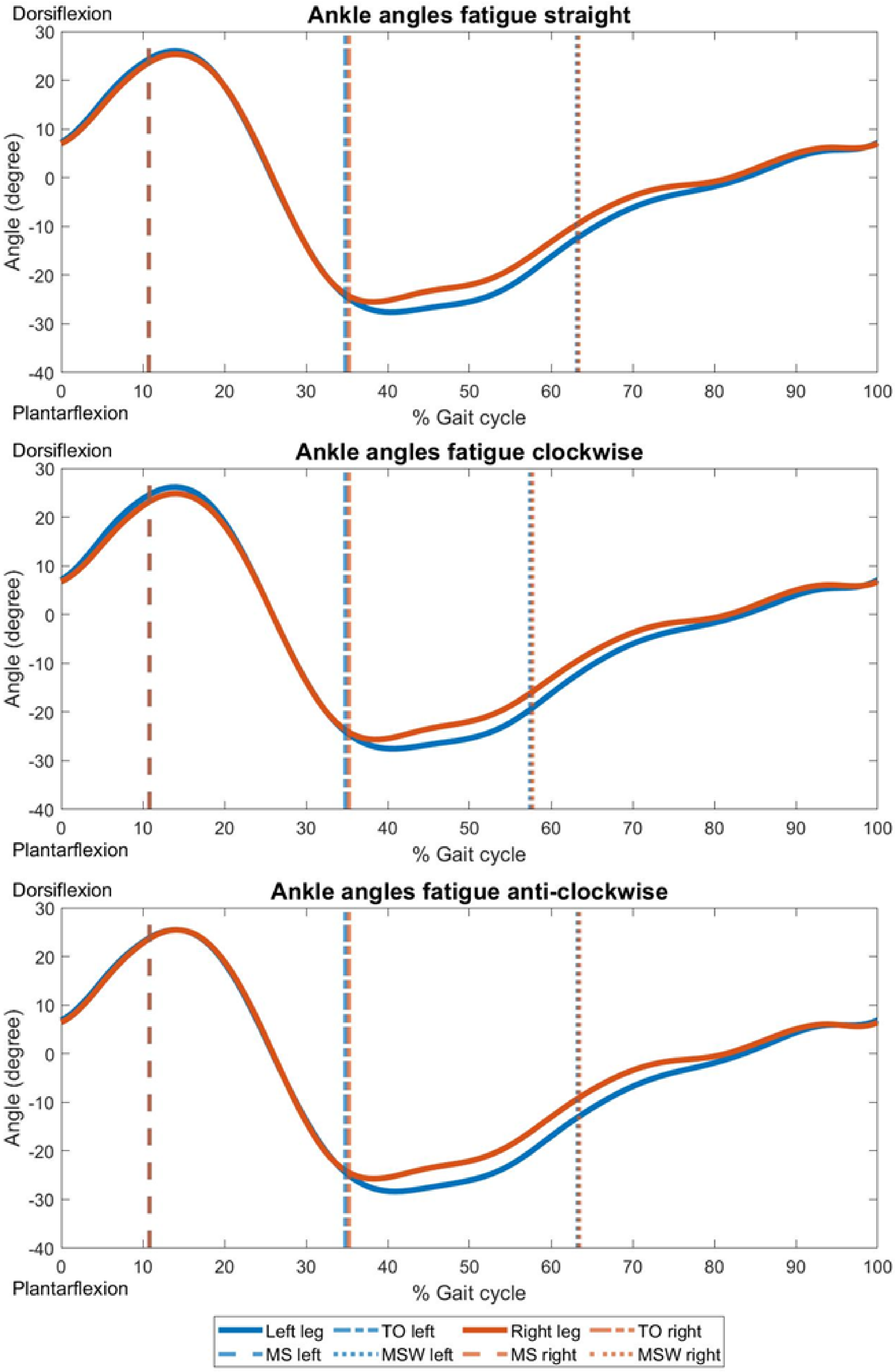

Figure A.6: Gait cycle of the ankle joint angle for the left and right leg during straight, clockwise and anti-clockwise running in the fatigued state. The upper figure shows the straight direction, middle figure shows the clockwise direction and the lower figure shows the anti-clockwise direction. MS means midstance, TO means toe-off and MSW means midswing

B The left and right kinematic and spatiotemporal parameters for each direction

Table B.1: Average values for the defined kinematic parameters for each direction (straight, clockwise and anti-clockwise) during the non-fatigued and fatigued state.

Parameter	Leg	Non fatigue (4 km)						Fatigue (1.2 km)					
		Straight		Clockwise		Anti Clockwise		Straight		Clockwise		Anti Clockwise	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Sagittal plane													
Hip @ IC	L	29.60	3.80	29.45	3.67	29.70	3.88	29.72	4.16	29.60	4.37	29.76	4.12
(degrees)	R	29.47	4.19	29.33	4.00	29.84	4.43	29.79	4.78	29.48	4.92	29.87	4.76
Hip @ MSW	L	22.07	5.17	22.13	4.33	23.03	4.76	22.34	4.73	19.62	9.41	21.15	3.63
(degrees)	R	21.50	6.59	22.73	4.56	22.16	5.10	22.12	5.84	17.15	13.07	21.59	5.06
Knee @ IC	L	22.63	6.25	22.64	6.29	22.35	6.28	23.46	5.79	23.67	5.81	22.99	5.68
(degrees)	R	21.81	7.10	22.27	7.28	21.89	7.45	22.36	7.65	22.20	7.62	22.01	7.48
Knee @ MS	L	40.13	4.93	40.33	5.26	39.87	4.79	41.05	5.20	41.08	5.15	40.59	5.16
(degrees)	R	40.18	4.27	40.38	4.20	40.20	4.59	40.87	5.01	40.57	4.98	40.80	5.14
Knee @ MSW	L	87.58	14.43	87.92	14.86	87.37	14.62	89.16	14.59	87.51	28.28	89.18	14.78
(degrees)	R	85.89	19.19	88.57	14.21	87.57	14.27	89.23	14.71	87.52	30.00	88.90	14.98
Ankle @ MS	L	23.53	3.05	23.73	3.19	23.27	3.08	23.97	3.31	24.14	3.55	23.32	3.41
(degrees)	R	22.95	3.73	23.06	3.78	23.08	3.95	22.87	3.86	22.59	3.82	23.00	3.41
Ankle @ MSW	L	-10.90	5.97	-11.12	6.63	-10.08	6.06	-12.97	7.22	-12.48	8.78	-13.69	7.40
(degrees)	R	-8.18	4.94	-8.18	5.92	-7.81	5.59	-9.52	6.89	-11.95	6.96	-9.43	6.66
Frontal plane													
Hip @ IC	L	-8.33	4.40	-8.17	4.75	-8.97	3.91	-8.76	4.29	-8.67	4.31	-9.06	4.28
(degrees)	R	-9.22	3.95	-9.14	3.96	-9.11	3.88	-9.64	3.42	-9.75	3.34	-9.25	3.51

Table B.2: Average values for the defined spatiotemporal parameters for each direction (straight, clockwise and anti-clockwise) during the non-fatigued and fatigued state.

Parameter	Leg	Non fatigue (4 km)						Fatigue (1.2 km)					
		Straight		Clockwise		Anti Clockwise		Straight		Clockwise		Anti Clockwise	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Step length	L	1.22	0.20	1.19	0.21	1.21	0.20	1.23	0.20	1.28	0.27	1.21	0.22
(m)	R	1.19	0.22	1.21	0.22	1.22	0.22	1.26	0.24	1.26	0.42	1.20	0.23
Step	L	167.01	18.48	158.58	4.82	158.58	4.81	163.82	19.17	157.47	4.19	157.47	4.19
frequency (steps/minute)	R	166.58	14.18	161.31	2.14	161.31	2.14	160.27	21.53	160.56	1.20	160.56	1.20
Contact time	L	0.33	0.11	0.32	0.11	0.34	0.10	0.32	0.11	0.32	0.11	0.32	0.10
(s)	R	0.34	0.10	0.33	0.12	0.34	0.11	0.32	0.10	0.32	0.11	0.32	0.10