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„Differences in the kinematic and muscular activity of lower extremity during stance phases between treadmill and overground running“

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Abstract

Introduction: Treadmills are often used for scientific research to analyse running movement. But to use the treadmill as a clinical assessment instrument it is important to demonstrate, that the kinematic as well as the muscular activity are the same or the variations are too small to cause clinical significance. Different authors (Alton et al., 1998; Elliott & Blanksby, 1976; Fellin et al., 2010; Sinclair et al., 2013, etc.) have focused for many years on examining these differences with fractionally conflicting results. Outcomes described by various authors in treadmill running are: a decreased hip flexion at the foot-strike (Schache et al., 2001; Sinclair et al., 2013; Sinclair, Hobbs, Taylor, Currigan, & Greenhalgh, 2014); a lower peak knee flexion during the stance period (Riley et al., 2008; Sinclair et al., 2013); a less dorsiflexed ankle joint at the foot-strike (Fellin et al., 2010; Nigg et al., 1995; Sinclair et al., 2013) and a lower magnitude of m. biceps femoris during the stance period (Wang, Hong, & Xian Li, 2014; Wank, Frick, & Schmidtbleicher, 1998).

The aim of the conducted study is to identify the level of agreement between the observed parameters during the stance period with the help of the Bland & Altmann analysis.

Methods: Fourteen healthy male students participated in the study. They were asked to run on a treadmill and an indoor runway with a velocity of 3.5 m/s. With a simplified four segment model filmed by the Vicon®-System, the movement of the hip, knee and ankle joints was reconstructed. Information about the muscular activity of four muscles of the lower extremity was obtained with surface electrodes of the TrignoTM Wireless System from Delsys®. The Pedar®-X system was used to determine the exact stance time. After the data acquisition the stance time was normalized to 100%. The collected data was edited with MatLab and the statistical analysis was performed with SPSS.

Results: The ankle joint kinematic showed no sig. differences (except for 20-30%) and a high limit of agreement with the Bland-Altman-Plot. The hip joint is sig. ($p<0.05$) more flexed in treadmill running throughout the whole stance phase. The knee joint showed sig. differences ($p<0.05$) at the beginning, in the middle and at the end of the stance phase. M. vastus lateralis is sig. less ($p> 0.05$) activated in treadmill running. M. gastrocnemius medialis has the same activation pattern in both modalities (only sig. difference at 10%).

Discussion: The high similarity of the ankle joint and the muscular activity of m. gastrocnemius medialis is in line with other literature (Riley et al., 2008; Wang et al., 2014; Wank et al., 1998). The less flexed knee joint in overground running leads to a better running economy according to Clermont et al., (2017) (Clermontetal.,É. The reduced activation of m. vastus lateralis can be explained with the lower vertical displacement for the center of gravity in treadmill running (Wank et al., 1998). The sig. lower hip flexion in overground running is contradictory to present literature (Fellin et al., 2010; Riley et al., 2008; Schache et al., 2001).

Conclusion: The innovative of this study is the precise separation of the stance phase into intervals of 10%, thus new information about the exact time when significant differences occur can be obtained. And the analyzation with the Bland-Altman-Plot, which reveals high agreement for the ankle joint but not for the hip joint.

Zusammenfassung

Einleitung: Laufbänder werden oft für wissenschaftliche Untersuchungen eingesetzt, welche die Laufbewegung analysieren. Um das Laufband für Forschungszwecke verwenden zu können, ist es notwendig zu demonstrieren, dass sowohl die Kinematik als auch die muskuläre Aktivität die gleiche ist, oder dass sie in einem Bereich liegen, der keine klinische Signifikanz verursacht. Verschiedene Autoren (Alton et al., 1998; Elliott & Blanksby, 1976; Fellin et al., 2010; Nigg et al., 1995; Riley et al., 2008; Schache et al., 2001; Sinclair et al., 2013) bemühen sich seit Jahren, diese Unterschiede zu überprüfen, mit teilweise widersprüchlichen Ergebnissen. Unterschiede, die mehrere Autoren beim Laufen auf dem Laufband beschrieben haben, sind: eine verringerte Hüftbeugung beim Fußaufsatz (Schache et al., 2001; Sinclair et al., 2013; Sinclair et al., 2014); eine geringere maximale Kniebeugung während der Bodenkontaktzeit (Riley et al., 2008; Sinclair et al., 2013); eine geringere Dorsalflexion im Sprunggelenk beim Fußaufsatz (Fellin et al., 2010; Nigg et al., 1995; Sinclair et al., 2013) und eine geringere muskuläre Aktivität des M. biceps femoris während der Bodenkontaktzeit (Wang et al., 2014; Wank et al., 1998).

Das Ziel der durchgeführten Studie ist das Übereinstimmungsniveau der beobachteten Parameter während der Bodenkontaktzeit mit Hilfe der Bland & Altmann Analyse zu bestimmen.

Methoden: 14 gesunde männliche Studenten nahmen an der Studie teil. Sie liefen auf einem Laufband und einer Indoor-Laufbahn mit einer Geschwindigkeit von 3.5 m/s. Ein vereinfachtes vier Segment Modell, gefilmt mit dem Vicon®-System, wurde verwendet, um die Hüft-, Knie- und Sprunggelenksbewegung zu rekonstruieren. Drahtlose Sensoren des TrignoTM Wireless Systems von Delsys®, platziert an vier Muskeln der unteren Extremitäten, wurden genutzt, um Informationen über die muskuläre Aktivität zu erhalten. Mit Hilfe des Pedar®-X Systems wurde die genaue Bodenkontaktzeit bestimmt. Nach der Datengewinnung wurde die Bodenkontaktzeit auf 100% normiert. Die gewonnenen Daten wurden mit MatLab aufbereitet und die statistische Analyse mit SPSS durchgeführt.

Ergebnisse: Das Sprunggelenk zeigt keine sig. Unterschiede (außer bei 20-30%) und ein hohes Übereinstimmungsniveau bei der Bland-Altman-Analyse. Das Hüftgelenk ist beim Laufen auf dem Laufband während der gesamten Bodenkontaktzeit sig. ($p<0.05$) stärker gebeugt. Das Kniegelenk zeigt sig. Unterschiede ($p<0.05$) am Anfang, in der Mitte und am Ende der Bodenkontaktzeit. M. vastus lateralis ist beim Laufbandlaufen sig. ($p<0.05$) aktiviert. M. gastrocnemius medialis hat ein gleiches Aktivierungsmuster in beiden Laufmodalitäten (einziger sig. Unterschied bei 10%).

Diskussion: Die große Übereinstimmung des Sprunggelenks und die muskuläre Aktivität des m. gastrocnemius medialis spiegeln Ergebnisse der Literatur wider (Riley et al., 2008; Wang et al., 20

14; Wank et al., 1998). Laut Clermont et al.(2017) führt die geringere Flexion des Kniegelenks beim Overground-Laufen zu einer besseren Laufökonomie. Die geringere Aktivität des m. vastus lateralis kann auf eine geringere Vertikalbewegung des Schwerpunktes bei Laufbandlaufen zurückgeführt werden (Wank et al., 1998). Die sig. größere Hüftflexion beim Laufbandlaufen ist widersprüchlich zur vorhandenen Literatur (Fellin et al., 2010; Riley et al., 2008; Schache et al., 2001).

Schlussfolgerung: Das Innovative der durchgeführten Studie war die genaue Unterteilung der Bodenkontaktzeit in Intervalle von 10%, dadurch konnten neue Informationen über die genaue Zeit des Auftretens von signifikanten Unterschieden gewonnen werden. Weiters ist die Analyse mit dem Bland-Altman-Plot, welche ein großes Übereinstimmungsniveau für das Sprunggelenk, jedoch nicht für das Hüftgelenk zeigt, neuartig.

Table of contents

1. INTRODUCTION 1

2. OBJECTIVE 2

2.1. RESEARCH QUESTION 2

3. THEORY 3

3.1. BIOMECHANICS OF RUNNING 3
3.1.1. Walking - Running - Sprinting 3
3.1.2. Running gait cycle 4
3.1.3. Muscular Activity during running 5
3.1.3.1. Muscles for flexion 6
3.1.3.2. Muscles for extension 6
3.1.3.3. Muscle activity during the phases of the gait cycle 6
3.1.4. Parameter for describing the running gait 7
3.2. CURRENT STATE 9
3.2.1. Biomechanical differences of overground and treadmill running 9
3.2.2. Kinematic differences of overground and treadmill running 9
3.2.2.1. Time – distance parameters 9
3.2.2.2. Hip joint kinematics 11
3.2.2.3. Knee joint kinematics 12
3.2.2.4. Ankle joint kinematics 12
3.2.3. Muscular activity 13
3.2.4. Familiarization 13
3.2.5. Possible limitations to the studies 14
3.3. BLAND & ALTMAN ANALYSIS 15
3.3.1. Measuring the agreement 15
3.3.2. Plotting the data 15
3.3.3. Inappropriate use of correlation coefficient 17

4. METHODS 18

4.1. THEORETICAL ASPECTS 18
4.1.1. Two-dimensional kinematic analysis 18
4.1.2. Electromyography 18
4.1.2.1. Physiological background 18
4.1.2.2. Surface electromyography 19
4.1.2.3. Influencing factors 19
4.1.2.3.1. Tissue characteristics 20
4.1.2.3.2. Physiological cross talk 20
4.1.2.3.3. Change of the geometry 20
4.1.2.3.4. Electrode and amplifiers 20
4.1.3. Foot Plantar Pressure Measurement Systems 20
4.1.3.1. Requirements 21
4.1.3.2. Capacitive Sensors 21
4.1.3.3. Linear length normalization 21
4.2. USED MATERIALS AND METHODS 22
4.2.1. Vicon motion tracking system 22
4.2.2. Surface electromyography 23
4.2.2.1. Skin preparation 25
4.2.3. Pedar pressure insole system 26
4.2.4. Light barrier 26

4.3. Running modalities 26
4.3.1. Treadmill running 26
4.3.2. Overground running 27
4.4. Cohort 28
4.5. Measurement report 29
4.5.1. Preparation 29
4.5.1.1. Laboratory preparation 29
4.5.1.2. Subject preparation 30
4.5.2. Data acquisition 31
4.5.3. Processing of the raw data 33
4.5.4. Statistical evaluation 34

5. RESULTS 35

5.1. Descriptive kinematic analysis 35
5.1.1. Hip Joint 35
5.1.2. Knee joint 37
5.1.3. Ankle joint 39
5.2. Descriptive analysis of the muscular activity 41
5.2.1. M. vastus lateralis 43
5.2.2. M. biceps femoris 44
5.2.3. M. tibialis anterior 45
5.2.4. M. gastrocnemius medialis 46
5.3. Statistical analysis 48
5.3.1. Velocity – Time parameters 48
5.3.1.1. Running Velocities 48
5.3.1.2. Stance Time 49
5.3.2. Correlation coefficient 49
5.3.3. Kinematic parameters 49
5.3.3.1. Hip Joint 50
5.3.3.2. Knee joint 51
5.3.3.3. Ankle joint 52
5.3.4. Muscular activity 54
5.3.4.1. M. vastus lateralis 54
5.3.4.2. M. biceps femoris 56
5.3.4.3. M. tibialis anterior 57
5.3.4.4. M. gastrocnemius medialis 59
5.3.5. Results Bland & Altman analysis 60
5.3.5.1. Hip joint 61
5.3.5.2. Knee joint 61
5.3.5.3. Ankle joint 63

6. DISCUSSION 66

6.1. Temporal parameters 66
6.2. Kinematic parameters 67
6.2.1. Hip joint 67
6.2.2. Knee joint 68
6.2.3. Ankle joint 70
6.3. Muscular activity 71
6.3.1. M. vastus lateralis 72
6.3.2. M. biceps femoris 72

6.3.3. M. tibialis anterior 73
6.3.4. M. gastrocnemius medialis 74
6.4. Bland & Altman analysis 75
6.5. Quality of the results 76
6.5.1. Limitations to the study 76
7. CONCLUSION 77
8. REFERENCES 79
9. APPENDIX 83
9.1. List of tables 83
9.2. List of figures 84
10. DECLARATION 86

1. Introduction

Treadmills are often used for scientific research to analyse the running gait cycle, because they provide a number of advantages. The velocity and inclination can be adjusted in advance and the outside conditions do not affect the measurement; hence standardised circumstances are granted. Moreover, the required calibration volume compared to overground running is reduced. Furthermore, it is possible to capture a larger number of gait cycles during one test trial (Schache et al., 2001). Being able to film more gait cycles ensures having results of continuous kinematics (Fellin et al., 2010).

The main focus of existing literature is on analysing the maxima and minima of various parameters during the running gait cycle (for example (Riley et al., 2008); Wank et al., 1998). Many of these minima and maxima occur during the swing phase, which leads to a lack of information about the kinematics and muscular activity during the stance period. It is in the interest of scientists to clarify the lack of information, because the stance phase is the time period, where the lower extremity is most likely to get injured (Fellin et al., 2010).

In order to use the treadmill as a clinical assessment instrument it is important to demonstrate that the kinematics and kinetics of treadmill vs. overground running are the same or the variations are too small to cause clinical significance.

So far, differences between treadmill and overground running have been calculated by the correlation coefficient (Bland & Altman, 1986). According to Bland and Altman (1986), this is not an appropriate method of analysis, as the correlation coefficient measures the strength of a relation between two variables and not the agreement between them. Therefore, the scope of this study is to examine the agreement in various mechanical and kinematical parameters by using the Bland & Altman analysis for both methods.

This thesis should provide a decision support for scientists, as to whether or not the results found on the treadmill can be generalized to overground running and vice versa.

2. Objective

The main aim of this study is to identify the level of agreement on various kinematic parameters and muscular activity of the lower extremity during the stance phase on overground and treadmill running. The identification of the level of agreement between the two running types can help future scientists in the decision-making process as to whether to use treadmill running and overground running interchangeably.

2.1. Research question

The information from the theoretical input and the lack of information about the agreement of the two running methods lead to the need to perform a new clinical set up with the following criteria:

- Running on a treadmill and an indoor runway
- Analysis of kinematic and electromyographic data
- Same marker and camera position for both set ups
- A standardized velocity of 3.5 m/s
- Subjects need to perform in weekly running activities, like endurance training, ball sport activities etc.
- Familiarization time a priori the treadmill running
- Analysis of the results with the Bland & Altman method

Hence the following research question for the thesis is derived from the information:

> What is the range of agreement of the kinematic differences or differences in the muscular activity of the lower extremity between running on a treadmill or an indoor runway during the stance period at a velocity of 3.5 m/s that have clinical significance?

3. Theory

3.1. Biomechanics of running

The following chapter will characterise the movement of running. An overview of the running cycle, the different phases and relevant parameters for describing the running gait cycle will be provided. Special interest will be placed on kinematic details and the muscular activity of the lower extremities.

3.1.1. Walking - Running - Sprinting

Running and walking are fundamental movements, which were adapted throughout evolution to reach an optimal economization. Running at a self-selected speed leads to the least energy cost for everyone (Marquardt, 2012, p. 63). An increase or decrease of this velocity is combined with a higher energy demand (Kramers de Quervain et al., 2009, p. 192).

Accordingly, Marquardt (2012, p. 63) running cannot be described as a fast walking movement, because flight phases occur only in running and not in walking. The walking movement always contains a double supported stance phase, in which both legs touch the ground. Afterwards there is a one leg support phase, where one leg swings to the front. With an increasing velocity the double supported stance phase becomes shorter than the swing phase, which leads to a flight phase, where neither foot is on the ground, which characterizes the running motion. During one gait cycle two periods of double float occur, at the beginning and the end of the swing phase (Marquardt, 2012, p. 63). Kramers de Quervain (2009, p. 192) describe an average percentage distribution of 30% stance phase to 70% flight phase at a running speed of 5 m/s, the duration of the stance phase while walking already increases to 62% of the whole gait cycle. In comparison with increasing velocities the stance phase becomes shorter and the flight phase longer (80% flight phase of the whole gait cycle at a running velocity of 9 m/s). Accordingly, Novacheck (1998) reported that higher velocity also causes a change from rearfoot to forefoot landing, which leads to the occurrence that elite sprinters never hit the ground with the rearfoot. This change marks the typical distinction between running and sprinting. In practice running and sprinting differ in the goal to be achieved. For long distances endurance training and running economy per gait cycle must be accomplished while for sprinting maximal power output per gait cycle is important in order to reach a certain distance in the shortest time possible (Novacheck, 1998).

3.1.2. Running gait cycle

Walking and running are cyclic movements. One gait cycle is defined as the period between the initial ground contact of one foot and the second ground contact of the same foot (Kramers de Quervain et al., 2009, p. 192). For better visualisation and description, the gait cycle is divided into different phases, which are named and classified differently throughout literature. The four-phases-model described by Bauersfeld and Schröter (1992, pp. 120–123) is often quoted (for example Marquardt, 2012, pp. 64–65 and Neumann, Pfützner, & Hottenrott, 2010, pp. 54–55).

The phase of support (stance phase) and the flight phase are both divided into two subdivisions (Neumann et al., 2010, p. 54). The stance phase has a greater impact on the running velocity, because the acceleration of the centre of mass is produced by the push off from the legs during the stance phase. The swing phase creates the conditions for the push off (Bauersfeld & Schröter, 1992, pp. 120-123).

The four phases of the running gait described by Bauersfeld and Schröter (1992, pp. 120-123) are:

- *Initial stance*: The initial stance phase starts with an active ground contact of the foot (Fig. 1, frame 1). Whether the heel, the midfoot or the forefoot touches the ground first, depends on the running style and the velocity. After the foot contact the knee angle of the leg of the stance side gets further flexed (Neumann et al., 2010, p. 56). The musculature for knee extension gets stretched in order to support the body weight, which is the reason why the stance phase is also called eccentric phase. The end of the initial stance is the transition from the knee flexion to the knee extension, which is the point where the centre of mass (CoM) is exactly over the centre of pressure (CoP) (Fig. 1, frame 2). The duration of the phase depends on the degree of the knee flexion (Neumann et al., 2010, p. 56).

- *Terminal stance*: The terminal stance starts with the location of the CoM exactly over the CoP and ends with the toe-off of the same leg (Fig. 1, frame 2-4). Concerning the knee, the phase starts with the extension of the leg and ends after the toe–off or after the maximal extension of the knee. The musculature for the knee extension shortens, hence the phase is called concentric phase (Neumann et al., 2010, p. 56). Due to the fast extension of the knee and the hip a fast propulsion is achieved, which can be supported by the swinging of the arms. As a general running position the elbow joint angles of the arms are at ~90° and the trunk is upright till slightly bent forward (Bauersfeld & Schröter, 1992, pp. 120–123).

- *Terminal swing*: As seen in figure 1 (frame 4-6) the terminal swing phase starts with the toe-off and ends with the transition from knee flexion to knee extension of the contralateral leg (Neumann et al., 2010, pp. 56–57). This is the point where the CoM reaches a vertical position above the CoP. After the push off the supporting leg becomes the swinging leg, this leg is behind the centre of mass until the push off occurs. The next goal is to bring the swinging leg in front of the body, to do so the knee is bent and the heel is lead to the buttock. The aim of bringing the leg to the buttock is to reduce the moments of inertia by minimizing the distance of the lower leg centre of mass to the rotational axis and consequently the force needed to position the leg to the front. Furthermore, the knee lift is prepared (Bauersfeld & Schröter, 1992, pp. 120–123).

- *Initial swing*: The initial swing phase starts with the extension of the swinging leg (fig. 1, frame 7/ left leg) and ends with the foot contact of the same leg (fig. 1, frame 1). While swinging the leg to the front the knee flexion decreases and the hip flexion increases constantly. The maximal knee lift is reached during the push off of the contralateral leg. Before the leg hits the ground the knee angle is flexed at about 10-20°. The kinaesthetic receptors of the muscles of the lower extremity prepare for the ground contact and the muscles involved in the absorption of the impact of the landing are activated in advance. This pre-activation is called anticipation (Neumann et al., 2010, p. 57).

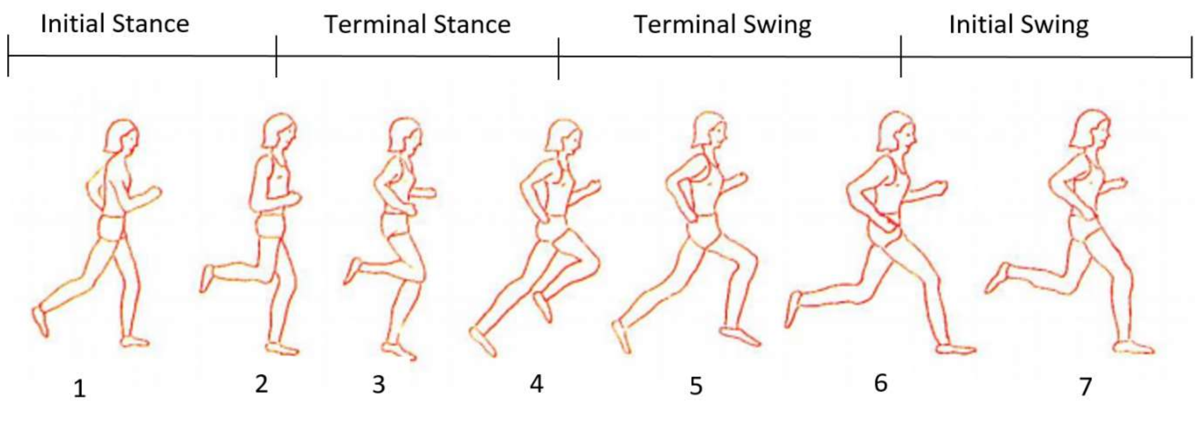


Figure 1: Running gait cycle divided into the four phases (ed. by Neumann et al., 2010, p. 56)

3.1.3. Muscular Activity during running

During running different muscles are active at different times The activation pattern of the muscles of the lower extremity is a coordinated process (Neumann et al., 2010, p. 58). The next paragraphs will describe the muscles necessary for the flexion and extension of the hip, knee and ankle joints, which are important for the study conducted and their activation duration during the running gait cycle.

3.1.3.1. Muscles for flexion

Musculus (M.) tibialis anterior and m. extensor digitorum longus are essential for the dorsiflexion of the ankle joint at the landing. Three posterior muscles of the thigh (m. biceps femoris, m. semitendinosus, m. semimembranosus) supported by the m. sartorius are the great flexion muscles of the knee. Flexion of the hip joint is enabled through m. iliopsoas and m. rectus femoris (Neumann et al., 2010, p. 58).

3.1.3.2. Muscles for extension

The plantarflexion of the ankle, which is actually an extension movement, becomes possible due to the m. gastrocnemius medialis and lateralis and m. soleus. The quadriceps femoris, is a large muscle group consisting of m. rectus femoris, m. vastus lateralis, m. vastus intermedius, m. vastus medialis, which is required for extending the knee. Three muscles (musculi glutei, m. adductor agnus, m. ischiocrurales) are necessary for the extension of the hip (Neumann et al., 2010, p. 58).

3.1.3.3. Muscle activity during the phases of the gait cycle

The muscles of the lower extremity are already activated before the initial contact. This pre-activation leads to an increased muscle stiffness, which results in a better stability of the hip, knee and ankle joints (Neumann et al., 2010, p. 60).

At the *initial stance phase* several muscles are active, which will be specified later, to absorb the impact of the landing (see fig. 2). Especially m. gastrocnemius and the muscles of the quadriceps femoris reach their maximum activation during the initial stance phase. Not only the extensors, but also the muscles for flexion are activated. The overall muscular activity of the lower extremity during the initial stance phase is the highest before the push off (Neumann et al., 2010, p. 60). Novacheck (1998) mentioned in his review, that the muscular activity is apparently more important for a smooth landing than it is for preparing the act of leaving the ground.

During the *terminal stance phase* the muscles for extension are dominant, but their maximum activation varies. The knee extension muscles are activated throughout the beginning of the terminal stance; m. gastrocnemius and m. ischiocrurales are activated until the first half of the initial stance (Neumann et al., 2010, p. 60).

At the *terminal swing phase* m. rectus fermoris and m. tibialis anterior are the most activated muscles as seen in figure 2. The activation of m. rectus femoris occurs during the hip extension and knee flexion. Consequently, this muscle is essential for stabilising the pelvis and controlling the knee bending. M. tibialis anterior is mandatory for the dorsiflexion of the ankle.

During the *initial swing phase*, the activation of the m. tibialis anterior continues until the ground contact of the foot. At the end of the initial swing phase all the muscles for joint extension get activated (Neumann et al., 2010, p. 60).

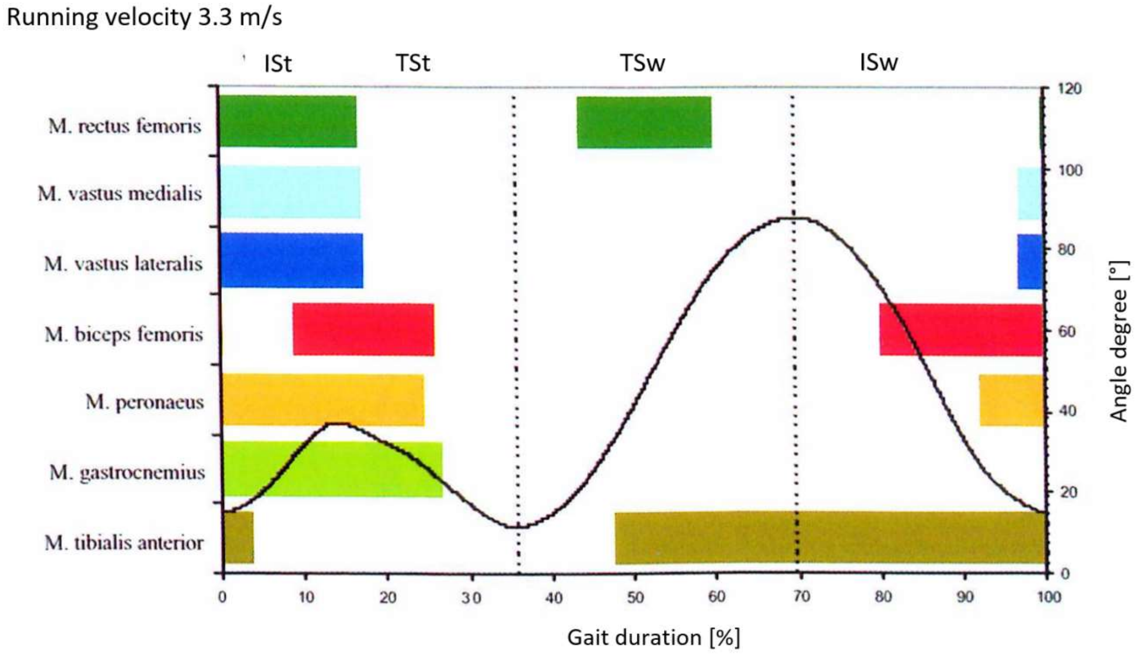


Figure 2: Duration of the muscle activity and knee angle (black line)- time gradient (ISt … Initial Stance, TSt …Terminal Stance, TSw …Terminal Swing, ISw … Initial Swing) (ed. by (Neumann et al., 2010, p. 60))

3.1.4. Parameter for describing the running gait

In the following paragraphs, important parameters to evaluate the gait cycle, will be described.

- Stride length [m]
  The stride length is defined as the distance between two initial ground contacts of the same foot as seen in figure 3. During walking the mean stride length is about 165.5 cm (Giannini, 1994, p. 70).

- Step length [m]
  The step length shows the distance between the foot-strike of the two legs, measured at the heel at a normal walking movement (see fig. 3). While running the first ground contact depends on the running style, like forefoot, midfoot or rearfoot gait pattern. The side (right or left) is always indicated by the foot, which initially hits the ground after the swing phase. The step length should be identical on each side. If a difference occurs an asymmetric gait can be assumed (Giannini, 1994, p. 70).

- Frequency f [Hz or beats/min]
  The frequency describes the number of steps made during a certain period of time, usually one minute. The average frequency for walking is 110 steps/min. The velocity can be raised either by increasing the step length or the frequency. The frequency increases proportionally more than the step length (Giannini, 1994, pp. 70–71).

- Velocity v [m/s]
  The velocity is the product of the step length and the frequency and is characterised by the mean forward motion of the centre of mass. By increasing the step length and the step frequency a higher velocity can be obtained. The swing phase can only be reduced until a certain point. A sustaining reduction of the stance phase leads to a flight phase, which is, as aforementioned, a characteristic of the running movement (Giannini, 1994, p. 71).

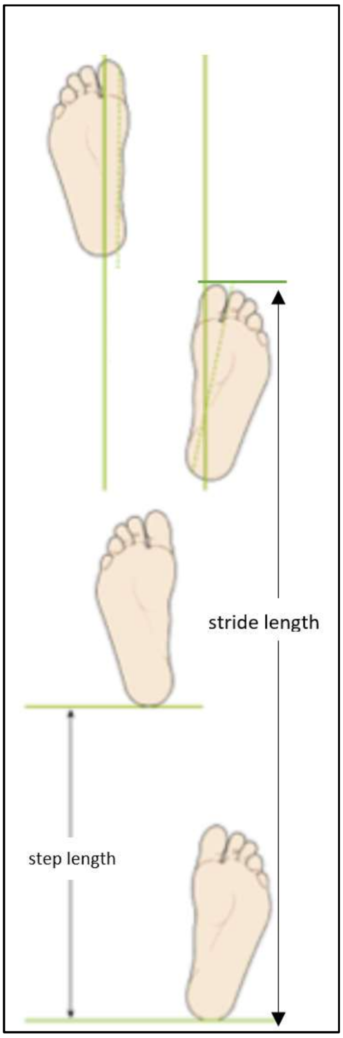


Figure 3: Step length, step width and stride length (ed. by Marquardt, 2012, p. 72)

3.2. Current state

Numerous studies have been conducted in order to examine the differences between overground and treadmill running. Some of the analyzed parameters showed conflicting results throughout different studies (Alton et al., 1998; Elliott & Blanksby, 1976; Fellin et al., 2010; Nigg et al., 1995; Riley et al., 2008; Schache et al., 2001; Sinclair et al., 2013)

3.2.1. Biomechanical differences of overground and treadmill running

Van Ingen Schenau (1980) compared overground with treadmill running by using theoretical models. He came to the conclusion that the two running modes are the same as long as the mechanical variables are described in respect of the surface on which the subjects move. Moreover, the treadmill motor must be strong enough to create a constant belt speed, including absorbing the load moving on the belt. Furthermore, the feedback system must be fast enough to keep a constant speed, also in consideration of an increasing load on the belt. Otherwise there could be an exchange of energy between the belt and the runner (Schache et al., 2001). A change of the surface structure of the treadmill belt can lead to changed proprioceptive information with could change the style of locomotion (van Ingen Schenau, 1980).

If all the previously mentioned aspects are implemented, only non-mechanical factors such as air resistance, treadmill familiarization and changed visual and auditory information can lead to diverse results.

The air resistance is very little in walking, but increases with higher velocities. For sprinting the total energy cost can rise by 13% due to air resistance (van Ingen Schenau, 1980).

The visual information is necessary to maintain the equilibrium and stability (van Ingen Schenau, 1980). During overground running the subject moves towards the surroundings, which does not occur in treadmill running. Treadmill running can be frightening and stressful for people who are not used to it. This might lead to changes in the kinematic, such as a longer double supported phase while walking on the treadmill, to ensure that the equilibrium is maintained (van Ingen Schenau, 1980).

3.2.2. Kinematic differences of overground and treadmill running

3.2.2.1. Time – distance parameters

In the study of Schache et al. (2001) nine men and one woman participated to compare the differences of the lumbo-pelvic-hip complex during overground and treadmill running. The cohort were experienced runners, also on a treadmill, with at least 20 running kilometres per week. For the trial the subjects were asked to run at their self- selected ten kilometre running speed, which led to an average speed of 3.99±0.5 m/s (with a standard deviation (SD) of 0.5). The findings of the study showed a significant ($p<0.05$) higher frequency accompanied with a shorter stride length (-0.14 m) and time on treadmill running in comparison to overground running.

These findings are supported by the results of a study by Riley et al. (2008); Wank et al. (1998) and Elliott and Blanksby (1976). Wank and associates (1998) indicated a reduced step length by 0.6 m at a running velocity of 4 m/s. Additionally, the results of Wank et al. (1998) showed an increasing step length reduction of 0.12 m with a faster running speed of 5 m/s. The cohort in that study (one female and nine males) had experience in treadmill running. The examined result is very similar to the observed result of Schache et al. (2001), who analyzed the reduction of the stride length (Giannini, 1994, p. 70).

Frishberg (1983) examined the sprinting kinematics of five collegiate level sprinters in overground (mean velocity 8.54 ±0.09 m/s) and treadmill (mean velocity 8.46 ±0.13 m/s) conditions. He did not observe any significant differences in stride length, time or frequency.

Changes in the proportion of the stance phase and the swing phase show inconsistent findings throughout literature (Frishberg, 1983; Nelson, Dillman, Lagasse, & Bickett, 1972; Schache et al., 2001; Wank et al., 1998). Schache et al. (2001) found a decreased swing phase and an increased stance phase when running on a treadmill at a mean velocity of 3.99 m/s. In both the experiment of Wank et al. (1998) and Frishberg (1983) in comparison, the stance phase was reduced in the treadmill conditions. Wank and associates (1998) found a significant ($p<0.01$) reduction both at a speed of 4 m/s and 6 m/s in nine out of the ten subjects. The authors mentioned that the change of proportion between the stance and swing phase leads to a running style which seemed hastier, due to the higher step frequency (Wank et al., 1998). Frishberg (1983) examined at velocities over 8 m/s a significant ($p<0.05$) reduction of the total stride of the stance phase from 47.23% on overground running to 45.42% on the treadmill. The conflicting results may occur from the different procedures used to classify the initial contact and the take-off, the treadmill running experience and the accommodation (Schache et al., 2001). Furthermore, the distinct velocities used for testing might cause different results (Schache et al., 2001). Both Wank et al. (1998) and Frishberg (1983) tested experienced runners at high velocities. Wank et al. (1998) only recruited male physical education students, who were familiar with treadmill running. They were also familiar with the treadmill prior to the measuring session. The cohort of Frishberg (1983) participated in sprinting events and had a least ten treadmill training sessions before the testing. Experienced treadmill runners might not have the often mentioned fear of falling off the back of the treadmill (Alton et al., 1998).

3.2.2.2. *Hip joint kinematics*

With their study Sinclair et al. (2013) aimed to provide a three-dimensional kinematic comparison of the lower extremity between running on a runway and a treadmill. A cohort of eleven males and one female ran on a treadmill and an indoor runway with a velocity of 4 m/s ±5%. The subjects were trained runners with at least three training sessions and a minimum of 25 running kilometres per week. Outcomes regarding the hip kinematics are 12° less hip flexion at foot-strike (p=0.001) and a 17° lower hip range of motion (p=0.001) while running on a treadmill.

The aforementioned experiment of Schache et al. (2001) with only trained runners and an average running velocity of 3.99 m/s also found a significant (p<0.05) decreased hip flexion at foot-strike in treadmill running. Furthermore, an increased hip extension at toe-off and an increased maximum hip extension was detected in treadmill running when compared to overground running.

Fellin and colleagues (2010) examined 20 (ten male and ten female) hobby runners, who ran at least 10 km per week. The running pace during the testing procedure was 3.35 m/s ±5%. The trend symmetry method was used by Crenshaw and Richards (2006) to evaluate the symmetry of the kinematic between the two running modes. This method uses eigenvectors to compare different waveforms of the hip, knee and ankle joints during the gait cycle. The mean trend symmetry value for all kinematic data of the hip joint was 0.94, which indicated that the two running modes are similar (1.0 indicates a perfect symmetry). In this study the hip joint was the most similar joint during overground and treadmill running compared to the ankle and knee joint. The author mentioned the slower running velocity of 3.35 m/s compared to 4 m/s in the study of Schache et al. (2001) as a possible explanation for the high symmetry of the hip joint (Fellin et al., 2010).

The findings of a decreased hip flexion at foot-strike is in line with both the results of Sinclair et al. (2013) and Schache et al. (2001). The change in the hip range of motion in the experiment of Sinclair et al. (2013) is not seen in the outcomes of Schache et al. (2001) and Fellin et al. (2010), who did not find any differences in the hip range of motion. The reduced range of motion might originate from a reduced step length observed in early studies as stated before (Sinclair et al., 2013).

In his study Alton et al. (1998) found conflicting results with his treadmill walking experiment. A significant (p<0.004) greater hip flexion (+7.6°) and hip range of motion (+3.65°) in treadmill walking was observed. The sample included eight male and nine female participants. According to the author the greater hip movement originates from a shorter stance phase caused by a higher stride cadence. The subjects utilized those changes in the gait cycle to decrease the fear of falling off the back of the treadmill and keeping up with the belt speed (Alton et al., 1998).

In the experiment of Riley et al. (2008) twenty (ten female and ten male) regular joggers, who ran at least 15 miles per week were recruited. The cohort was asked to run at their 10 km race pace, which led to a mean velocity of 3.8 m/s. Riley and associated (2008) evaluated time- distance, kinematic and kinetic parameters. Considering the hip kinematic the hip flexion, adduction and internal rotation were examined and no significant differences were observed.

3.2.2.3. Knee joint kinematics

Riley et al. (2008) investigated kinematic and kinetic differences between overground and treadmill running. The only significant difference ($p<0.05$) occurred at the peak knee angle in the sagittal plane. During treadmill running the maximal and minimal knee peak was significantly ($p<0.05$) lower in comparison with treadmill running. One limitation to the study was, that the participants only had 1.5 – 2 min of familiarization time with treadmill running. The recommended familiarization time stated by many researchers (Lavcanska, Taylor, & Schache, 2005; Matsas, Taylor, & McBurney, 2000) is six minutes. Further explanation is given in chapter 3.2.4 (Familiarization).

The results of Sinclair et al. (2013) are in line with the findings of Riley et al. (2008). The treadmill running condition exhibited a significant ($p=0.01$) lower peak knee flexion of 5° during the stance period. An explanation for the differences is the reduced horizontal movement of the centre of mass during treadmill running found in the study of Millet et al. (2009). Accordingly, Sinclair et al. (2013) during treadmill running the centre of mass (CoM) moves over the stance limb, therefore the tibia must move over the ankle joint, which leads to the increasing knee flexion, hence the movement of the CoM is reduced in treadmill running also the knee flexion is reduced.

In another study Fellin et al. (2010) observed the most deviations for the knee kinematic between the two running modes in the frontal plane. The result of the trend symmetry, examined with the trend symmetry method by Crenshaw and Richards (2006) was 0.86 compared to 0.99 in the sagittal plane, values >0.95 are considered highly similar.

3.2.2.4. Ankle joint kinematics

The ankle is less dorsiflexed at foot-strike when running on a treadmill compared to running on an overground runway. This conclusion has been reported by various authors (Fellin et al., 2010; Nigg et al., 1995; Sinclair et al., 2013). Sinclair et al. (2013) detected a significant reduced ankle dorsiflexion by 6.6% ($p=0.01$) on the treadmill compared to overground running. (Fellin et al., 2010) noted that the change in foot-strike position could be caused by a reduced step length or the change from rear foot to forefoot or midfoot strike position. A limitation to their study was the lack of information to ascertain whether a change in strike pattern or the reduced step length caused the changes in the ankle kinematics.

3.2.3. Muscular activity

A study by Wang et al. (2014) compared the muscular activity of four muscles of the lower extremity (m. rectus femoris, m. tibialis anterior, m. biceps femoris, m. gastrocnemius) during overground and treadmill running. Thirteen male runners with experience in treadmill or overground running participated in the study. The subjects ran on the treadmill and different overground surfaces (concrete, synthetic rubber and natural grass) at a velocity of 3.8 m/s. The researchers observed two significant differences ($p<0.05$) between the overground and treadmill conditions. The m. rectus femoris and m. biceps femoris showed higher magnitudes on the overground surfaces during the stance phase compared to treadmill running. Moreover, the differences were higher on concrete and synthetic rubber than natural grass.

The results of the m. rectus femoris are consistent with the findings of the early study of Wank et al. (1998), but m. biceps femoris shows conflicting findings. Wank et al. (1998) reported a higher magnitude of m. biceps femoris during ground contact and the first part of the swing phase. Furthermore, the duration of the activity of this muscle was longer in treadmill running than overground running. The contradictory results might be as a result of the varied running velocities (4 m/s and 6m/s vs. 3.8 m/s) or the different division of the gait cycle (Wang et al.'s study 4 phases vs. Wank et al.'s 3 phases).

The muscular differences at the stance phase can be supported with kinematic data. The trunk is bent less forward during treadmill running, because no forward movement of the trunk is required as the running speed is maintained by the treadmill (Wang et al., 2014).

3.2.4. Familiarization

The treadmill familiarization is a non-mechanical factor which can lead to deviating results between the two running conditions. There is a distinction between familiarization and habituation. Habituation is a long-term adaptation process, which results in reliable data after a short period every time when a person starts running on a treadmill. Familiarization describes an adaptation process which occurs within a training session. This adaptation does not last for more sessions (Sinclair et al., 2013).

In his study Matsas et al. (2000) investigated the required familiarization time in treadmill walking. Eight female and eight male subjects with a mean age of 21.1 years were asked to walk with their self-selected walking speed on an overground walkway and a treadmill. The walking velocity ranged from 1.14 to 1.46 m/s. The findings show reliable knee joint measurements, with no significant differences ($p>0.05$) after four minutes and reliable temporal and spatial parameters (cadence, stride time and step length), with no significant differences ($p>0.05$) in measurements after six minutes of treadmill walking. Kinematic data of the knee compared at zero minutes, which means the analysis began five seconds after the subjects started walking, shows significant differences ($p<0.05$) and cannot be generalized to overground walking.

Lavcanska et al. (2005) used a similar set up and tested the familiarization time for the three-dimensional (3D) pelvis and lower limb angular kinematics. The reliability between the two running modalities was demonstrated with the interclass correlation coefficient (ICC). After six minutes of treadmill running at a self-selected running speed the angles of the pelvis, hip, knee, ankle, cadence and stride time showed a maximum (ICC=0.95) reliability. After two to ten minutes the values were already highly reliable (ICC=0.9). In comparison after the first two minutes the ICC only showed a moderate (ICC=0.76) reliability.

3.2.5. Possible limitations to the studies

There are different explanations for the contradictory results in literature. Limitations mentioned by various authors are:

- *Variation in speed*. It is difficult to maintain a constant speed for the overground condition. The velocity of each overground trial varies slightly (Riley et al., 2008). Some authors (Riley et al., 2008; Schache et al., 2001) also use a self-selected running speed for the testing. This can lead to big variations in velocity throughout the cohort and further to different running styles.
- *Short indoor runway*: Riley et al. (2008) mentioned the relative short runway (about 15 meters) for the experimental set up, which leads to an uncertainty whether they were able to measure the parameters in a steady-state condition, whereas steady-state condition can be assumed for treadmill running.
- *Various techniques to determine foot contact*: If the treadmill is not instrumented different methods are used to determine the foot-strike and take-off. Fellin et al. (2010) used the change in the vertical velocity of the distal heel marker from negative to positive to determine foot-strike. Take-off was defined as the time of the peak knee extension. Schache et al. (2001) used two different methods for classifying the gait cycle events. For overground running the ground reaction force data from a force platform was used. As the treadmill was not instrumented foot-strike and take-off were determined using the vertical displacement and vertical velocity of markers

set on the malleoli. Sinclair et al. (2013) exclusively used kinematic data to determine the stance phase. Foot-strike was defined as the first peak in knee extension and toe-off as the second peak. The author perceives that methods for separating swing and stance phase based on kinematic data are used repeatedly, but they are known to lead to distinctions when compared with the gold-standard method, force platform data.

3.3. Bland & Altman analysis

The Bland & Altman method is a statistical analysis procedure, which is used to compare two different measurement methods. So far the correlation coefficient has often been used for expressing such results, but Bland and Altman do not agree with the use of the correlation coefficient (Bland & Altman, 1986). In the next chapter the Bland and Altman method is described and the reasons why other methods show misleading results will be explained.

3.3.1. Measuring the agreement

In medicine, when a new measurement technique is compared with an established one, it is important to know, how far apart the measured results are. It is most unlikely that the two methods show exactly the same results, because there is always some lack of agreement. Depending on the range of agreement the old method can be replaced by the new one, or they can be used interchangeably. How wide the range of difference of the measurements can be without causing problems, depends on the individual research question. Ideally the limits should be defined in advance to help with the interpretation.

In clinical measurements the true value is unknown. The best estimation of a correct result is the mean of the two measurements. For plotting the data, it is necessary to calculate the standard deviation (s). If the differences are normally distributed, 95% of all the values will lie within the mean ±2s (or more precise ±1.96 s). This range is called the limit of agreement (Bland & Altman, 1986).

3.3.2. Plotting the data

Graphical techniques are useful for comparing measurements. According to Bland and Altman (1999), the first step is to plot the results from one measurement against the other by drawing the line of equality (Fig. 4).

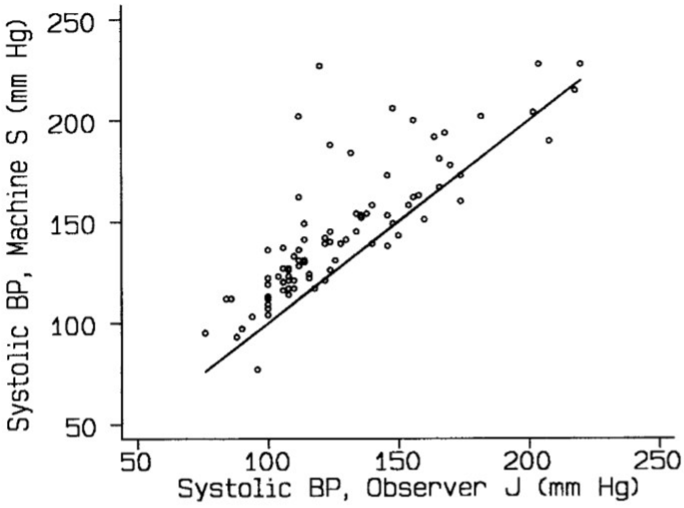


Figure 4: Systolic blood pressure measured by observer and machine (Bland & Altman, 1999)

If the two techniques gave exactly the same results, all points would lie on the line of equality. It is important that the scale of both axes is the same, to assess better visual information of the agreement of the measurements. However, this plot obscures information especially if the range of variation of the measurements is large in comparison with the differences between the methods.

As seen in Fig. 5 a better graphical analysis is to plot the differences of one measurement against the mean.

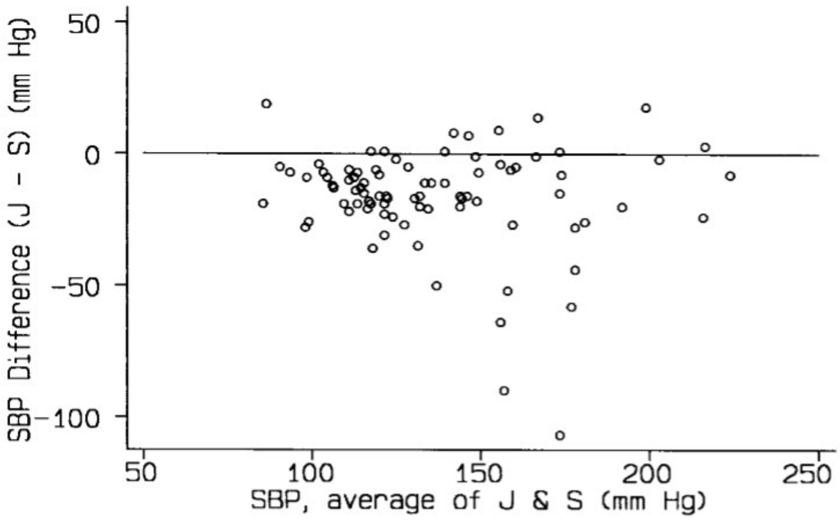


Figure 5: Systolic blood pressure: differences observer (J) – machine (S) against average (Bland & Altman, 1999).

In this method the lack of agreement is visual and the discrepancies in relation to size are well seen. Furthermore, extreme or outlying results are also shown. To get the clearest graphical plot the line for the ±1.96 s and the mean of the measurements as the best approach to the real quantity should be added, an example can be seen in Figure 6. It shows the same graphic as Figure 5 with all further information added.

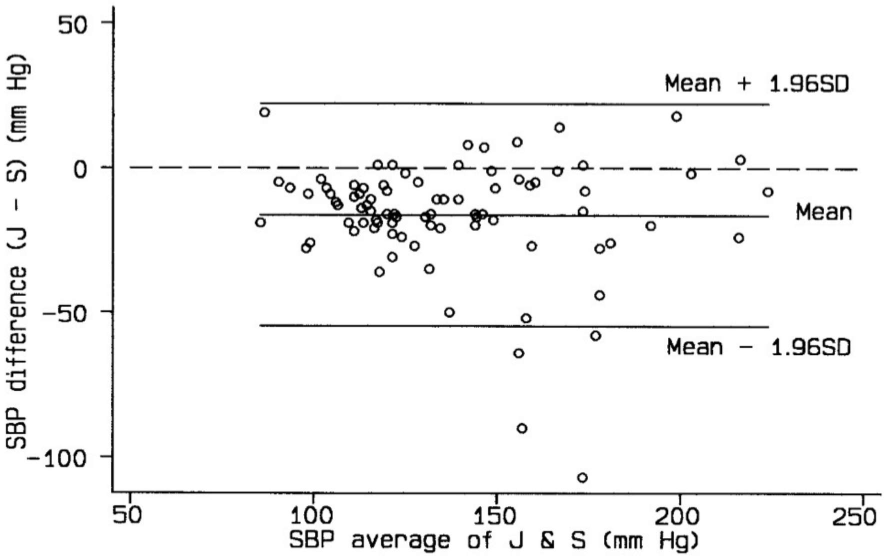


Figure 6: Systolic blood pressure: differences observer (J) – machine (S) against mean with 95% limits of agreement (Bland and Altman, 1999)

3.3.3. Inappropriate use of correlation coefficient

The correlation coefficient (r) is often used to compare different measuring methods. Bland and Altman (1986) mentioned different reasons why the correlation coefficient is not an adequate way of describing an agreement between measurements.

- The correlation coefficient measures the strength of relation and not the agreement of two variables. A perfect relation is given when one measurement is plotted against another and all points lie along a straight line. A perfect agreement is only reached when all points lie along the line of equality (see Fig. 4).
- The correlation coefficient is not affected by changing the scale, the agreement certainly is, because it makes a difference if one method always measures twice the amount of the other.
- The correlation coefficient depends on the quantity measured. The wider the range the higher is r.
- The null hypothesis of r is, that there is no linear relation between variables. If significance is reached it means, that the methods are related, which is obvious when two methods are designed to measure the same thing. In this case the test of significance is irrelevant for analysing the agreement (Bland & Altman, 1986).
- The correlation coefficient does not show any systematic bias between two variables (Bland & Altman, 2003).

4. Methods

4.1. Theoretical aspects

The next chapter will describe the theoretical aspects of the biomechanical methods used in the study.

4.1.1. Two-dimensional kinematic analysis

The two-dimensional video based analysis is often used for biomechanical research. The theoretical background for getting two-dimensional data out of filming retroreflective markers with two-dimensional cameras has been well studied. The Vicon motion tracking system is a common tool for the kinematic analysis of movements (Windolf, Gotzen, & Morlock, 2008).

A big advantage of the three-dimensional video based analysis compared to the two-dimensional, is that the parallax error can be eliminated. This results in the possibility to calculate the angles of the body kinematics at any point during the video, also if the motor segment leaves the movement plane. With a two-dimensional analysis the distortion of the camera lenses makes it impossible to analyse angles, which are not located at the centrum of the recorded image. The parallax error is more present in the frontal plane than in the sagittal plane, because the leg kinematics hardly leaves the sagittal plane during the running and walking movement (Marquardt, 2012, p. 113).

4.1.2. Electromyography

The electromyography (EMG) is a clinical field discovered by Aloisius Galvani in 1971. At the beginning of the 20th century the discovery of needle electrodes made it possible to measure the action potential of a muscle (Luca, 1997). Nowadays needle electrodes are used in the clinical research field, especially in the neuro – and myopathy. In sports science an alternative to needle electrodes is used more frequently, the surface electrodes (Gruber et al., 2009, S. 120ff.). The use of the surface EMG is widespread throughout different fields, for example for medical research, rehabilitation, ergonomics, like risk prevention and sports science, here especially for the strength training of athletes or movement analysis (Konrad, 2006).

4.1.2.1. Physiological background

For a better understanding of how the surface electromyography works, the physiological background will be explained in the following paragraph.

The fundamental unit of the muscle is a motor unit. One motor unit includes a motoneuron and all the muscle fibres which are stimulated by the axonal branch of the motoneuron. The muscle fibres of one motor neuron always act as one, which leads to the term “unit”. These motor units create a motor unit action potential (MUAP). The central nervous system sends out signals as long as the muscle should be contracted, which leads to various motor unit action potentials with short time intervals in between. This pattern describes the so called motor unit action potential train (MUAPT), which is measured with the EMG electrodes. The firing frequency and the amount of motor units recruited are the two parameters which influence the visual signal the most (Konrad, 2006).

According to Konrad (2006) the waveform of the MUAP is influenced by different aspects:

- The distance of the muscle fibres to the surface, where the electrode is placed.
- The volume of the muscle fibres. The amplitude is proportional to the diameter of the fibre.
- The amount of muscle fibres innervated by one motoneuron.

4.1.2.2. Surface electromyography

Two main types of electrodes exist - the invasive (needle or wire) electrodes and the surface/skin electrodes. The electrode can either be used alone (monopolar) or in pairs (bipolar) The choice of the electrodes always depends on the study and there is not one type of electrodes which can be used every time (Luca, 1997). The skin electrodes are mostly used for studying in the kinesiology. The big advantage for surface EMG is the simple use, because the sensors only need to be placed on the skin above the muscle. The correct placement will be explained later. Limitations to the skin electromyography are that only surface muscles can be measured. If a deeper lying muscle should be measured it is necessary to use invasive electrodes such as fine wire electrodes. A second disadvantage of the surface electromyography is the high risk of a cross talk, which describes the phenomena that the showing amplitude is not only the muscular activity of the analysed muscles but also the activity of muscles nearby (Konrad, 2006). To reduce the extent of the cross talk, small electrodes should be used to ensure a short distance between the electrodes (Mogk & Keir, 2003).

4.1.2.3. Influencing factors

Konrad (2006) describes different factors, which can influence the EMG-Signal. A selection is described in the following chapter.

4.1.2.3.1. Tissue characteristics

The EMG signal depends on the conductivity, which varies with the type and the thickness of the tissue, the temperature and physiological changes. These circumstances can alter from subject to subject and even within one subject. A direct quantitative comparison of the signals would lead to misleading results (Konrad, 2006).

4.1.2.3.2. Physiological cross talk

The activity of neighbouring muscles can influence the local EMG signal. This cross talk does not usually make up more than 10 – 15% of the signal amplitude. For data analysis it is important to keep that number in mind, especially with signals, which have their origin close to each other (Konrad, 2006).

4.1.2.3.3. Change of the geometry

Any change in distance between the electrode and the signal of origin influences the EMG signal. Changes can be caused by dynamic movement or external pressure. This problem has particular importance with dynamic measurements (Konrad, 2006).

4.1.2.3.4. Electrode and amplifiers

The noise of the amplifier inside the electrode can be seen at the baseline of the EMG signal and should never exceed 5 root-mean-square voltage (vrms). The amplifier noise can be minimized by careful preparation of the skin and the laboratory (Konrad, 2006).

4.1.3. Foot Plantar Pressure Measurement Systems

During daily locomotion the feet get in contact with the environment first, thus it is important to diagnose feet problems at an early stage, to prevent injuries. For injury prevention important information needed is the foot plantar pressure. The foot plantar pressure is defined as the pressure field between the foot and the support surface, for example the insole, during locomotion. To obtain information about the foot plantar pressure is in the interest of scientists for example for diagnosing lower limb problems, for adapting footwear designs, for analysing sport biomechanics and to reduce the risk of injuries (Razak, Zayegh, Begg, & Wahab, 2012). At present two different types of plantar pressure measuring devices exist: platform systems and in-shoe systems (Razak et al., 2012). In the further paragraphs only information about in-shoe systems will be provided, because it is the type of device used in the study.

The big advantage of in-shoe systems is the high mobility, which allows plantar pressure to be measured in a wide variety of terrains and footwear designs. The high mobility comes with a disadvantage, the possibility of the sensor slipping during the measurement (Razak et al., 2012).

4.1.3.1. Requirements

There are different requirements of in-shoe systems as mentioned by Razak et al. (2012).

- *Sensors*: The sensors have to be small and light and the insoles should be available in all sizes. To guarantee a comfortable wearing of the sensors in the shoes, they have to be thin and flexible.
- *Cabling*: The wire necessary to transmit the received data to a computer for analysis, has to be limited, to ensure a natural gait. Ideally the data is transmitted wireless via Bluetooth.
- *Power consumption*: The device should work with a low power consumption, in order for a small battery to sufficiently record the necessary data.
- *Pressure range*: Different scientific issues require different pressure ranges to be recorded. The range of the foot plantar pressure can value up to 1.900 kilo Pascal (kPa) (Razak et al., 2012).

4.1.3.2. Capacitive Sensors

Different sensors are available to measure the foot plantar pressure, such as resistive sensors, piezoelectric sensors, piezoresistive sensors and capacitive sensors. In this study we used an in-shoe system equipped with capacitive sensors.

The sensors have two conductive electrically charged plates, which are separated by a dielectric elastic layer. Once pressure is applied to a sensor, the elastic layer bends and the distance between the two plates changes. This distance change leads to a voltage change proportional to the applied pressure (Razak et al., 2012).

4.1.3.3. Linear length normalization

The time duration of a running gait cycle and the timing of the events within a cycle not only vary between populations but also within one subject. Because of these differences the gait cycle is described as pseudo-periodic, hence there is a need to apply temporal alignment techniques to be able to compare the running gait cycles. A method often used is the linear length normalization, in which the time duration is converted into a scale up to 100%. This method removes temporal differences between the whole gait cycle, however temporal differences between events, which happen during one gait cycle, like peaks and valleys still exist. Therefore, point-by-point comparisons can lead to misleading results (Helwig, Hong, Hsiao-Wecksler, & Polk, 2011). In this study the running stance time from one subject between the two running modalities are compared and not the stance time of different subjects.

4.2. Used materials and methods

The following chapter provides technical information about the equipment actually used.

4.2.1. Vicon motion tracking system

For the kinematic analysis of the two different running modes the Vicon®-MX-Motion-Capturing-System (Oxford, UK) at the Department for Biomechanics, Kinesiology and Sports Informatics of the Institute for Sports Science of the University of Vienna was used. Eight infrared cameras (2x T40S and 6xT10) were used to capture the markers in the three-dimensional room with a sampling rate of 250 hertz (Hz). The set-up of the laboratory can be seen in figure 7. The resolution of the T40S model was 4 megapixels and of the T10 model 1.3 megapixels. The cameras were connected with an acquisition station system (Vicon MX Net, Oxford), which synchronised the signals of the cameras externally. The data capturing was performed with the Vison Nexus 2.5 software.

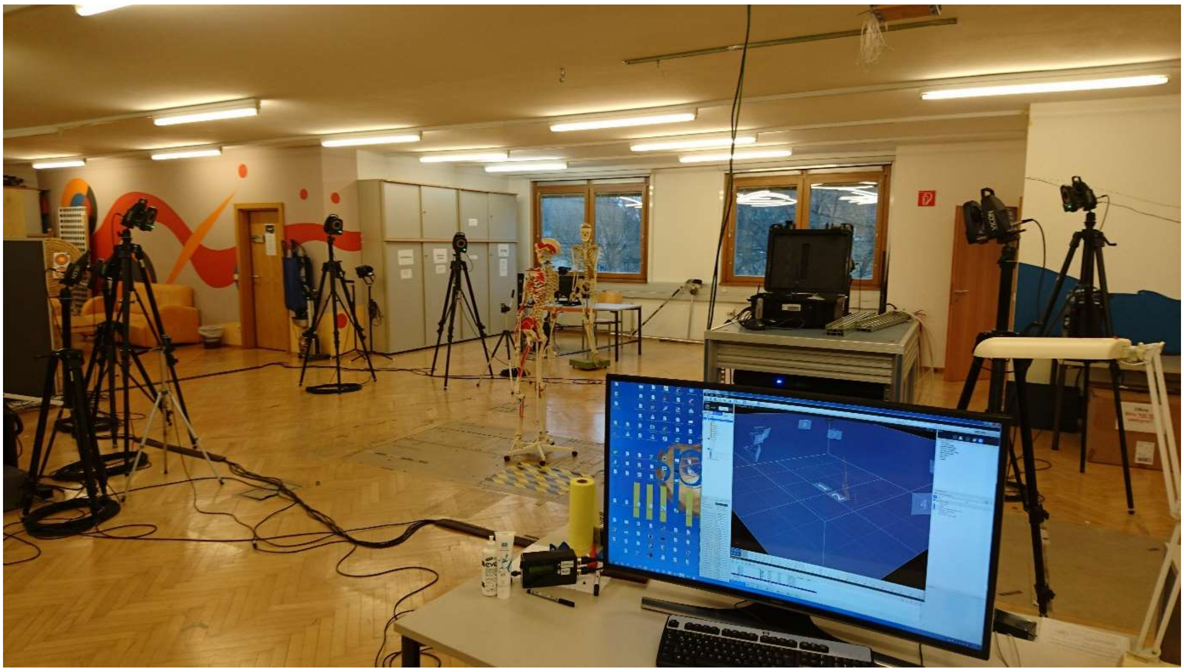


Figure 7: Laboratory with Set Up for the Vicon® motion tracking system

For the marker positioning a simplified four segment model was used for reconstructing the kinematic data as seen in figure 8. The reflective markers were set on C7, trochanter major, epicondylus lateralis – medialis, maleolous lateralis – medialis, tuberositas calcanei and fifth metatarsal which defined the trunk, thigh, shank and foot segment respectively and allow us to calculate the knee, hip, ankle and trunk angles. The diameter of the markers was 14 mm, except for the C7 and trojanter major, where for better visualization bigger markers with a diameter of 19 mm were used.

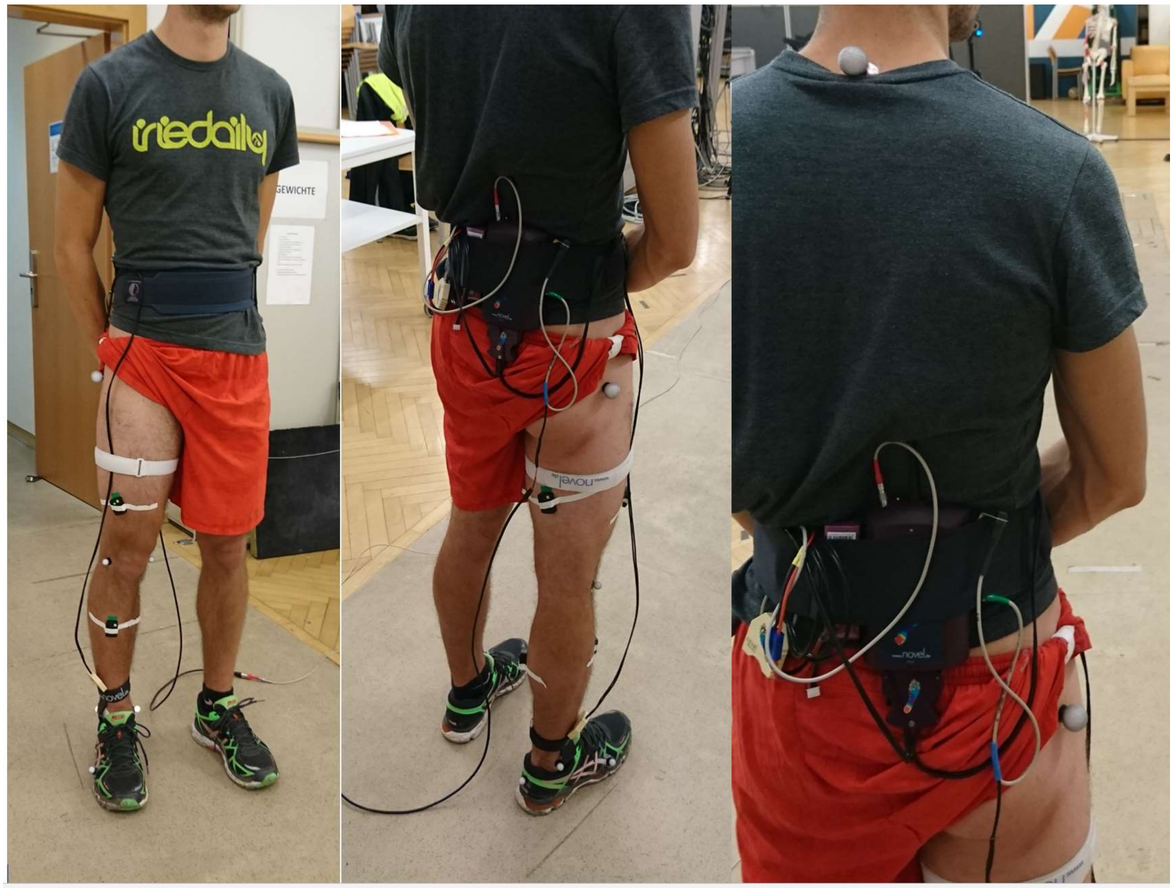


Figure 8: Four segment marker placement on a subject

4.2.2. Surface electromyography

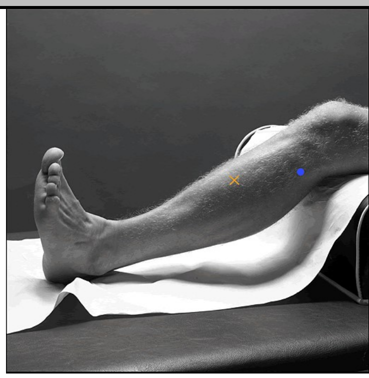
The measurement of the electrophysiological activity was performed with a TrignoTM Wireless System from Delsys® (the system is shown in figure 9) with a sampling rate from 1 kHz and a gain of 1000. This setup complies with literature which says, that the conversion rate of the A/D card should be at least double the amount of the highest expected result of muscular activity during the measurement. In the field of electromyography frequencies between 10 and 500 are expected which leads to the aforementioned value of 1000Hz (Konrad, 2006; Luca, 1997).

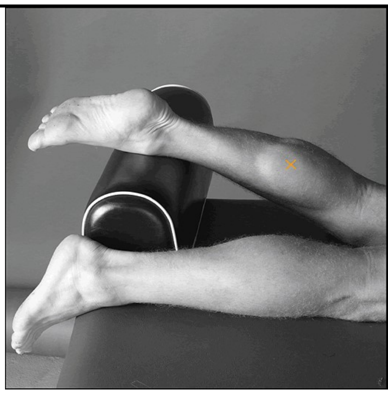
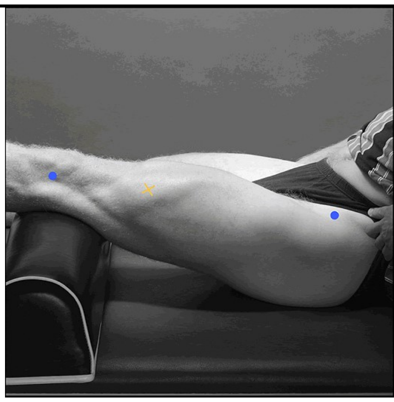
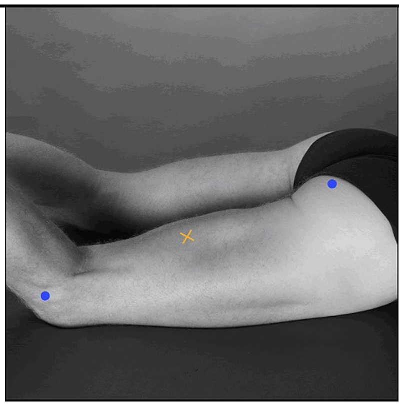
Figure 9: right: TrignoTM Wireless System from Delsys® left: Delsys® Sensor

For the experiment the following four muscles of the lower right extremity were analysed; m. vastus lateralis, m. bizeps femoris, m. gastrocnemius medialis and m. tibialis anterior. The exact placement of the sensors was in consideration with the SENIAM-Protocol as seen in table 1.

The position of the surface electrodes on the subject can be seen in figure 8.

Table 1: Sensor placement recommended by the SENIAM-Protocol (Project Management Group (2016, 19. December). Recommendations for sensor locations on individual muscles. Accessed on 19. December 2016 under http://www.seniam.org/)

Muscle	Position of the electrode	Graphic
M. tibialis anterior	The electrodes need to be placed at 1/3 on the line between the tip of the fibula and the tip of the medial malleolus.	

M. gastrocnemius medialis	Electrodes need to be placed on the most prominent bulge of the muscle.	
M. vastus lateralis	Electrodes need to be placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella.	
M. biceps femoris	The electrodes need to be placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.	

4.2.2.1. Skin preparation

To keep the baseline noise of the EMG signal to a minimum, skin preparation was performed as recommended by Konrad (2006).

Firstly, the hair on the body parts, on which the sensors were placed, was removed. Removing the hair leads to an improved adhesion of the sensor, which is especially important when dynamic movements are measured and when there is the possibility of a higher sweat production. Secondly the body parts were cleaned with cotton pads soaked in alcohol. A light red colour of the skin indicates a sufficient skin preparation, which leads to a good skin impedance.

4.2.3. Pedar pressure insole system

To determine the exact time of the stance phase, the Pedar®-X (novel) was used. The system has an integrated flash memory, which allowed the results to be downloaded to the computer after the measurement was finished, via a Bluetooth connection. The Pedar®-X system is connected with elastic insoles, which contain 256 capacitive sensors. The sensors are placed over the whole insole, making it possible to monitor the whole plantar surface of both feet. In this study only the right insole was used. The insole was placed in the running shoe underneath the foot. If possible the insole of the running shoe was taken out, to avoid an unpleasant feeling of pressure in the shoe. The sensors convert the measured force per area into a pressure. The results were transferred to the computer and analysed with the Pedar®-Software.

Since some of the areas showed misleading results, for example continuous pressure values were registered during the flight phase, each analysed gait cycle was controlled individually and the exact stance time was noted.

4.2.4. Light barrier

To control the speed of the overground running modality an infrared light barrier with reflectors was used. The photoelectric cells were placed at a distance of 3.5 m. After each run the specific hardware calculated and immediately showed the running speed of the subject, which was directly noted in the measurement protocol.

4.3. Running modalities

4.3.1. Treadmill running

The treadmill running was performed on a Cardiostrong TX50 treadmill with a surface size of 152 cm in length and 51 cm in width. The used treadmill is shown in figure 10. The velocity of the belt could be adjusted from 0.8 till 20.0 km/h in steps of 0.1 km/h and the incline could be varied between 1 and 15° in steps of 1%. In the study a velocity of 3.5 m/s and an inclination of 1° were used. The treadmill belt was driven by a DC-motor with a continuous duty of 3 horsepower to maintain a constant velocity. The display showed the duration, distance, speed, incline, calories and heart rate.

Figure 10: Treadmill Cardiostrong TX 50

4.3.2. Overground running

The overground running took place on the artificial floor of the laboratory of the department of biomechanics. As seen in the sketch in figure 11 the whole runway had a length of 13m. The track was divided into a run up (6.5 m), measurement (3.5 m) and declaration (3 m) segment. During the run up the subject had to accelerate to the needed velocity, while passing the measurement zone the velocity had to be maintained and the slow down should only be started after reaching the declaration area. To assure a velocity of 3.5 m/s with a maximal deviation of 5%, light barriers were placed at the beginning and the end of the measurement segment. For testing the treadmill running modality, the treadmill was placed centrally in the measurement segment. Figure 12 shows the real set up with the treadmill placed in the measurement segment.

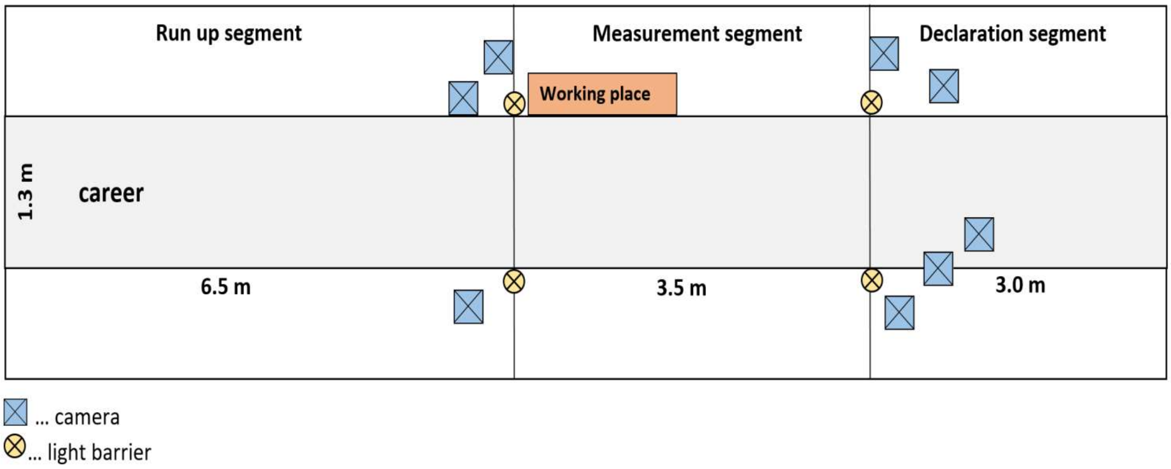
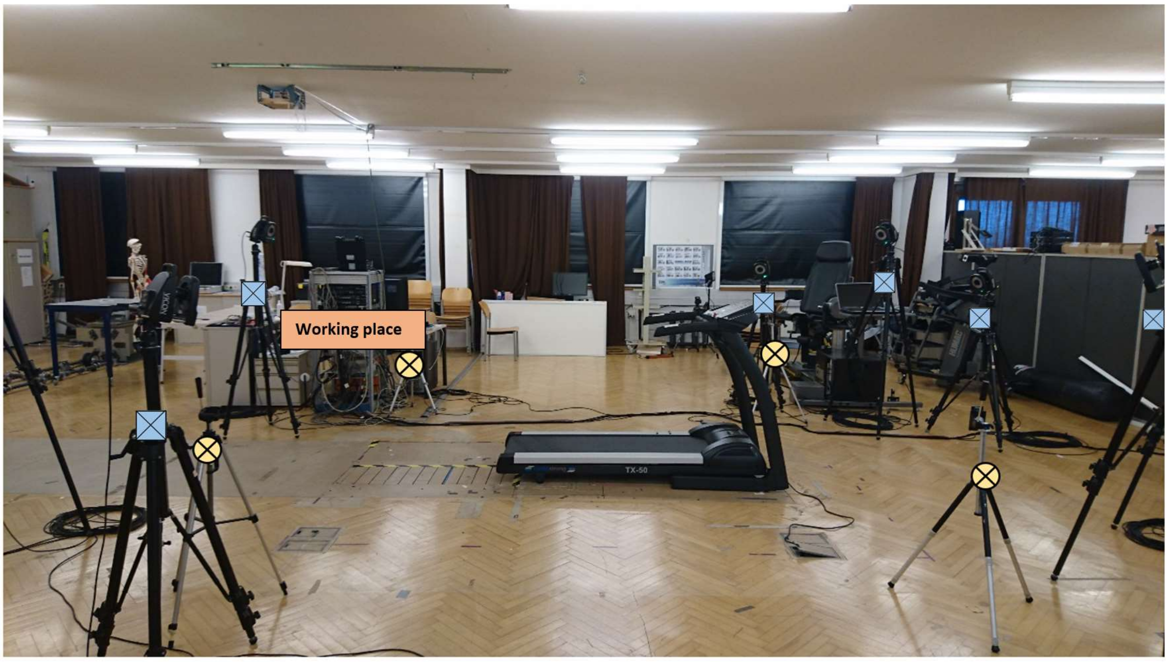


Figure 11: Sketch of laboratory with set up for the Vicon®-System and the light barriers



... camera
... light barrier

Figure 12: Laboratory the Vicon®-System and the light barriers

4.4. Cohort

Fourteen male subjects, free from any injuries or pain and in a good physical condition were recruited to join in the study. Other inclusion criteria were weekly regular running activities, either during endurance training or other training like team sports, martial arts etc. According to this information the subjects were divided into either endurance athletes and non-endurance athletes. A minimum of one endurance training session was necessary to rank among the endurance athlete group. The study design was approved by the ethics committee of the University of Vienna.

Table 2 shows the anthropometric data and the athlete type of the cohort.

Table 2: Anthropometric data of the cohort (n=14)

Cohort	Age	Height	Weight	BMI	endurance athlete
Subject 1	26	182	77	23,25	Yes
Subject 2	25	181	82	25,03	No
Subject 3	26	188	78	22,07	Yes
Subject 4	26	183	75	22,40	Yes
Subject 5	26	181	94	28,69	Yes
Subject 6	24	178	72	22,72	No
Subject 7	25	178	77	24,30	No
Subject 8	23	180	75	23,15	No
Subject 9	27	180	80	24,69	No
Subject 10	24	184	78	23,04	No
Subject 11	25	175	68	22,20	Yes
Subject 12	25	180	87	26,85	No
Subject 13	26	182	82	24,76	Yes
Subject 14	27	186	75	21,68	Yes
MEAN	25,36	181,29	78,57	23,92	
MIN	23	175	68	21,68	
MAX	27	188	94	28,69	
SD	1,15	3,34	6,41	1,98	

Age [years]; Height [cm]; Weight [kg]; BMI = Body Mass Index [kg/m²]; SD = standard deviation

4.5. Measurement report

The description of the measurement report should help in understanding how the study was carried out exactly.

4.5.1. Preparation

4.5.1.1. Laboratory preparation

Before the measurement started the position of the eight cameras of the Vicon®-MX-Motion-Capturing-Systems was set in a way, so that every marker was filmed by as many cameras as possible for the longest time period achievable. The focus and aperture of each camera as well as the strobe intensity and gain were adjusted by the used Software Vicon® Nexus 2.5.

Furthermore, the laboratory was darkened to avoid reflections. If there were still any reflections, for example from the other cameras, masks were created with the Nexus Software for each camera. The calibration was performed as recommended by the Nexus 2.5 manual. The three-marker-wand with a size of 240 mm and the Ergo-Carl L-frame with a marker size of 9mm was used to carry out the procedure before the first measurement of the day

The distance between the photoelectric cells was controlled every day and adjusted if necessary.

4.5.1.2. Subject preparation

During the measurement only the right side of the body was captured and then analysed. Firstly the skin, on which the surface electrodes were placed, was shaved and thoroughly cleaned with alcohol. This procedure ensures, that particles of dirt and dry skin are removed and the blood circulation is increased, which leads to a reduced impedance (Pfeifer, Vogt, & Banzer, 2003, Konrad, 2006). The spots where the electrodes need to be placed according to the SENIAM recommendations were determined by palpation and then the skin was cleaned and prepared as mentioned before.

The marker set was placed on the subject with double-sided adhesive tape. Moreover, the body parts were pointed with a marker, in case the marker fell off due to the dynamic movement and the formation of sweat, so that it could be placed on the same spot again. Furthermore, regular adhesive tape was used to ensure stability of the markers set on the medial and lateral epicondylus and for other markers with the same problematic.

The matching Pedar® insole was placed in the right running shoe with particular attention that the insole was not bent inside the shoe. The Pedar®-x system was placed around the hip with an elastic belt with Velcro strips to attach the system itself, the battery, the unused cable for the left insole and the cable for synchronising with other systems. Furthermore, the cable, which was attached to the insole, was fixed with two other slim belts on the lower leg and thigh. Figure 13 shows a participating person completely prepared for a measurement.

Figure 13: Subject preparation (EMG sensors, Markers, Pedar®-x system)

4.5.2. Data acquisition

After the subjects arrived, the first step was to inform them about the whole process. When all questions had been answered, they were asked to read and sign the informed consent. Afterwards the preparation of the cohort could start. The first step was the correct placement of the electrodes. The second step was placing the eight markers with the doubled sided adhesive tape. The third step of the preparation was to place the right Pedar® insole into the running shoe of the subject. After the preparation had been completed and if the cohort felt comfortable, the familiarization could start.

One half of the participants started with treadmill and the other half with overground running, in alternating order. The familiarization for the treadmill running modality was a six minutes run on the treadmill at a self-selected pace, all subjects picked a velocity between 8 km/h and 12 km/h (2.2-3.3 m/s). After they had finished, the treadmill was stopped to continue with the last arrangements for the testing. For the overground running it was required to maintain a constant running velocity of 3.5 m/s with a maximal deviation of 5 %, which leads to valid running speeds from 3.33 m/s to 3.68 m/s at the measurement segment. Furthermore, it was necessary that the subjects had one stance phase of the right leg in the measurement segment, to enable the visibility of all markers by the cameras of the Vicon®-MX-Motion-Capturing-System. For training purposes and to get used to all the systems placed on the body of the subject, practice runs were performed until a constant running style with the required velocity was achieved.

After the familiarization for the first running modality had been completed, a static measurement was performed. The data was used for the static subject calibration of the created labelling template to the exact body measurements of each person, to enable an automatic marker tracking of the Nexus Software. To do so the testing person was asked to stand wide with straight legs and the arms crossed in front of the chest, as seen in figure 13. If a marker became loose during the testing procedure and had to be placed again, another static measurement was performed.

The next step was to plug in the cable necessary for synchronising the data of the Pedar®-x system to the Vicon®-MX-Motion-Capturing-System and EMG data from the Delsys® system.

The data acquisition during treadmill running was performed after the treadmill had reached a constant velocity of 3.5 m/s. While the subjects ran continuously, three samples were filmed, then the treadmill was stopped. If there were three valid trials, the treadmill session was finished, after checking the visibility of all the markers and the propriety of the stance phase data of the Pedar®-x system,. Afterwards the familiarization of the overground running could be started. For the overground running three valid trials needed to be captured. Firstly, it was checked, whether the velocity was in the predefined range. If the speed was valid, the data of Pedar®-x system was uploaded and the visibility of the markers was checked the same as with the treadmill running, which was done with the Vicon® Software 2.5 and Pedar® software at the working place as seen in figure 14.

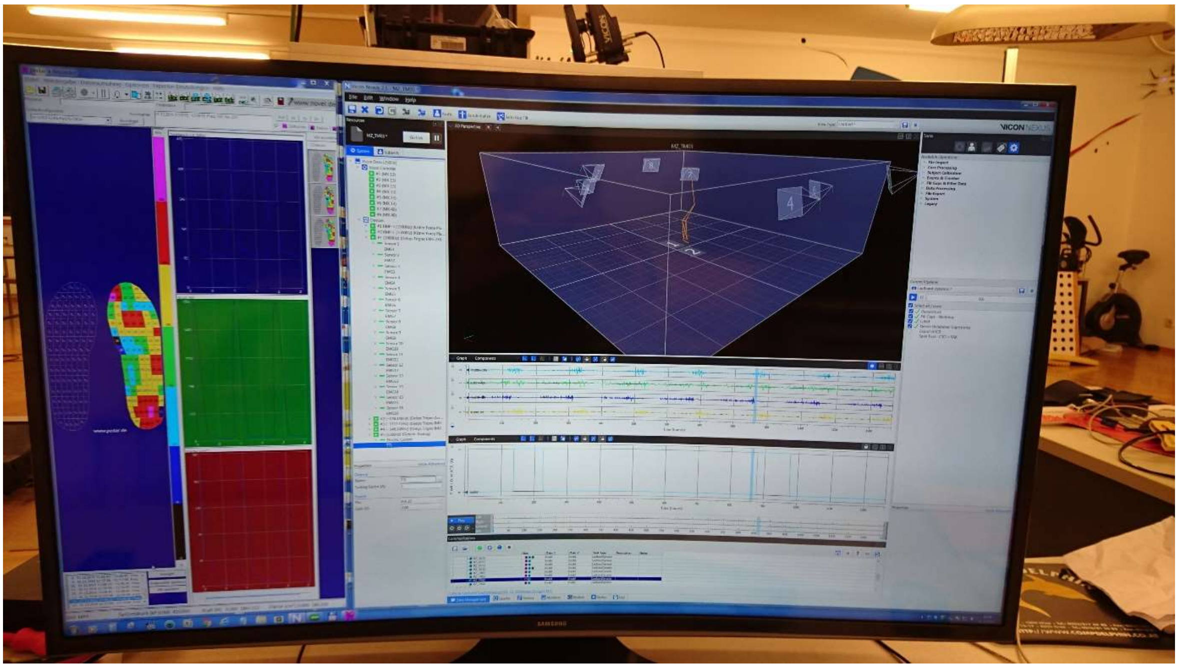


Figure 14: Working place with Vicon® Software 2.5 and Pedar® software

Once both modalities had been completed, the last step was to save and export the data for further analysis.

4.5.3. Processing of the raw data

After finishing the measurement, the kinematic, plantar pressure and the EMG data are presented in different formats and data flies. Before the actual interpretation could be started it was necessary to synchronize all data by means of the recorded trigger signal. Further the cubic spline interpolation method was used to achieve a common frequency (2000Hz) of the kinematic (250Hz) and pressure insole (100Hz) data. The kinematic data was filtered with a 4th order zero lag low-pass Buttworth filter with a cutoff frequency of 50Hz.

The exact time of the stance phase was ascertained by the results of the Pedar®-x system. Because some of the sensors showed artifacts, for example pressure values during the flight phase, the contact times were determined by watching the visual data.

The EMG data were band pass (10-500Hz) filtered and the Root Mean Square (80 window 79 overlap, zeropad) of every muscle was calculated. According to Konrad (2006) this is an established operation for presenting EMG signals. The pattern of a raw EMG signal of the same measurement varies every time, because the number of recruited motor units constantly differs. Using digital smoothing algorithms cuts away amplitude spikes and the mean trend of the signal is shown (Konrad, 2006). The calculated Root Mean Square values were then normalized to the highest EMG activity of the respected muscle measured at either the overground or treadmill condition.

4.5.4. Statistical evaluation

The statistical evaluation was performed with the SPSS program. First it was tested, whether the values of the eleven subjects at all the time points analyzed for both running modalities are normally distributed. For this analyzation, the Sapiro-Wilk-Test was used. If a normal distribution exists at a certain point of time for both running modalities the parametric Paired Sample T-Test was performed to find out whether there is a significant difference between overground and treadmill running regarding either the joint angle or the muscular activity. If the values were not normally distributed, for the further evaluation as a non-parametric procedure the Wilcoxon-Test was performed. If the results of the Paired Sample T-Test or the Wilcoxon-Test have reached a certain level of significance (5%), the values were significant different and the null hypothesis was disproved and the alternative hypothesis accepted. Furthermore, the Bland and Altman Analysis was performed for the eleven time points during the stance phase for the kinematic data. Four from the fourteen subjects could not be evaluated and therefore were excluded from the further analysis.

5. Results

In the next chapter the results of the study conducted are presented. The first part deals with some examples of one subject and it should show how the collected data was processed. The second part points out the average statistical differences between the two running modalities of all subjects and trials. The last part deals with the results of the Bland & Altman analysis of the kinematic parameters.

5.1. Descriptive kinematic analysis

With the help of the eight markers, placed on the trunk and the right leg of the subjects captured by the Vicon® system, the movement of the hip, knee and ankle joint can be reconstructed. The following figures will give an impression of how the analysis was made and show specific examples of one subject.

5.1.1. Hip Joint

The horizontal axis, for all three figures (15, 16, 17) demonstrating the hip joint, shows the time of the stance phase in percent, whereby 0% defines the touchdown and 100% the take-off. On the vertical axis, the hip joint angle in degrees is noted. For the hip joint zero degree defines a fully stretched hip in a regular standing position, obtained from the data of the static subject calibration. Higher values refer to a flexion and lower to an extension of the hip joint.

Figure 15 shows the hip joint movement of the three measured trials of one subject in overground running. At the touchdown, the hip joint angle measures between 25.4° and 28.3°. During the first quarter of the stance phase a flexion of the hip joint angle is visible, followed by a steady extension of the hip. At the take-off, the hip joint is overstretched by -13.8° to -17.8°compared to the straight (0°) position.

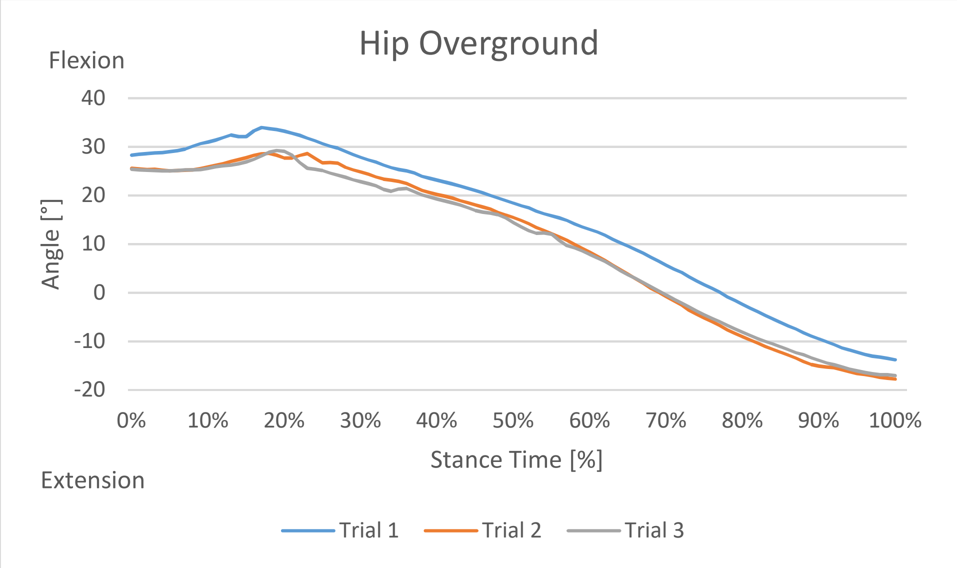


Figure 15: Hip movement in overground running – 3 trials of the same subject

Figure 16 shows the kinematic waveform of the hip joint in treadmill and overground running of the same subject. At the first ground contact the hip joint angle lies between 27.0° and 28.8°. During the first quarter of the stance period an increase of the joint angle occurs. Starting at 22% of the stance time a constant decrease of the hip joint angle is visible until the end of the stance phase, with values of about -16° at the take-off.

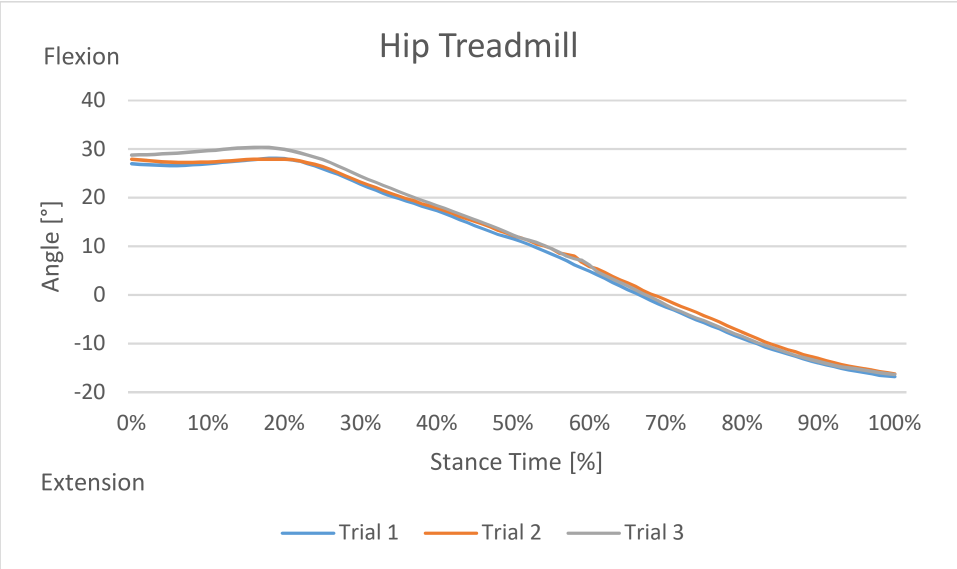


Figure 16: Hip movement in treadmill running – 3 trials of the same subject

Figure 17 presents the mean hip movement of the three overground and treadmill trials shown in figures 15 and 16. At the touchdown the angle in treadmill is 27.9° and 26.4° in overground running. The maximum hip flexion for the treadmill condition is 28.8° and 30.4° for the overground condition. After the slight flexion of the hip joint in the first quarter of the stance time a constant descent of the angle occurs until the take-off in both running modalities. At the last ground contact the hip joint angle reaches an extension of -16.4 in treadmill and -16.2 in overground running.

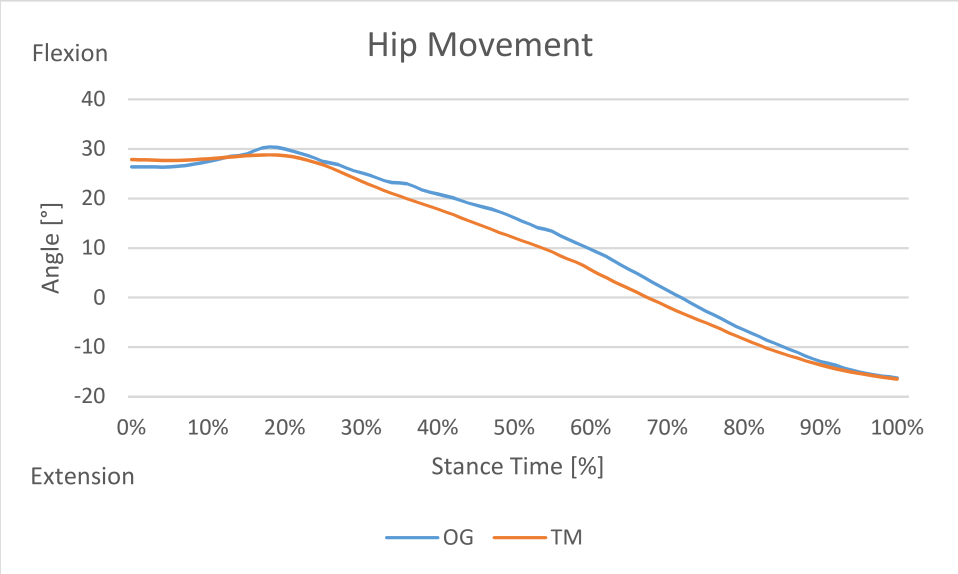


Figure 17: Hip joint movement - overground running (OG) vs. treadmill running (TM)

5.1.2. Knee joint

Figures 18, 19 and 20 present the angle movement of the knee. Again, on the horizontal axis the stance time in percent is shown, with 0% for the touchdown and 100% for the take-off. The vertical axis lists the knee joint angle in degrees. Zero degree characterizes a stretched knee joint in a neutral standing position, as raised during the static measurement. All values under 0° refer to a flexion, and all over 0° to an extension of the knee joint.

The three graphs shown in figure 18 demonstrate the knee joint movement in overground running for the three trials of one subject. At touchdown the knee is flexed by about -11° to -14°. In the first 20% of the stance time the knee flexes constantly more. From about 20% to 50% of the stance phase the knee joint angle stays almost the same, followed by an extension of the knee to -10° till -13° at take-off.

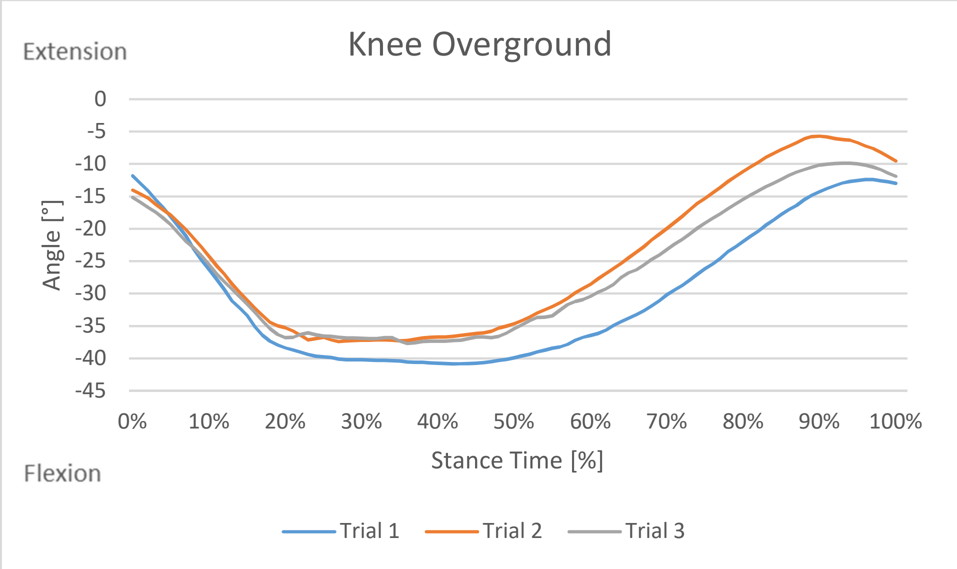


Figure 18: Hip movement in overground running – 3 trials of the same subject

Figure 19 illustrates the knee joint movement in treadmill running. At the touchdown the knee joint angle is around -10°, afterwards a constant flexion of the knee can be seen until at about 20% of the stance phase a maximum flexion of the knee (-32°) is reached. Starting from this point a steady stretching of the knee is visible until the last 10% of the stance phase. In this last part before the take-off the knee again flexes a little, until the joint angle is around -7° at the last ground contact.

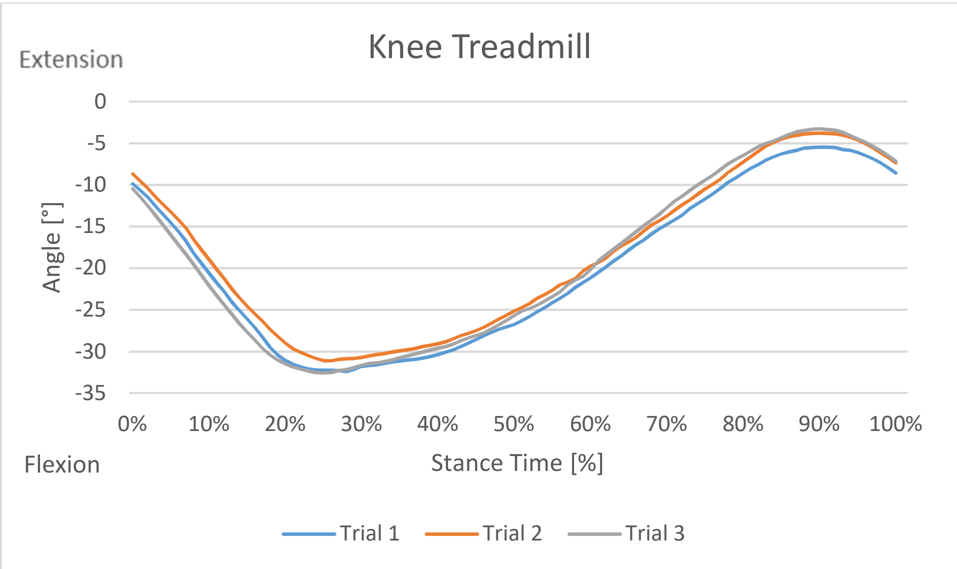


Figure 19: Hip movement in treadmill running – 3 trials of the same subject

Figure 20 represents the mean of the three trials in each running modality as shown in figures 18 and 19. The diagram depicts a knee joint angle of -13.7 in treadmill and -9.6 in overground running at the footstrike. In treadmill running after the peak joint angle is reached, the knee joint gets stretched until it almost reaches the value of a neutral standing position (-4.2°) at 90% of the stance time. At the take-off the knee has a flexion of -7.7°. In overground running the knee is flexed by more than -35° from 18% until 55% of the stance phase and the take-off occurs at -11.5 °.

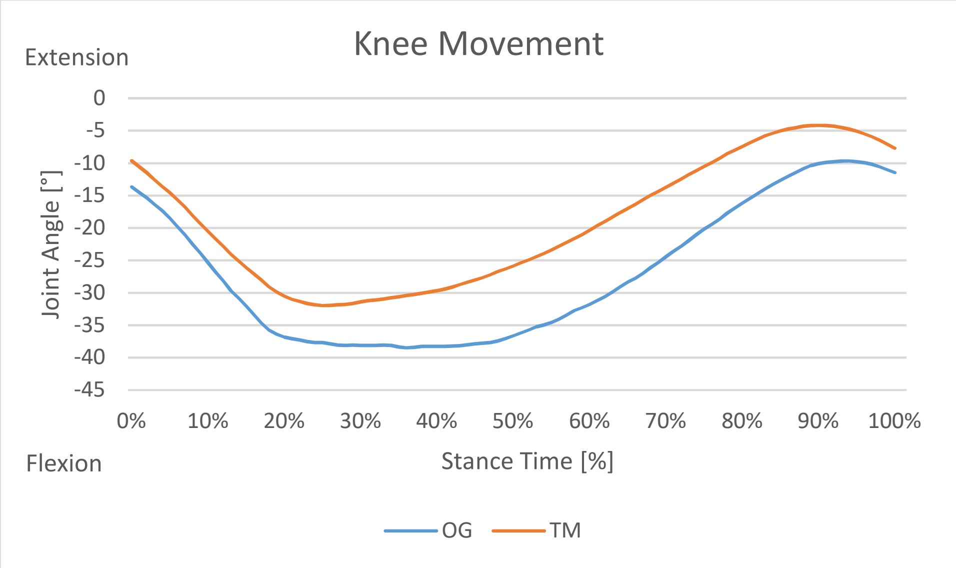


Figure 20: Knee joint movement - overground running (OG) vs. treadmill running (TM)

5.1.3. Ankle joint

The movement of the ankle joint is illustrated in figures 21, 22, and 23. On the horizontal axis the stance time in percent is marked with 0% for the touchdown and 100% for the take-off. The vertical axis shows the joint angle, whereby zero refers to a bend of 90° according to the data gained from a neutral standing position during the static measurement.

Figure 21 presents a slightly dorsiflexed (-7.4° - -9.5°) ankle joint at the first ground contact in overground running. After a small reduction during the first 5% of the stance time the dorsiflexion increases until the maximum value is reached at about 48% of the stance time. Afterwards a steady plantarflexion occurs until at the toe-off values of 2° in trial 1 and 11° in trials 2 & 3 are reached.

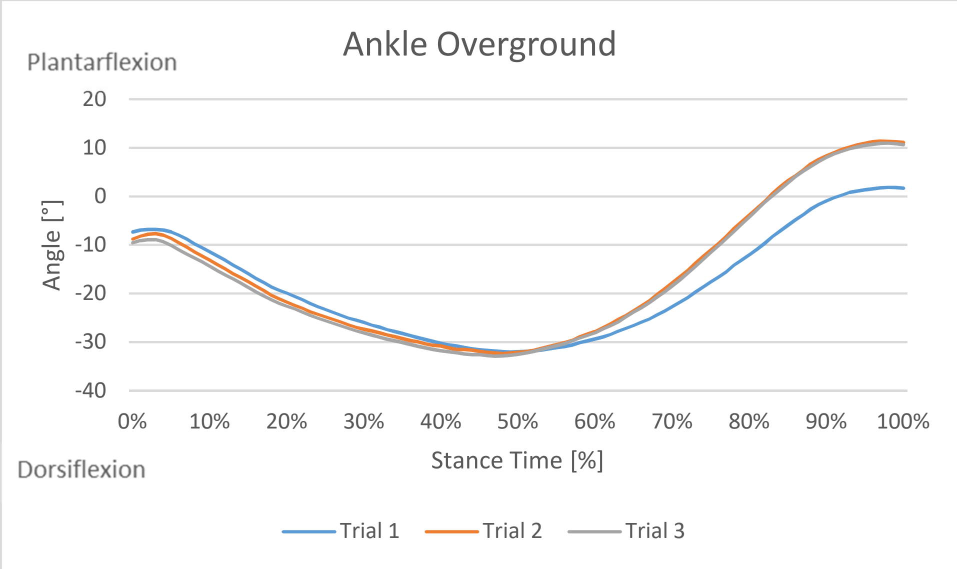


Figure 21: Ankle movement in overground running – 3 trials of the same subject

In treadmill running the ankle joint has a dorsiflexion of around -10° at the touchdown, as shown in figure 22. In the first 4% of the stance period a slight plantarflexion occurs, followed by a constant dorsiflexion with a peak joint angle of -29.9° in trial 1 and -29.8° in trials 2 & 3 at about 45% of the stance time. In the second half of the stance phase the ankle joint plantar flexes until an angle of 17.7° in trial 1 and 23.1 in trials 2 and 3 is reached at toe-off.

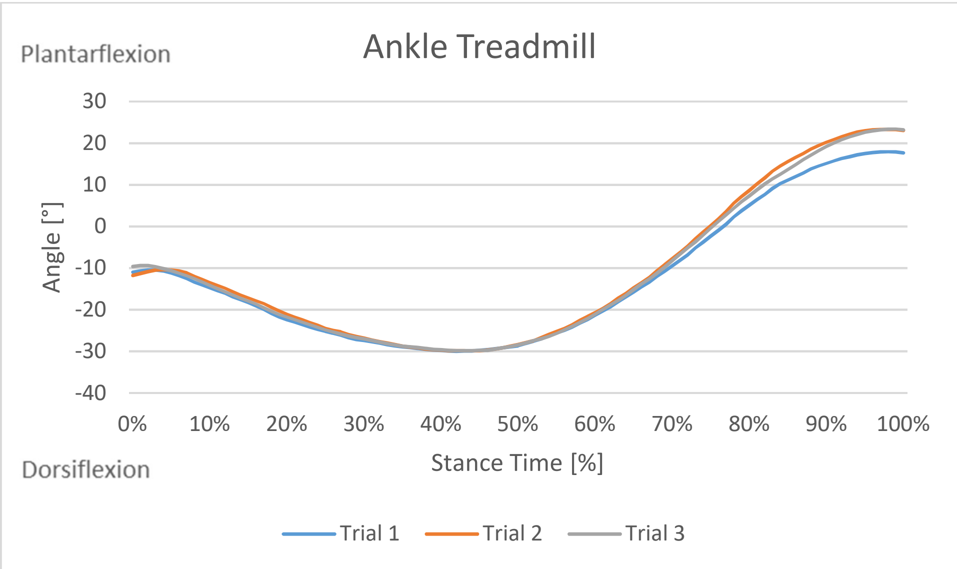


Figure 22: Ankle movement in treadmill running – 3 trials of the same subject

Figure 23 presents the ankle kinematic in treadmill and overground running of the mean value of the three trials shown in figure 21 for overground and figure 22 for treadmill running. After 46% of the stance period the treadmill modality reaches the peak dorsiflexion with a value of -29.7° and the overground modality after 50% with a peak value of 32.2°. At the touchdown the joint angle reaches a dorsiflexion of -8.6 in overground and -10.8 in treadmill running. In the second half of the analysed period a constant plantarflexion is visible, with peak values at the toe-off (21.3° in treadmill running and 7.8° in overground running).

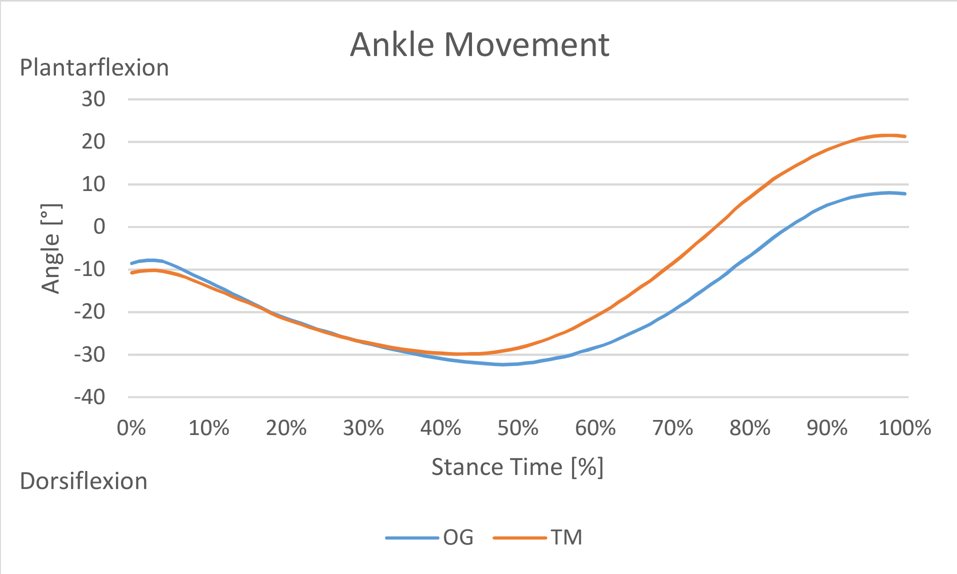


Figure 23: Knee joint movement - overground running (OG) vs. treadmill running (TM)

5.2. Descriptive analysis of the muscular activity

The Root Mean Square values of the smoothed EMG signals of the four muscles for both, the overground and the treadmill running condition, are presented in figures 24 & 25. On the horizontal axis, the duration of the stance phase in milliseconds is marked, whereby 0 equals the touchdown and the last value equals the toe off,. The vertical axis demonstrates the amplitude of the EMG signals in millivolt.

Figure 24 shows the EMG signal of one trial of m. vastus lateralis, m. biceps femoris, m. tibialis anterior and m. gastrocnemius medialis in overground running of one subject. Figure 25 shows the muscular activity of the same subject in the treadmill running condition. For a statistical evaluation, the relative mean of the results of all subjects and all trials will be used. The relative muscular activity will be presented in a percentage ratio of an average EMG output to that obtained during the stance phase in all trials. The following figures should therefore help achieve a better understanding of the measurements made.

The activation patterns of this subject show, that m. vastus lateralis (Sensor 1) shows a high peak in the amplitude in the second half of the stance phase in overground running, which is not visible in treadmill running. M. biceps femoris (Sensor 2) only is activated at the beginning of the stance phase in treadmill running, but is also activated in the middle and at the end of the stance period in overground running. M. tibialis anterior shows two peaks, one at the beginning and one in the middle of the stance phase in overground running, but only one peak at the beginning in treadmill running. M. gastrocnemius medialis has two peaks in treadmill and only one in overground running.

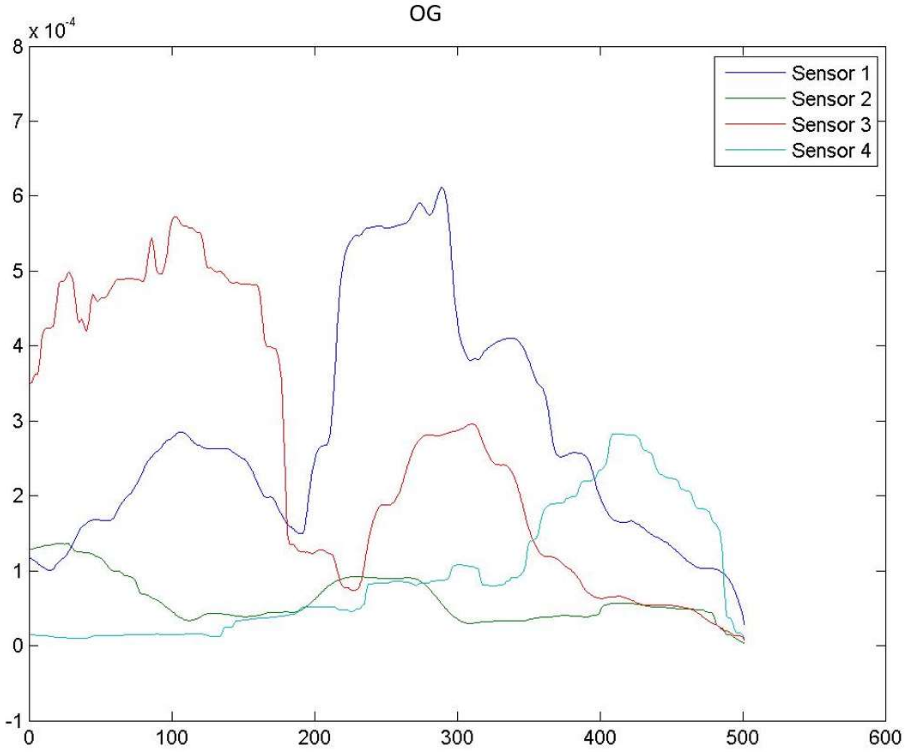


Figure 24: RMS of Sensor 1 (m. vastus lateralis), Sensor 2 (m. biceps femoris), Sensor 3 (m. tibialis anterior), Sensor 4 (m. gastrocnemius medialis) of overground running (OG).

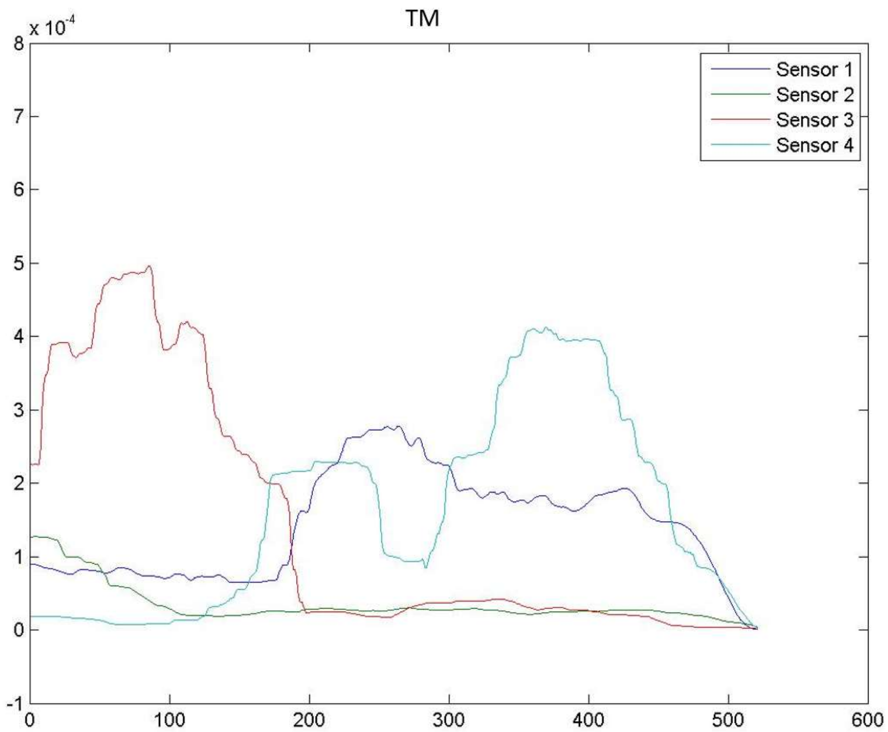


Figure 25: RMS of Sensor 1 (m. vastus lateralis), Sensor 2 (m. biceps femoris), Sensor 3 (m. tibialis anterior), Sensor 4 (m. gastrocnemius medialis) of treadmill running (TM).

The following figures show the muscular activity of the four muscles of one subject in separate diagrams and with different units. For all the figures on the horizontal axis the stance time in percent is shown, 0% refers to the touchdown and 100% to the take-off. On the vertical axis the muscular activity in percent is listed, whereby 100% refers to the maximum activation measured during the stance phase indifferent of the running modality,.

5.2.1. M. vastus lateralis

Figure 26 shows the activation pattern of m. vastus lateralis of one subject for the three measured trials in both running modalities On the left the results of overground running are presented, and on the right the results of treadmill running. It can be seen, that the outcomes of the different trials within the running modalities vary in the activation amplitude and time. In overground running in trial 3 the peak activation is 99.3% and a strong rise can be seen at about 40% to 70% of the stance time. At the trajectory of the second trial a rise is still visible at this period but flatter. Trial number one shows a steady increase until 70% of the stance time and a constant decrease afterwards, with no high peak. The first trials graph has an activation maximum of only 37.3 % in comparison to the 99.3% reached in trial 3. In treadmill running the course of the graph of trials 1 and 2 both show an activation maximum of about 50% of the stance time. For the third trial the activation maximum is reached at 67% of the stance time. In all trials an initial activation of the muscle by about 14% is visible.

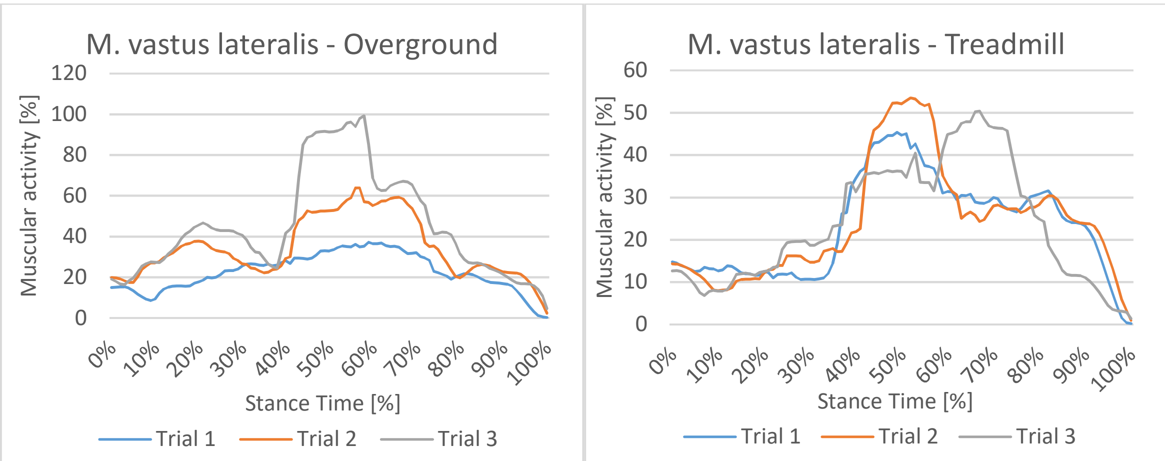


Figure 26: Muscular activity of m. vastus lateralis in overground (left) treadmill (right) running – 3 trials of the same subject

Figure 27 presents the muscular activity of m. vastus lateralis for both running modalities, each graph shows the mean of the respective trials shown in figure 26. The activation maximum in treadmill running is 45.4% and 65.6% for the overground condition. For both running modalities the maximum activation occurs in the second third of the stance period. Furthermore, an initial activation of the muscle at the touchdown is visible (18% overground running, 14% treadmill running). In overground running a clear rise of the amplitude is also visible between 10% and 20% of the stance time, which does not happen in treadmill running.

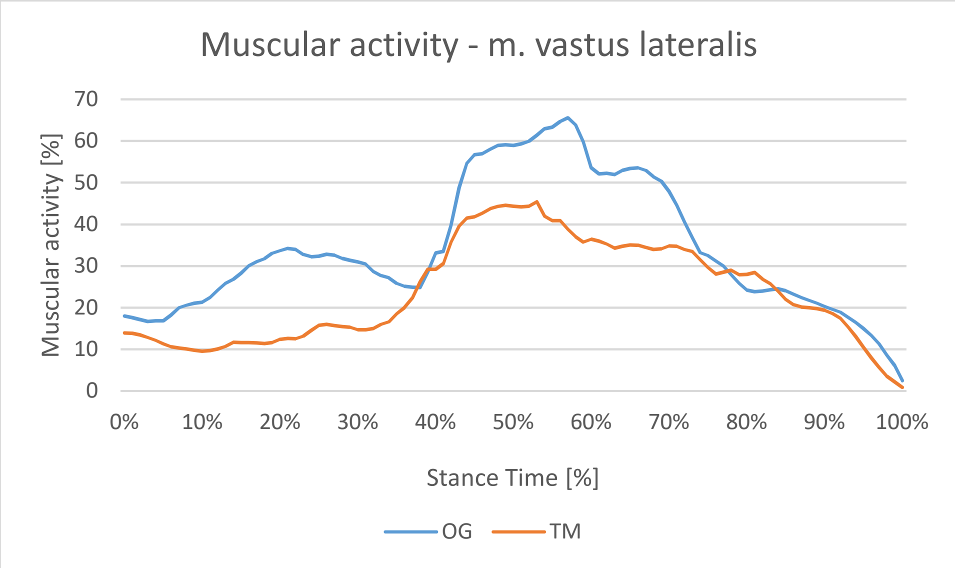


Figure 27: Muscular activity of m. vastus lateralis - overground running (OG) vs. treadmill running (TM)

5.2.2. M. biceps femoris

Figure 28 presents the muscular activity of m. biceps femoris, as before the three trials from overground running are shown in the left diagram, and on the right the trials from treadmill running. The trajectories for the respective running conditions have a similar pattern. In overground running trial 3 has a very high initial activation, with a value from 94% of the maximum measured amplitude, whereby trial 1 has 52% and trial 2 60%. The graph of trial two shows another activation of the muscles before the take-off with a maximum value of 74.8%, which is not as explicit in the other trajectories (30.8% Trial 1, 41.5% Trial 3). In treadmill running an initial activation of 92.5 to 64.1% is visible. Afterwards the amplitude in all trials falls under 26% from 25% to 70% of the stance time. In the last quarter of the stance period the maximum activation for trial 1 is 20.2%, for the second trial 42.4% and for the third trial 59.6%.

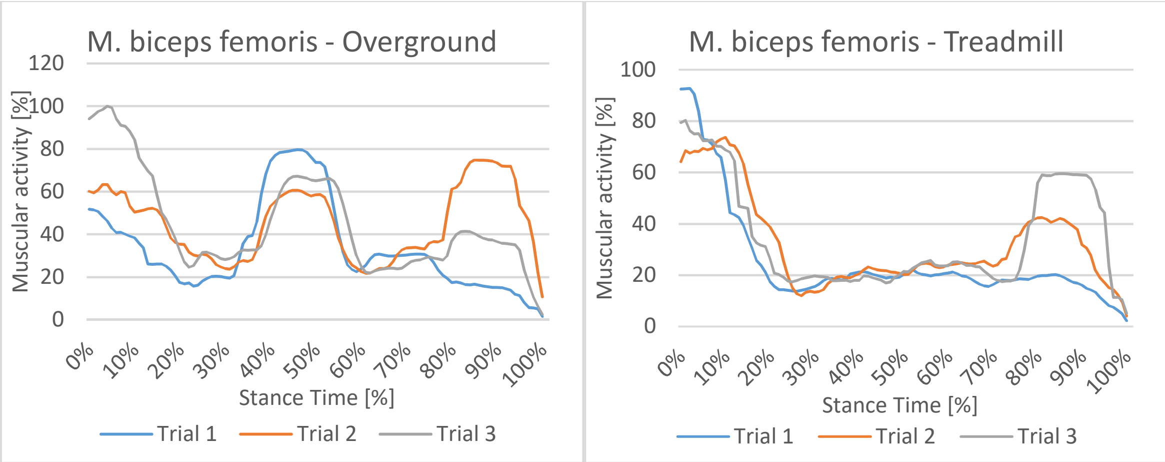


Figure 28: Muscular activity of m. biceps femoris in overground (left) treadmill (right) running – 3 trials of the same subject

The averaged values of the activation pattern of m. vastus lateralis for the two running conditions are presented in figure 29. Clearly visible is the rise of the amplitude from 35% to 60% of the stance period up to 70.1% of the maximum activation in overground running, which does not happen in treadmill running.

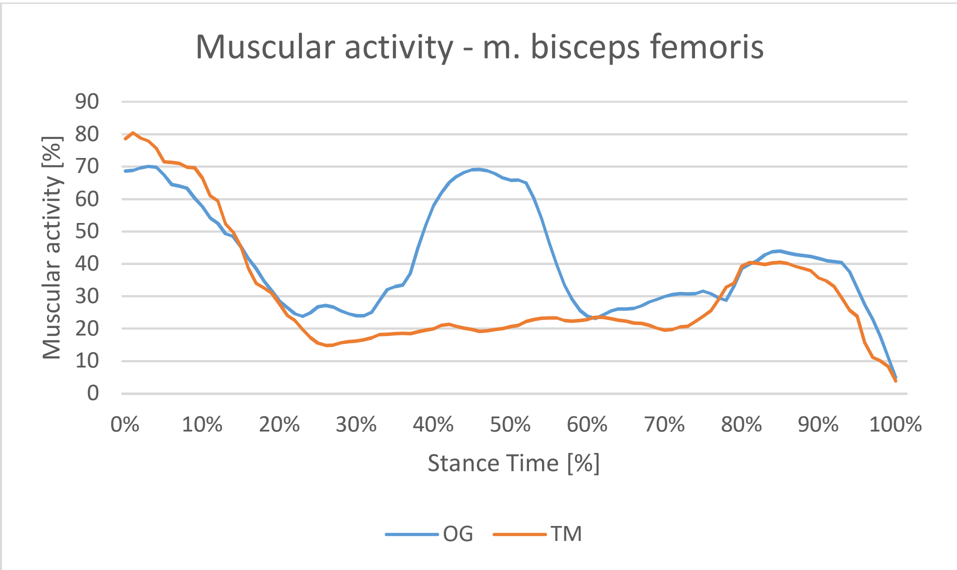


Figure 29: Muscular activity of m. vastus lateralis - overground running (OG) vs. treadmill running (TM)

5.2.3. M. tibialis anterior

Figure 30 gives information about the activation pattern of m. tibialis anterior in the two running conditions. In overground running (diagram on the left) the innitial activation lies between 37.5% and 61.2%. The course of the graph shows two peaks, one at the beginning of the stance period, with a maximum value of 99.8% and another one in the second half of the measured time, with a peak amplitude of 54%. In treadmill running (diagram on the right) the muscular initial activation is between 39.5% and 53.6%, followed by an ascent to 86.3% of the muscular activation in the first quarter of the stance time. Afterwards, the graphs show a steep decrease and after 40% of the stance time has passed, the maximum reached amplitude is 12.6%.

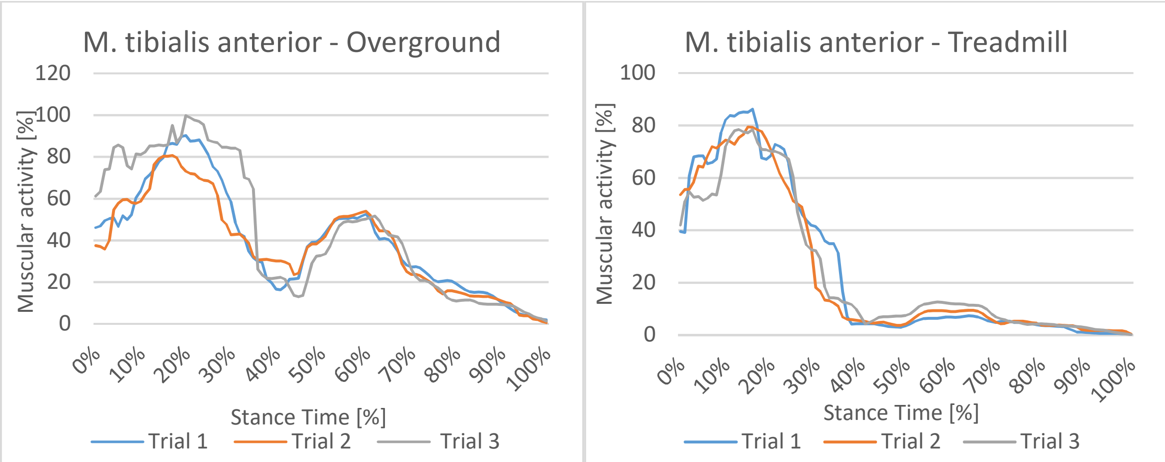


Figure 30: Muscular activity of m. tibialis anterior in overground (left) treadmill (right) running – 3 trials of the same subject

Figure 31 highlights the muscular activity of m. tibialis anterior for the examined running modalities. After the initial activation of 48.3% in overground and 45% in treadmill running the amplitude rises to the peak values of 87.8 in overground and 81.3 in treadmill running. A steep descent starts after 17% of the stance time in treadmill and 22% in overground running. In overground running another activation with a maximum of 52.3% occurs in the second quarter of the stance period, which does not happen in treadmill running.

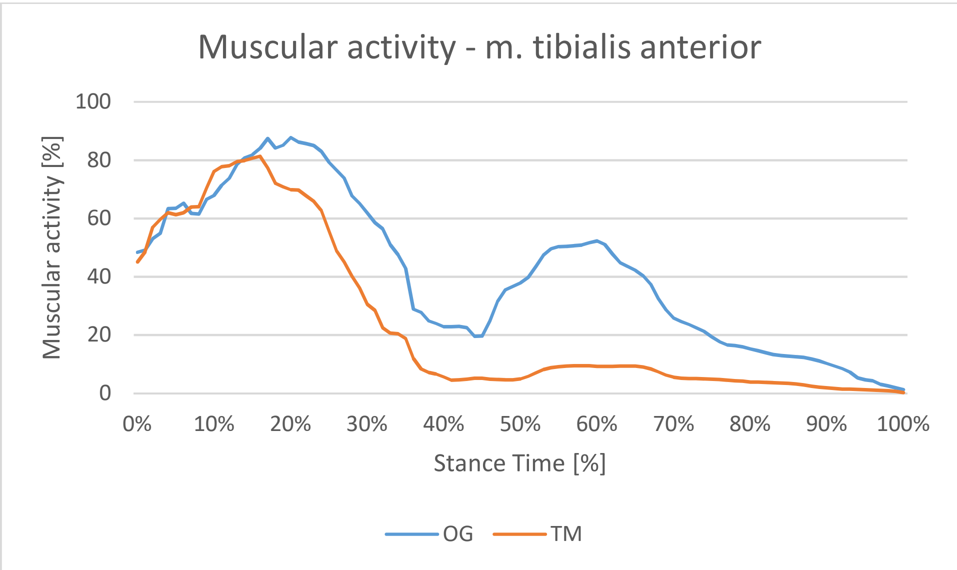
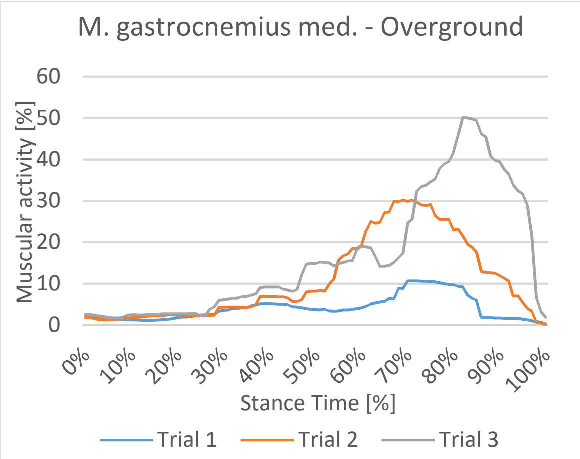


Figure 31: Muscular activity of m. tibialis anterior - overground running (OG) vs. treadmill running (TM)

5.2.4. M. gastrocnemius medialis

Figure 32 presents the muscular activity of m. gastrocnemius medialis of one subject in overground (left) and treadmill running (right). In overground running the graphs show no or only very little activation of the muscle during the first third of the stance time. Later, in the second half of the analysed period, an increase in the amplitude is visible, but the extent varies between the three trials. Trial 1 shows very little activation throughout the whole stance phase, with a maximum of 10.7%. Trial 2 has a maximum activation of 30.2% at 69% of the stance time. Trial 3 has the highest activation measured in overground running with 50.1%, the peak value occurs at 83% of the stance time. Further investigation would be necessary to ascertain the reason for these big differences and to be able to exclude a measuring error. In treadmill running the trajectories show no or hardly any initial activation, followed by an increase in activity at about 15% of the stance time. At around half of the stance phase the activation decreases slightly, followed by a steep increase starting at about 60% of the stance phase. The highest value of 99.4% was measured at 78% of the stance period.



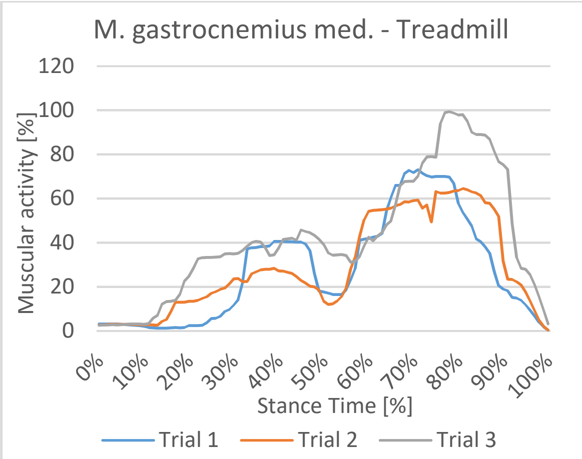


Figure 32: Muscular activity of m. gastrocnemius medialis (med.) in overground (left) treadmill (right) running – 3 trials of the same subject

The muscular activity of m. gastrocnemius medialis in treadmill and overground running is presented in figure 33. The peak value in treadmill running is 77.3% and occurs at 78% of the stance time. For the overground condition the maximum amplitude is 27% of the maximum measured activation at 82% of the ground contact time. The low values can be derived from the fact that in overground running one of the three trials has a very low activation as shown in figure 32. The graph in figure 33 presents the averaged values of these trials, whereby trial 1 has a high influence on the mean. In treadmill running two peaks are visible, one in the second and one in the last third of the stance time. In overground running there is only one peak with only a flat ascent.

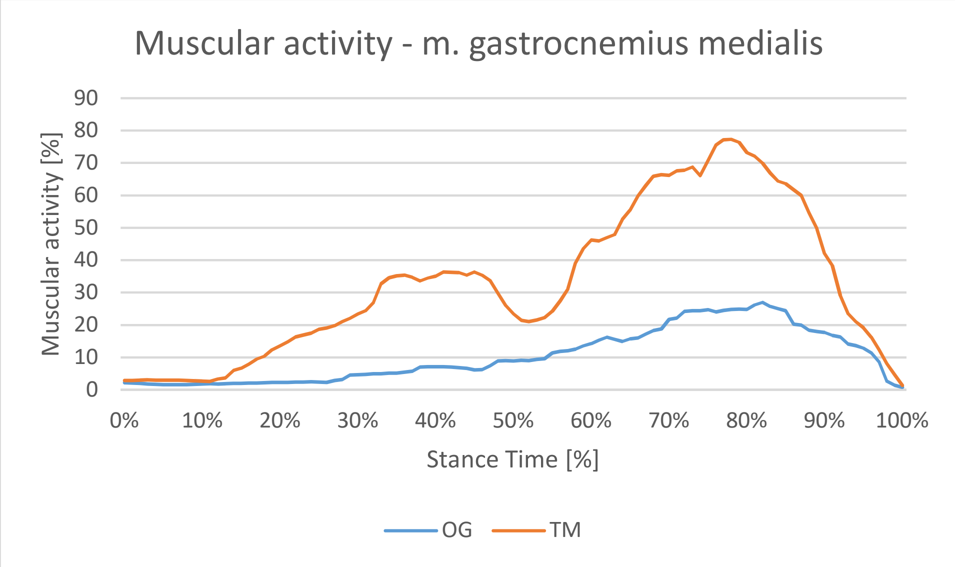


Figure 33: Muscular activity of m. gastrocnemius medialis - overground running (OG) vs. treadmill running (TM)

5.3. Statistical analysis

The following chapter will provide information about the statistical analysis of various variables. The main goal was to find out whether any differences between the running modalities are present. Hence the following hypotheses were proposed:

H_0: There is no significant difference between overground and treadmill running regarding the analysed joint angle or muscular activity at a certain point in time.

H_1: There is a significant difference between overground and treadmill running regarding the analysed joint angle or muscular activity at a certain point in time.

5.3.1. Velocity – Time parameters

5.3.1.1. Running Velocities

In treadmill running the velocity was constant at 3.5 m/s, but for the overground running modality the velocities could vary in a defined range of ±5%. To ensure that the mean velocity did not differ from the treadmill velocity, after ensuring that the values were normally distributed, a paired sample t-test was performed. Table 3 shows the actual speeds of the cohort in treadmill and overground running. The result of the paired t-test showed that the treadmill running speed was 3.5 m/s, which matched the averaged overground running velocity of 3.5 m/s (SD 0.1) and no significant difference ($p>0.05$) was present. The null hypothesis is retained, which leads to the conclusion, that possible differences in the kinematic or muscular activity between the two running modalities cannot be claimed on speed variations.

Table 3: Running velocities for overground and treadmill running

Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6	
OG	TM	OG	TM	OG	TM	OG	TM	OG	TM	OG	TM
3.39 m/s	3.5 m/s	3.66 m/s	3.5 m/s	3.39 m/s	3.5 m/s	3.33 m/s	3.5 m/s	3.54 m/s	3.5 m/s	3.46 m/s	3.5 m/s
3.34 m/s	3.5 m/s	3.42 m/s	3.5 m/s	3.58 m/s	3.5 m/s	3.66 m/s	3.5 m/s	3.50 m/s	3.5 m/s	3.66 m/s	3.5 m/s
3.47 m/s	3.5 m/s	3.42 m/s	3.5 m/s	3.43 m/s	3.5 m/s	3.58 m/s	3.5 m/s	3.54 m/s	3.5 m/s	3.62 m/s	3.5 m/s
Subject 7		Subject 8		Subject 9		Subject 10		Subject 11			
OG	TM	OG	TM	OG	TM	OG	TM	OG	TM		
3.42 m/s	3.5 m/s	3.43 m/s	3.5 m/s	3.58 m/s	3.5 m/s	3.47 m/s	3.5 m/s	3.66 m/s	3.5 m/s		
3.58 m/s	3.5 m/s	3.50 m/s	3.5 m/s	3.46 m/s	3.5 m/s	3.46 m/s	3.5 m/s	3.35 m/s	3.5 m/s		
3.54 m/s	3.5 m/s	3.49 m/s	3.5 m/s	3.66 m/s	3.5 m/s	3.50 m/s	3.5 m/s	3.46 m/s	3.5 m/s		

5.3.1.2. Stance Time

In Table 4 the stance times in seconds are presented. These values were used to perform a paired sample t-test to verify whether there is a significant difference in the contact times between the two running modalities. The statistical analysis showed no significant difference ($p>0.05$) and again the null hypothesis is maintained.

Table 4: Stance Time in seconds for all trials in overground and treadmill running

Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6	
OG	TM	OG	TM	OG	TM	OG	TM	OG	TM	OG	TM
0,25	0,24	0,19	0,22	0,25	0,25	0,25	0,24	0,22	0,23	0,27	0,27
0,26	0,24	0,19	0,22	0,25	0,25	0,24	0,23	0,23	0,23	0,28	0,27
0,25	0,23	0,2	0,21	0,25	0,26	0,24	0,24	0,21	0,23	0,28	0,27
Subject 7		Subject 8		Subject 9		Subject 10		Subject 11			
OG	TM	OG	TM	OG	TM	OG	TM	OG	TM		
0,23	0,24	0,26	0,25	0,22	0,24	0,26	0,26	0,25	0,26		
0,23	0,24	0,24	0,23	0,29	0,24	0,26	0,26	0,27	0,26		
0,25	0,23	0,23	0,23	0,22	0,24	0,25	0,25	0,25	0,26		

5.3.2. Correlation coefficient

The correlation coefficient for the three trials of each subject at every measured point in time for the two running modalities for the kinematic data was calculated. Afterwards the average of all the results for the individual joints was calculated. The mean correlation coefficients for all three joints show a smaller statistical scattering (hip & knee: $p=0.00$; ankle: $p=0.32$) in treadmill running compared to overground running.

5.3.3. Kinematic parameters

The next chapter will provide information about the statistical analysis of the joint angles individually. The table lists the mean, standard deviation and the results of either the paired-t-test or the Wilcoxon test, depending on whether the values are normally distributed or not. Significant differences at different significance levels are marked with asterisks. For those cases the null hypothesis is rejected and the alternative hypothesis is accepted.

Furthermore, the mean and standard deviation of the joint angles will be shown graphically for a better visualisation and understanding.

5.3.3.1. Hip Joint

Table 5 lists the mean and the standard deviation for overground and treadmill running at every 10% of the stance phase time, which are afterwards graphically shown in figure 34. Furthermore, the results of the comparison either calculated by the paired t-test or the Wilcoxon test, depending on the results of the Sharpio-Wilk test, are listed in the table. Significant differences, at different significance levels (p<0.05; p<0.01) are highlighted.

At all the points in time the pairs significantly differ (p<0.05) and for all the values the H_1-Hypothesis is accepted. This leads to the conclusion that there is a significant difference (p<0.05) in the kinematic of the hip joint throughout the whole stance phase between treadmill and overground running.

Table 5: Treadmill vs. overground running for the hip joint kinematic for the sagittal plane (flexion and extension); angles are measured in degrees; standard deviation (SD)

Stance Time	Overground		Treadmill		Comparison (p-value)
	Mean	SD	Mean	SD	
0%	27,86	4,82	33,31	3,46	,000[b, **]
10%	30,07	5,39	33,45	3,45	,001[b, **]
20%	32,35	6,26	34,40	4,29	,023[b, *]
30%	28,14	6,50	30,75	4,99	,005[b, **]
40%	23,07	6,60	25,22	5,04	,020[b, *]
50%	17,71	6,33	19,44	5,49	,035[b, *]
60%	10,48	6,08	12,68	5,52	,021[b, *]
70%	3,10	5,22	5,88	5,40	,005[b, **]
80%	-3,04	4,18	-0,37	5,07	,002[a, **]
90%	-7,24	3,90	-5,20	4,76	,004[a, **]
100%	-9,42	4,39	-7,99	4,51	,022[b, *]

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

Figure 34 shows the kinematic differences of the hip joint in treadmill and overground running. The graphs depict a significantly higher (p=0.00) hip flexion by 5.45° at the first ground contact in treadmill running. Furthermore, in treadmill running the joint angle of the hip is almost constant from the touchdown until 20% of the stance time, whereas in overground running a hip flexion from 27.86° to 32.35° occurs during this period. After 20% of the analysed time a steep descent of the curves is visible until the joint reaches a maximum extension at the toe-off (-9.42° OG; -7.99° TM). In general, the values of treadmill running are significantly higher (p<0.05) by an average of 2.6° throughout the whole stance time in comparison to overground running.

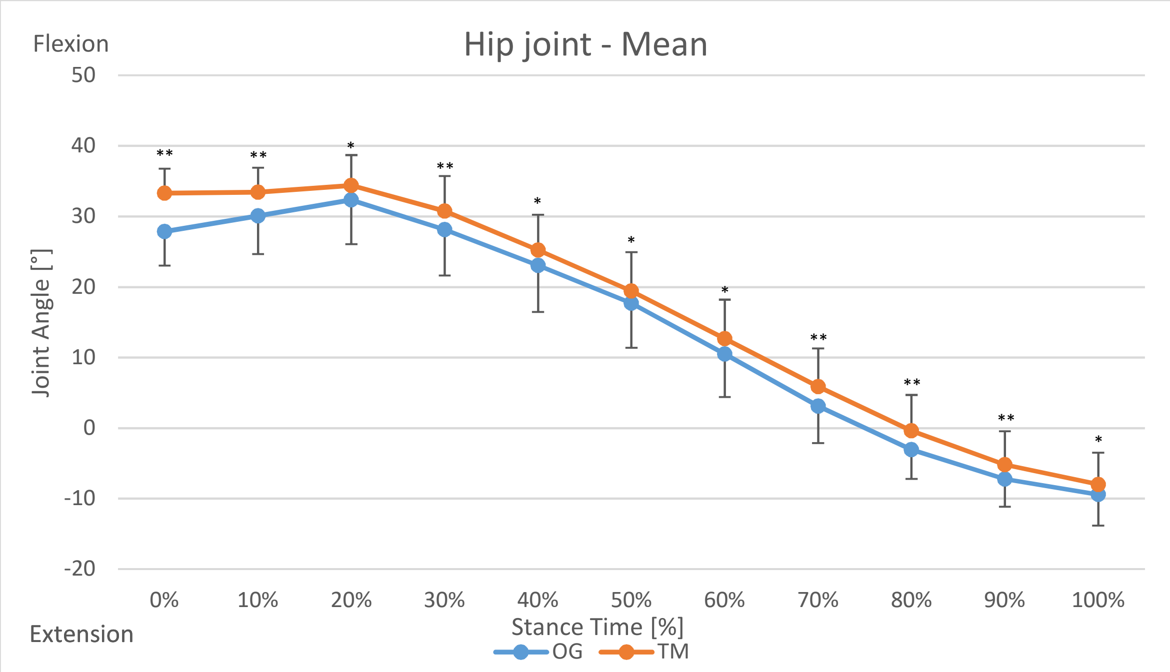


*Figure 34: Averaged hip joint movement with standard deviation - overground running (OG) vs. treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.3.2. Knee joint

In table 6 the mean and standard deviation of the knee joint throughout the whole stance phase can be seen. The same values are graphically illustrated in figure 35. The p-values of the paired t-test or Wilcoxon test can be seen in the right column. At 0%, 20%, 40%, 50%, 60%, 80%, 90% and 100% of the stance time a significant difference ($p<0.05$) is present. At the other points in time the measured joint angles did not showed significant differences between overground and treadmill running.

Table 6: Treadmill vs. overground running for the knee joint kinematic for the sagittal plane (extension and flexion); angles are measured in degrees; standard deviation (SD)

Stance Time	Overground		Treadmill		Comparison (p-value)
	Mean	SD	Mean	SD	
0%	-16,30	4,88	-18,37	5,25	,024[a], *
10%	-28,14	4,74	-27,94	5,65	,600[b]
20%	-38,41	3,95	-36,98	4,02	,026[a], *
30%	-40,48	4,28	-39,41	4,14	,165[b]
40%	-39,73	5,19	-37,68	4,11	,037[b], *
50%	-36,63	5,62	-33,89	4,17	,026[b], *
60%	-30,71	6,20	-28,15	4,42	,033[a], *
70%	-24,13	6,03	-21,86	4,56	,067[a]
80%	-18,51	5,15	-15,88	4,31	,014[a], *
90%	-15,99	4,86	-12,14	4,11	,000[b], **
100%	-18,50	6,38	-13,53	4,47	,000[a], **

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

The differences of the kinematic waveform of the knee joint angle between the two running modalities can be seen in figure 35. The two curves show a similar course until the last 20% of the stance time. At 80% of the stance time the difference in the knee joint kinematic is 2.6° and increases to 3.9° at 90% and 5.0° at the take-off. At the touchdown the knee joint significantly differs (p=0.024) with an angle of -16.3° in overground and -18.4° in treadmill running. Afterwards a steep ascent is visible until 30% of the stance phase in both graphs with a maximum bend of -40.5° in overground and -39.4° in treadmill running. Between 30% and 90% of the stance period the knee constantly gets extended, with maximum values of -16.0° for the overground and -12.1° for the treadmill condition.

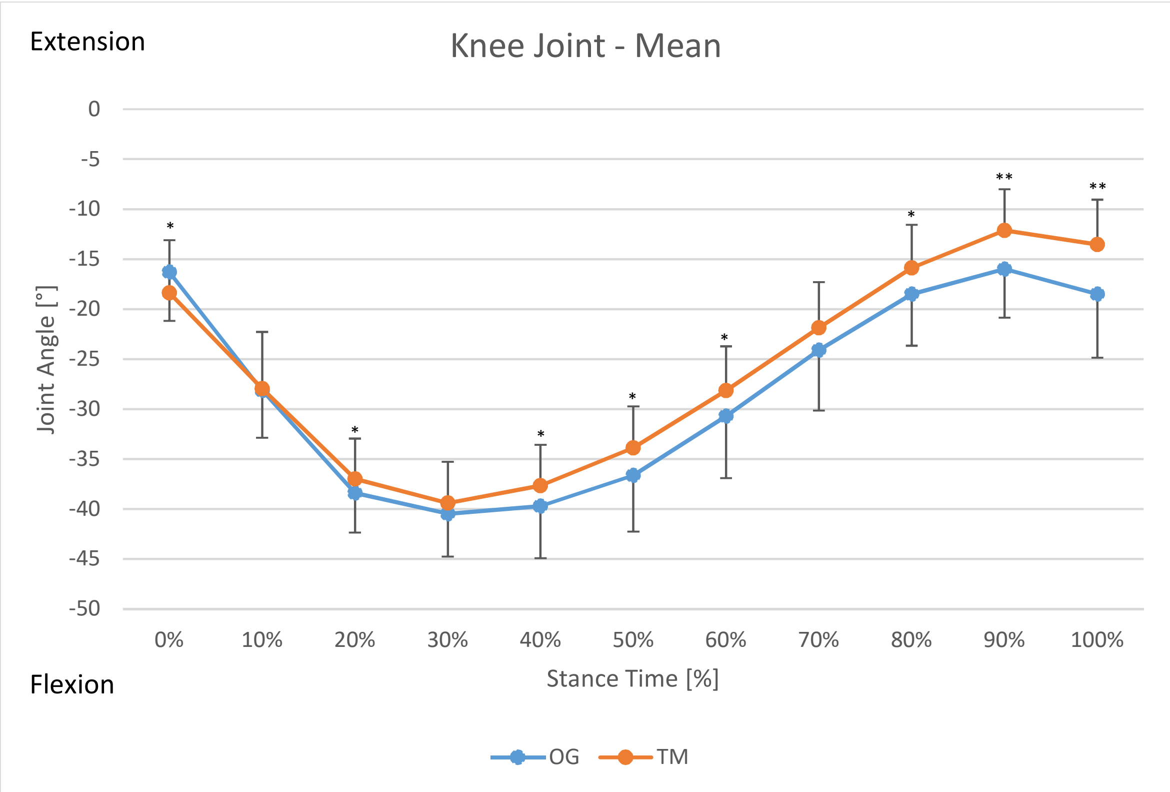


*Figure 35: Averaged knee joint movement with standard deviation - overground running (OG) vs. treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.3.3. Ankle joint

In table 7 the average values and the standard deviation of the ankle joint angles in overground and treadmill running can be seen. For a better understanding the same results are demonstrated graphically in figure 36. The results of the comparison of the two running modalities regarding the ankle joint point out, that there is a significant (p>0.05) differences at 20% and 30% of the stance time.

Table 7: Treadmill vs. overground running for the ankle joint kinematic for the sagittal plane (plantarflexion and dorsiflexion); angles are measured in degrees; standard deviation (SD)

Stance Time	**Overground**		**Treadmill**		**Comparison (p-value)**
	Mean	SD	Mean	SD	
0%	-7,21	8,85	-7,47	7,35	,600[b]
10%	-11,22	6,74	-12,49	5,89	,061[a]
20%	-19,05	5,84	-20,23	5,40	,029[a, *]
30%	-24,93	5,47	-25,91	5,47	,020[a, *]
40%	-28,33	5,64	-28,65	5,94	,395[a]
50%	-28,33	6,81	-28,35	6,85	,504[b]
60%	-23,48	8,69	-23,14	8,76	,766[b]
70%	-13,53	10,87	-12,70	11,16	,992[b]
80%	0,08	12,69	1,57	13,19	,704[b]
90%	12,66	13,09	14,58	13,32	,271[b]
100%	19,02	12,43	21,08	11,11	,141[b]

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

Figure 36 demonstrates the differences in the kinematic of the ankle joint, which are very small and lie within 2.1° variation for the whole stance time. At 20% and 30% of the stance time the overground locomotion shows a significantly ($p<0.05$) higher dorsiflexion of the ankle joint. Also the last measured point shows a slightly higher dorsiflexion for the overground measurement but reach no significant level, with values of 19.0° in overground and 21.0° in treadmill running at the last ground contact. From the touchdown until the first half of the stance period a flat decrease of the curves can be seen, with a maximum dorsiflexion of 28.3° in overground and 28.7° in treadmill running, followed by a steep ascent until the take-off. The standard deviation for the ankle joint is low (values under 10°) for the first six measured points. Afterwards the standard deviation increases with a maximum value of 13.3° in treadmill running at 90% of the stance time.

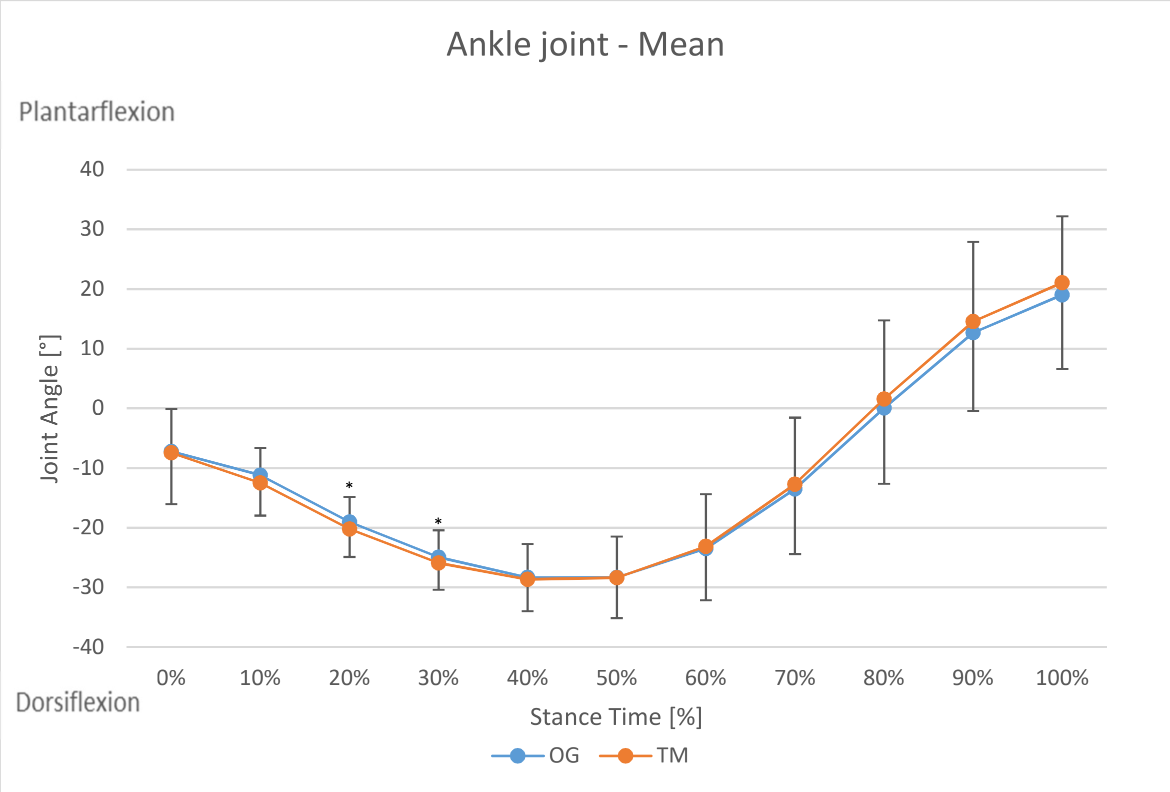


Figure 36: Averaged ankle joint movement with standard deviation - overground running (OG) vs. treadmill running (TM)

5.3.4. Muscular activity

As dealt with in chapter 5.3.3 the mean, standard deviation and the p-value of the test for significant difference (paired sample t-test or Wilcoxon test) for each of the four muscles is presented individually. Again, significant differences are highlighted with asterisks.

5.3.4.1. M. vastus lateralis

Table 8 shows the averaged values for the eleven points in time analysed and the related standard deviation, which are demonstrated graphically in figure 37. Furthermore, the p-values of the test are written in the right column. Throughout the stance time at eight measured points a significant difference exist, which shows, that the muscular activity for m. vasuts lateralis between the two locomotion modalities is different. At 0%, 30% and 90% the values reach no significant level ($p<0.05$). During the time period with the maximal activation (40%-80%) the difference is highly significant ($p<0.01$).

Table 8: Treadmill vs. overground running for the muscular activity of m. vastus lateralis; magnitude normalized to maximal reached activity (in percent); standard deviation (SD)

Stance Time	**Overground**		**Treadmill**		**Comparison (p-value)**
	Mean	SD	Mean	SD	
0%	10,81	8,09	8,51	6,54	,056[a]
10%	16,52	11,53	10,81	9,39	,001[a, **]
20%	21,55	12,37	17,10	12,05	,015[a, *]
30%	25,68	13,52	22,38	13,14	,079[a]
40%	41,30	23,39	29,50	15,83	,001[a, **]
50%	61,80	25,82	41,93	21,41	,000[a, **]
60%	63,69	25,12	37,06	19,75	,000[a, **]
70%	48,43	20,57	25,41	12,65	,000[a, **]
80%	25,95	18,18	15,04	8,71	,006[a, **]
90%	11,14	8,25	8,02	5,70	,057[a]
100%	1,07	1,13	0,54	0,49	,022[a, *]

[a] Paired t-test

[b] Wilcoxon test

* Significant difference at p<0.05

** Significant difference at p<0.01

Figure 37 shows that the muscular activity of m. vastus lateralis is significantly higher ($p<0.05$) in overground than in treadmill running throughout the stance time expect for 0%, 30% and 90% of the stance time. In overground running for the first 30% a continuous but flat ascent occurs, afterwards there is a steep increase in the muscular activity until a maximum value of 63.7% occurs at 60% of the stance time. In treadmill running an ascent is also visual but not that steep and up to a maximum value of 41.9% at 50% of the stance time, hence the maxima in treadmill running occurs one measured point earlier than in overground running. After the maxima were reached a decline is visible in both graphs until almost no activation (1.1% OG; 0.5% TM) is measured at the take-off.

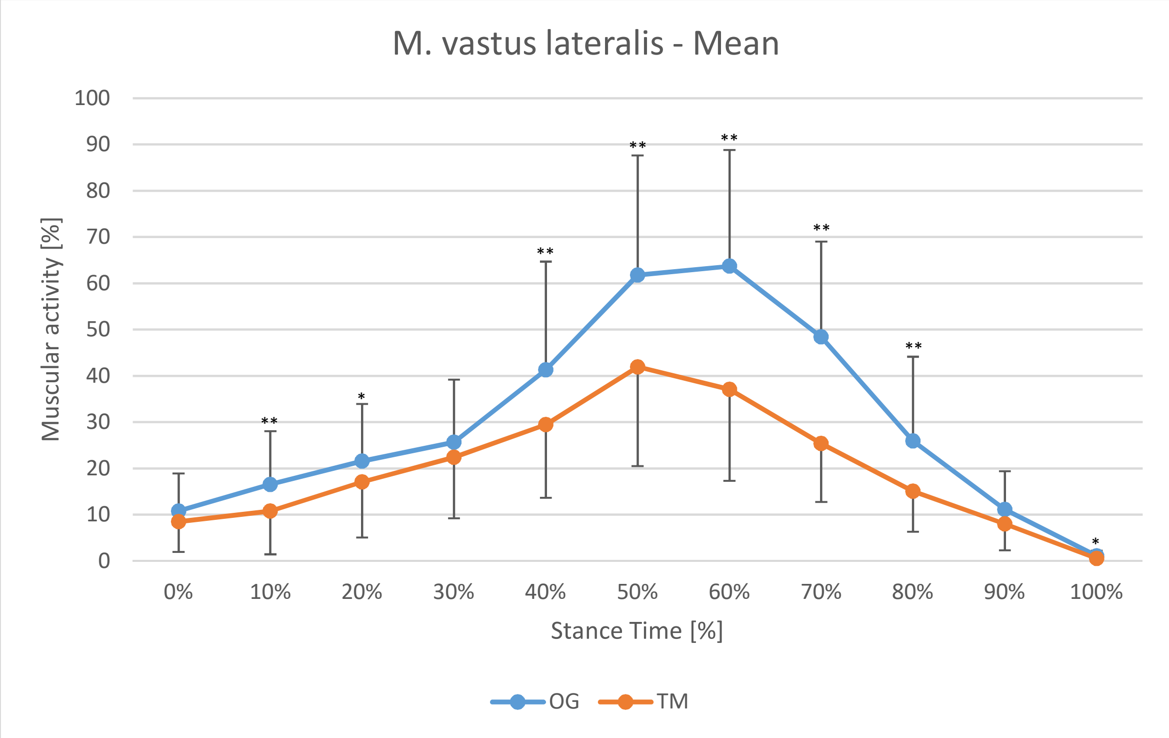


*Figure 37: Averaged muscular activation of m. vastus lateralis with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.4.2. M. biceps femoris

In table 9 the mean and the standard deviation of the muscular activity of m. biceps femoris at the 10% intervals can be seen as a list and in figure 38 as a diagram. The muscular activity of m. biceps femoris only shows significant differences ($p<0.01$) at 50% of the stance time. The values for the standard deviation are high with an average value of 18.5° in overground and 17.5° in treadmill running throughout the whole stance time.

Table 9: Treadmill vs. overground running for the muscular activity of m. biceps femoris; magnitude normalized to maximal reached activity (in percent); standard deviation (SD)

Stance Time	**Overground**		**Treadmill**		**Comparison (p-value)**
	Mean	SD	Mean	SD	
0%	44,02	24,76	52,93	27,41	,052[a]
10%	36,64	23,81	45,13	23,82	,057[a]
20%	23,05	11,81	27,87	17,36	,109[a]
30%	17,98	8,82	20,98	12,44	,195[a]
40%	29,93	20,62	24,14	15,93	,158[a]
50%	42,22	26,08	27,94	17,16	,004[a, **]
60%	41,16	24,39	32,55	21,52	,119[a]
70%	42,81	21,44	38,75	20,79	,359[a]
80%	50,00	21,11	43,40	19,12	,125[a]
90%	35,85	17,13	31,60	13,69	,244[a]
100%	4,11	3,85	2,76	3,19	,152[a]

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

Figure 38 shows that m. biceps femoris has a high muscular activation at the first ground contact, with a value of 44.0% in overground and 52.9 in treadmill running. In the first 30% of the stance time the activation decreases to a minimal value of 12.4% in treadmill and 18.0% in overground running. The descent is steeper in treadmill running and therefore after 30% of the stance time have passed the overground running modality shows higher values for the remaining stance time. From 30% to 80% the stance the amplitude increases, with a significant higher ($p<0.01$) muscular activation in overground running at 50% of the stance. In the last 20% of the stance phase a steep decrease of the curves can be seen in both running modalities until the values decline to under 5% at the take-off.

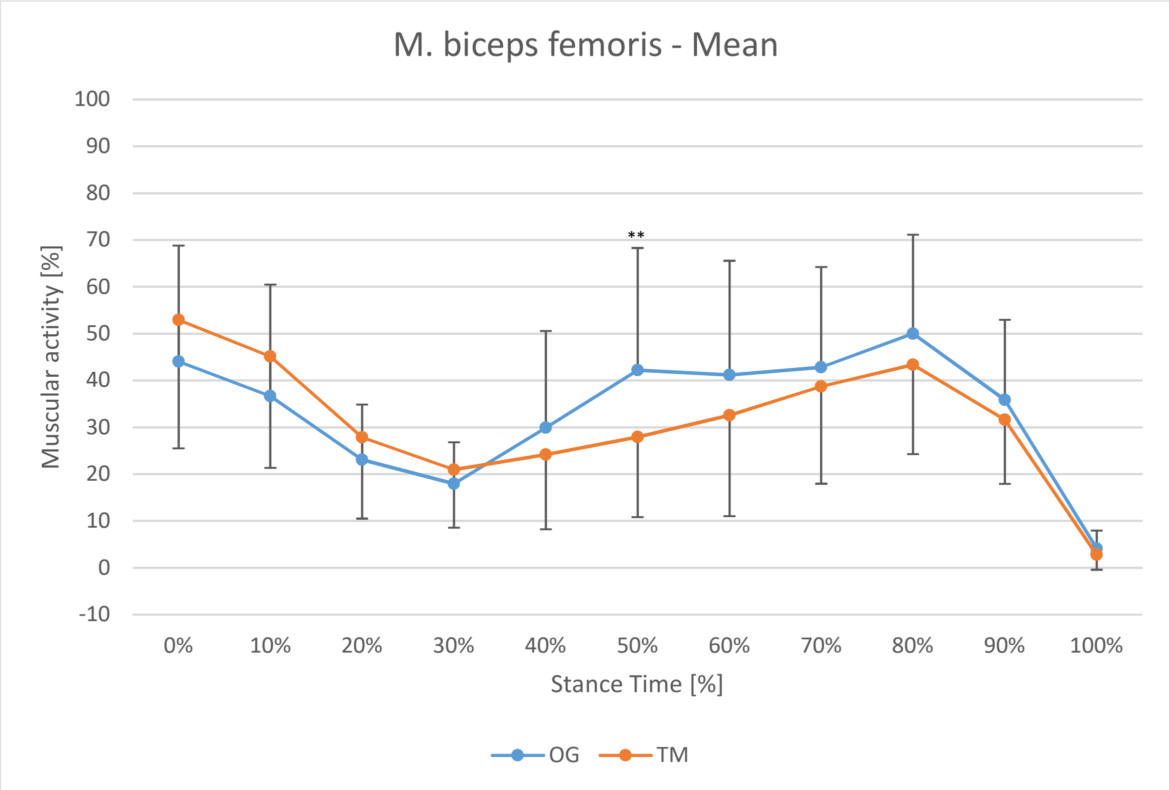


*Figure 38: Averaged muscular activity of m. biceps femoris with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.4.3. M. tibialis anterior

Table 10 points out the mean and the standard deviation for treadmill and overground running throughout the stance phase and figure 39 shows the associated graph. At the touchdown, 10% and 50% the muscular activity of the different subjects is highly different with a significance level of $p<0.01$. At 80% and 90% of the stance phase time the values also differ ($p<0.05$) significantly.

Table 10: Treadmill vs. overground running for the muscular activity of m. tibialis anterior; magnitude normalized to maximal reached activity (in percent); standard deviation (SD)

Stance Time	**Overground**		**Treadmill**		**Comparison (p-value)**
	Mean	SD	Mean	SD	
0%	55,86	20,59	44,96	16,63	,000[a], **
10%	64,02	19,30	54,32	20,69	,005[a], **
20%	61,40	25,56	52,73	22,29	,078[a]
30%	37,25	20,40	35,82	18,86	,779[a]
40%	26,09	17,88	22,26	24,00	,344[a]
50%	38,29	25,08	23,87	20,70	,002[a], **
60%	36,96	25,45	27,81	28,92	,165[a]
70%	29,40	23,51	23,47	27,24	,316[a]
80%	21,33	21,61	13,61	12,38	,045[a], *
90%	11,58	9,51	6,70	5,61	,015[a], *
100%	1,21	1,96	0,69	0,69	,154[a]

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

The two graphs in figure 39 demonstrate the differences in the activation pattern of the m. tibialis anterior between treadmill and overground running. The diagram highlights a large percentage difference of the muscular activity at the first ground contact with a 10.9% significantly higher (p<0.01) activation in overground running. After a slight increase in both curves until the second measuring point the activation decreases until 40% of the stance time has passed. Afterwards the magnitude in overground running has a steep ascent, whereby in treadmill running there is only a flat increase, which leads to a 14.4% significantly higher (p<0.05) activation in overground running at 50% of the stance time. After 60% of the analysed time the muscular activation declines in both running modalities to values around 1% at the last ground contact.

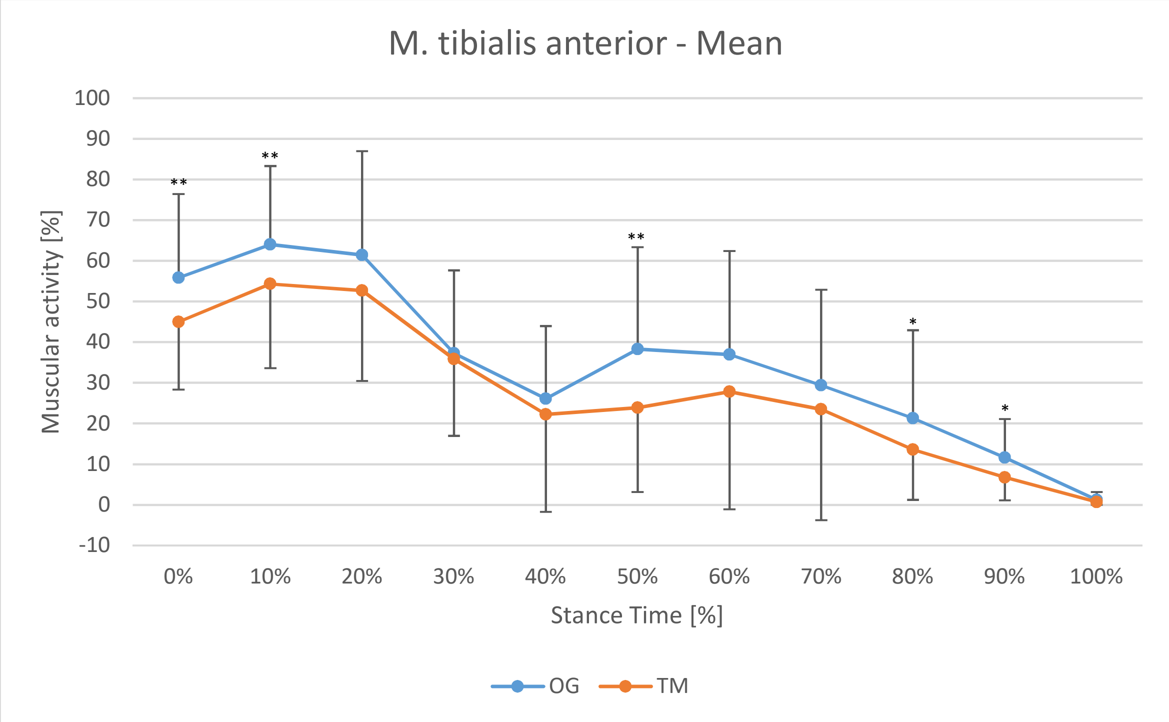


*Figure 39: Averaged muscular activation of m. tibialis anterior with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.4.4. M. gastrocnemius medialis

The paired statistic for m. gastrocnemius medialis with the mean and standard deviation is shown in table 11. Figure 40 provides the results graphically. The muscular activity of m. gastrocnemius medialis only reaches a significant difference ($p<0.01$) at 10% of the stance time. The other values are too similar with a too high standard deviation to cause a clinical significance ($p<0.05$).

Table 11: Treadmill vs. overground running for the muscular activity of m. gastrocnemius medialis; magnitude normalized to maximal reached activity (in percent); standard deviation (SD)

Stance Time	**Overground**		**Treadmill**		**Comparison (p-value)**
	Mean	SD	Mean	SD	
0%	14,22	22,05	17,51	22,89	,106[a]
10%	10,72	9,18	16,46	12,43	,004[a], **
20%	11,35	8,81	15,79	10,44	,068[a]
30%	15,66	8,66	18,33	10,78	,241[a]
40%	27,77	14,35	32,33	12,88	,169[a]
50%	42,05	19,80	42,88	19,32	,855[a]
60%	59,22	23,07	51,83	14,99	,104[a]
70%	65,66	22,62	59,38	14,76	,232[a]
80%	62,31	22,33	58,71	16,35	,446[a]
90%	41,76	19,14	41,31	16,21	,899[a]
100%	3,65	3,55	4,06	3,68	,671[a]

[a] Paired t-test
[b] Wilcoxon test
* Significant difference at p<0.05
** Significant difference at p<0.01

Figure 40 demonstrates the muscular activity of m. gastrocnemius medialis in treadmill and overground running. The values of the two running modalities differ by less than 8% during the whole stance time. There is an initial activation at the first ground contact of 17.5% in treadmill and 14.2% in overground running. Afterwards the activation increases until 70% of the stance time with a maximum of 65.7% for the overground and 59.3% for the treadmill modality. After 80% of the stance period a steep decrease of the magnitude is visible until the activation reaches 3.7% for both modalities at the take-off. At the first ground contact the standard deviation is very high for both running conditions with values over 20%.

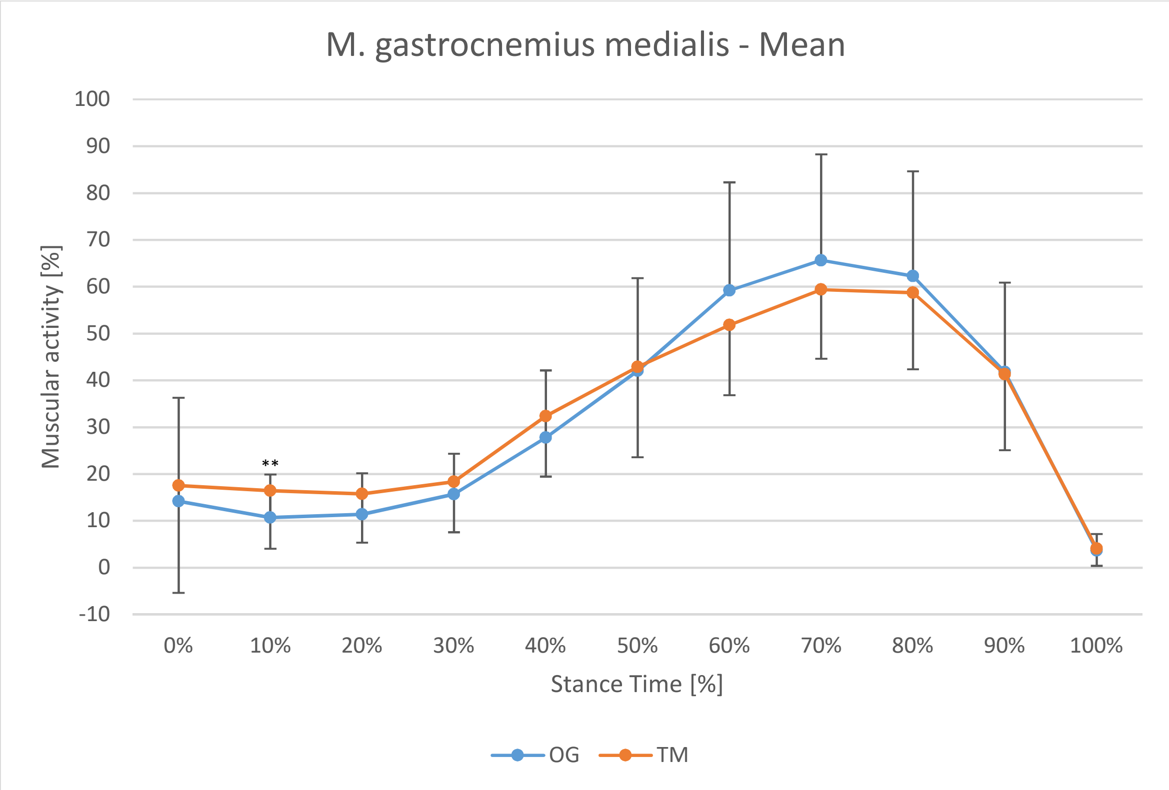


*Figure 40: Averaged muscular activation of m. gastrocnemius medialis with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)*

5.3.5. Results Bland & Altman analysis

The next chapter will show the results of the comparison of the two running modalities with the Bland & Altman method. Since overground running is considered to be the gold standard, we assessed its comparability with treadmill running For all three joints the results for the different points in time did not vary systematically over the range of measured values and the results are not proportional to the mean, therefore a logarithmic transformation was not necessary (Bland & Altman, 1986).

5.3.5.1. Hip joint

Table 12 lists the mean, the mean difference, the limits of agreement and the p-value of the one sample t-test of the Bland & Altman Analysis. The mean differences are positive values with deviations from 1.43° to 5.45° from zero, which indicates that the results from treadmill running are systematically higher, which in this case presents a systematically more flexed hip joint. Furthermore, all the p-values show a significance from the one sample t-test. These aspects lead to the assumption that systematic bias exists.

Table 12: Bland-Altman-Analysis of the hip joint; mean difference between the two running modalities (MD) including the standard deviation (SD); lower and upper limits of agreement representing ±1.96 SD (LoA); p- value of one sample t-test; all results are presented in degrees

Bland & Altman Analysis – Hip Joint					
Stance Time	Mean	MD (SD)	Upper LoA	Lower LoA	p-value
0%	30,59	5,45 (4,09)	13,46	-2,56	,000**
10%	31,76	3,38 (4,45)	12,11	-5,35	,000**
20%	33,38	2,05 (4,50)	10,87	-6,76	,018*
30%	29,45	2,61 (4,38)	11,20	-5,99	,003**
40%	24,15	2,15 (4,49)	10,94	-6,65	,014*
50%	18,58	1,73 (4,54)	10,62	-7,17	,046*
60%	11,58	2,20 (4,99)	11,97	-7,57	,022*
70%	4,49	2,78 (4,99)	12,55	-6,99	,005**
80%	-1,71	2,66 (4,31)	11,10	-5,78	,002**
90%	-6,22	2,04 (3,58)	9,07	-4,98	,004**
100%	-8,71	1,43 (3,17)	7,64	-4,77	,019*

* Significant difference at $p<0.05$
** Significant difference at $p<0.01$

5.3.5.2. Knee joint

The results of the Bland & Altman analysis shown in table 13 reveal distinct results for the different points in time measured. The average mean of the difference for the whole stance time is ~2°. At the end of the stance time (80-100%) the deviations from the mean increases with systematically higher values in treadmill running, reaching a maximum of 4.97° at take-off. The results of the one sample t-test show significant results ($p<0.05$) for all the points in time except 10%, 30% and 70%. The Bland-Altman-Plot (figure 41) for the points in time with no significant result of the one sample t-test will give further information about the differences between the running modalities.

Table 13: Bland-Altman-Analysis of the knee joint; mean difference between the two running modalities (MD) including the standard deviation (SD); lower and upper limits of agreement representing ±1.96 SD (LoA); p-value of one sample t-test; all results are presented in degrees

Bland & Altman Analysis – Knee Joint					
Stance Time	Mean	MD (SD)	Upper LoA	Lower LoA	p-value
0%	-17,34	-2,07 (4,77)	5,94	-10,08	,024*
10%	-28,04	0,20 (4,53)	8,93	-8,53	,812
20%	-37,70	1,43 (3,33)	10,25	-7,39	,026*
30%	-39,95	1,07 (3,57)	9,66	-7,52	,112
40%	-38,71	2,05 (4,54)	10,84	-6,74	,020*
50%	-35,26	2,74 (5,20)	11,63	-6,15	,007**
60%	-29,43	2,55 (6,24)	12,32	-7,22	,033*
70%	-23,00	2,26 (6,52)	12,04	-7,51	,067
80%	-17,20	2,64 (5,52)	11,08	-5,81	,014*
90%	-14,07	3,86 (4,51)	10,88	-3,17	,000**
100%	-16,02	4,97 (5,28)	11,17	-1,24	,000**

* Significant difference at p<0.05

** Significant difference at p<0.01

In figure 41 the Bland-Altman-Plots for 10%, 30% and 70% of the stance time are shown. The averaged range for the limits of agreement for the three points in time, in which 95% of the measured values lie, is 18.1°.

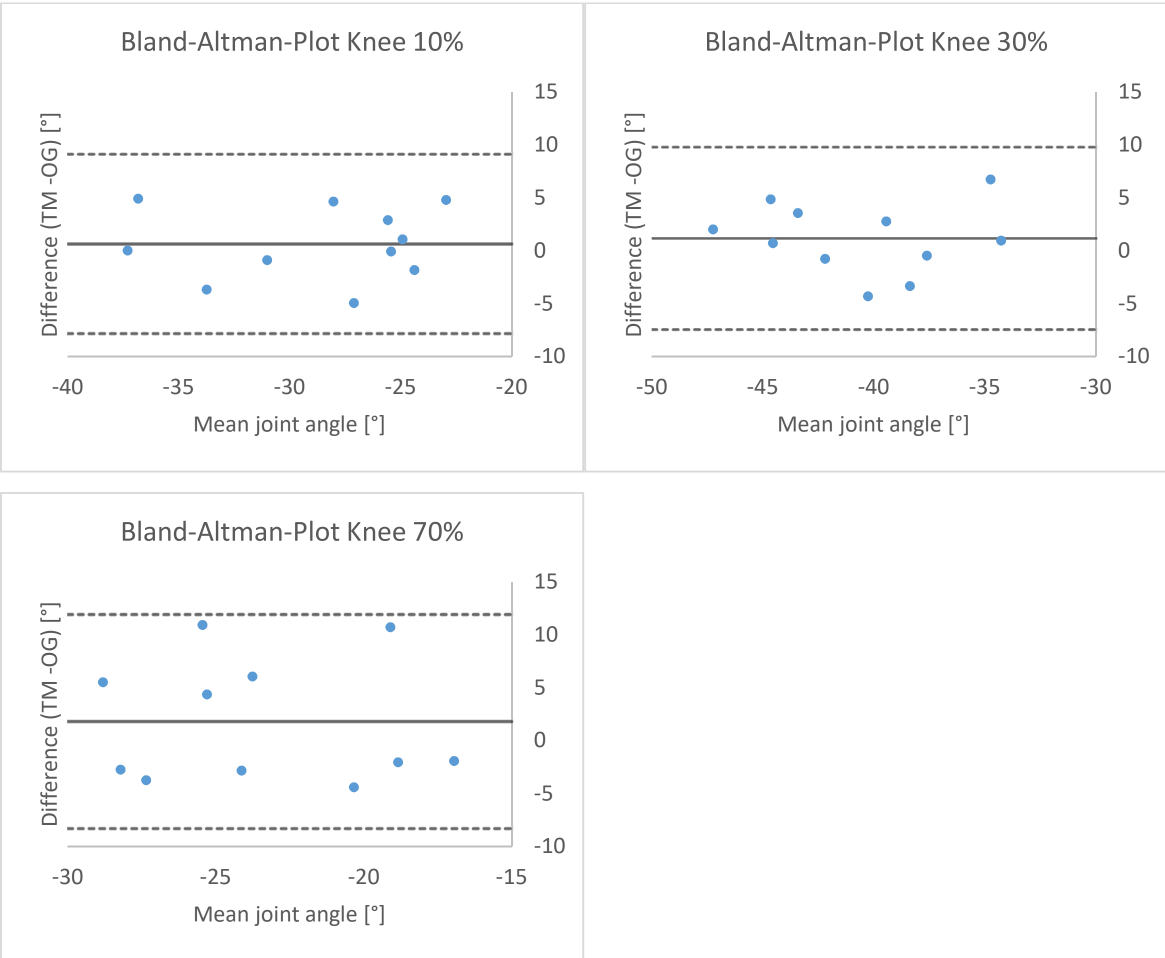


Figure 41: Bland-Altman-Plot from 10%, 30% & 70% of the stance time for the knee joint; mean of the differences (black horizontal line), upper and lower level of Agreement (dotted lines)

5.3.5.3. Ankle joint

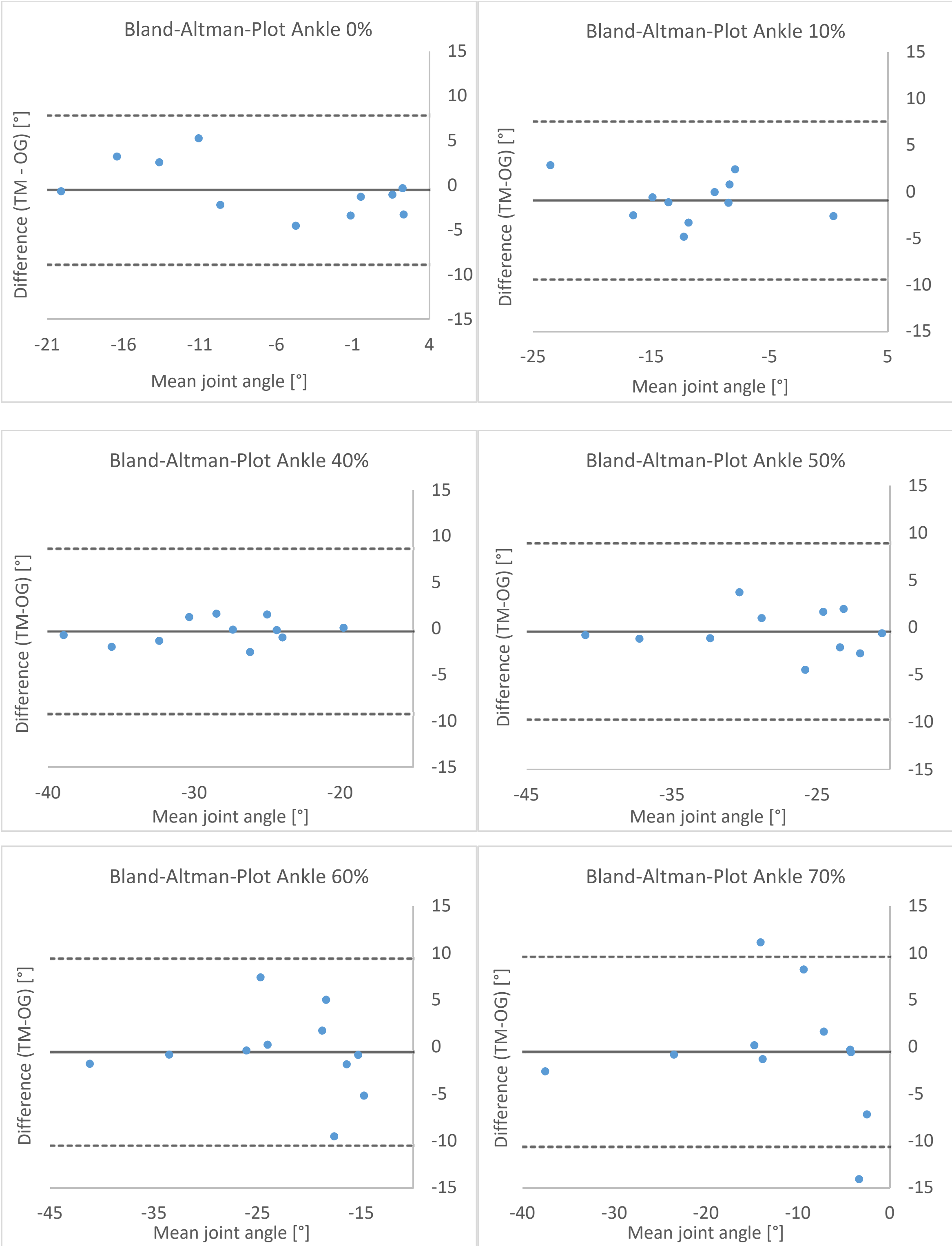
The results of the Bland & Altman analysis for the whole stance phase are shown in table 14. The mean differences between the values of overground and treadmill running are around zero (-0,0 – 2,06). At the end of the stance phase (90%-100%) the deviation from the mean difference from zero is higher and reaches a positive value, which demonstrates that in treadmill running the ankle joint is more plantarflexed. The results of the one sample t-test reach a significant level at 20% and 30% of the stance time. A graphical presentation for the other points in time can reveals further information.

Table 14: Bland-Altman-Analysis of the ankle joint; mean difference between the two running modalities (MD) including the standard deviation (SD); lower and upper limits of agreement representing ±1.96 SD (LoA); p-value of one sample t-test; all results are presented in degrees

Bland & Altman Analysis – Ankle Joint					
Stance Time	Mean	MD (SD)	Upper LoA	Lower LoA	p-value
0%	-7,34	-0,26 (4,90)	7,75	-8,27	,776
10%	-11,855	-1,27 (3,57)	7,46	-10,00	,061
20%	-19,64	-1,19 (2,84)	7,63	-10,00	,029*
30%	-25,42	-0,97 (2,17)	7,62	-9,57	,020*
40%	-28,49	-0,31 (2,00)	8,48	-9,11	,395
50%	-28,34	-0,01 (2,71)	8,88	-8,91	,976
60%	-23,31	0,34 (4,59)	10,11	-9,43	,687
70%	-13,115	0,83 (6,57)	10,61	-8,94	,493
80%	0,825	1,49 (7,56)	9,93	-6,95	,290
90%	13,62	1,92 (6,68)	8,95	-5,10	,126
100%	20,05	2,06 (6,64)	8,26	-4,15	,100

* Significant difference at p<0.05
** Significant difference at p<0.01

In figure 42 the Bland-Altman-Plots for all the points in time, which no significant ($p<0.05$) results of the one sample t-test are presented. The range of the limits of agreement are between 12.4° at 100% and 20.2° at 70% of the stance time. The figure depicts that in the second half of the stance time the mean values deviate more from the mean of the differences between the locomotion modalities than in the first half. The average result of the limits of agreement for the presented points in time is for the lower value -7.9° and for the upper value 8.9°. Therefore, any intervention leading to a change of the ankle joint kinematics of more than ±8.9° shows an actual change.


Bland-Altman-Plot Ankle 0%
Difference (TM - OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-21
-16
-11
-6
-1
4
Bland-Altman-Plot Ankle 10%
Difference (TM-OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-25
-15
-5
5
Bland-Altman-Plot Ankle 40%
Difference (TM-OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-40
-30
-20
Bland-Altman-Plot Ankle 50%
Difference (TM-OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-45
-35
-25
Bland-Altman-Plot Ankle 60%
Difference (TM-OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-45
-35
-25
-15
Bland-Altman-Plot Ankle 70%
Difference (TM-OG) [°]
Mean joint angle [°]
15
10
5
0
-5
-10
-15
-40
-30
-20
-10
0

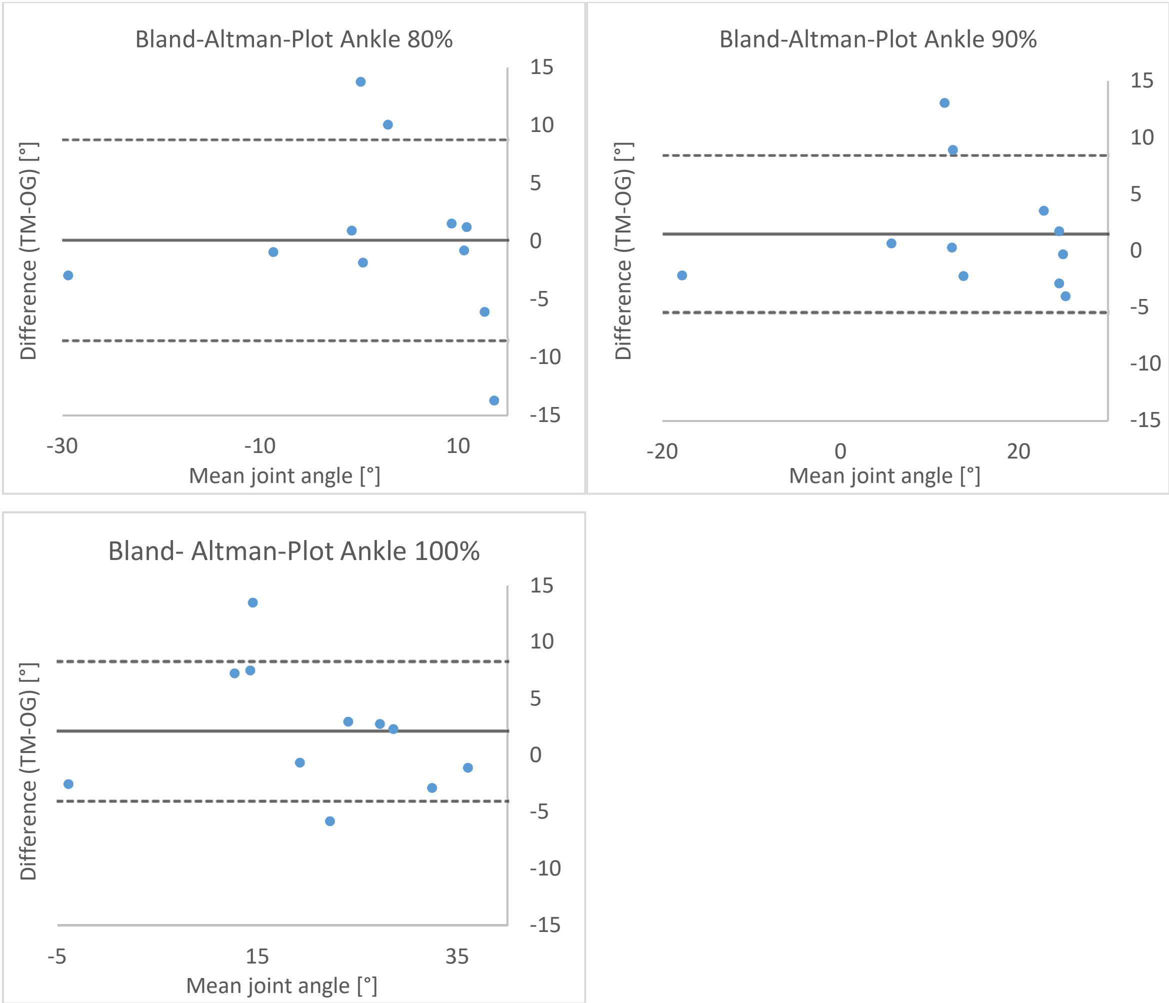


Figure 42: Bland-Altman-Plot from 0%, 10%, 40%-100% of the stance time for the ankle joint; mean of the differences (black horizontal line), upper and lower level of Agreement (dotted lines)

6. Discussion

6.1. Temporal parameters

The duration of the stance phase showed no significant difference between the two running modalities (OG: 0.24 ms ±0.024; TM: 0.24 ms ±0.016). The constant duration of the stance phase in both modalities can also be found in literature (Cronin & Finni, 2013; Elliott & Blanksby, 1976; Willy, Halsey, Hayek, Johnson, & Willson, 2016). On the contrary one study Wank et al. (1998) showed a decreased contact time ($p<0.05$) in treadmill compared to overground running, which, according to the authors, led to a running style that seemed hastier. The differences between the aforementioned study and the present one could be the sufficient familiarization time given to the subjects prior to the data acquisition. In the present study a six minutes familiarization time was used, while in the study of Wank et al. (1998) only a few seconds were given to the subjects to accustom themselves with the belt speed and immediately acquired the data in a five second time interval. Additionally, the fact that the subjects in the present study were familiar with treadmill running could also be a significant attribute in the absence of changes in the stance time. The role of familiarisation time in the treadmill trials was also stated in an earlier study by Alton et al. (1998) who compared overground to treadmill walking. Although the authors used a familiarization period of three minutes they reported that the kinematic alterations in the hip joint and the stance time observed in their study could be an attempt by the subjects to avoid falling off the back of the treadmill and keep the pace with the belt speed.

Nonetheless others (Schache et al., 2001) reported a significantly ($p=0.002$) lower stance duration in treadmill than overground running (3.99 m/s) expressed as percentage ratio of the stride duration. But in absolute terms the calculated stance time in both modalities appears to be similar (~0.22 s) indicating that different methodological approaches pointing to different hypotheses can alter the meaning of the measured outcomes. Another factor that can influence the temporal parameters which can lead to contrasting results is the identification method of the gait events. In literature we can find kinematic (Schache et al., 2001), kinetic (Lee & Hidler, 2008) by means of force plates or, as in the present study, the use of the pressure insole measuring devices. The accuracy of the pressure insole system (0.01 s) for the given pace (3.5 m/s) and overall contact time (~0.25 s) could produce an estimation error of 4% that is in our view acceptable. At higher speeds and shorter contact times more accurate devices may be needed to detect the instances of touchdown and take-off.

6.2. Kinematic parameters

6.2.1. Hip joint

There are conflicting results in literature concerning the mechanics of the human body between the treadmill and overground locomotion. Van Ingen Schenau (1980) proposed that the mechanics between the two modalities are similar but in the present study significant differences in the hip joint were observed. Lee and Hidler (2008), who compared treadmill with overground walking in healthy individuals, found no differences in the maximum hip flexion, maximum hip extension and the hip range of motion. The authors further suggested that the use of treadmills for training individuals with neurological injuries is justified from a therapeutic perspective. Although in walking similar patterns in the hip joint can be detected, the results in the present study showed that throughout the whole stance phase the hip joint is significantly less extended ($p<0.05$) in treadmill running. Our results are also in contrast with the findings of Fellin et al. (2010) who found the hip joint waveform to be the most similar of the three (hip, knee, ankle) examined joints. The authors also stated that the examined trend symmetry gave values above 0.95 for the sagittal and frontal but lower (0.90) for the transverse plane. In addition, the calculated ICC values were, according to the authors, not as high as expected (0.85) and lower (0.76) for the peak hip flexion angle. Moreover, in the study of Fellin et al. (2010) the mean difference of the hip joint angle between the two modalities at foot strike was ~1 degree which is in contrast to the results (~5.5 degrees) of the present study. This discrepancy could be part of the methodological differences in both studies. For example, in the study of Fellin et al. (2010) the hip joint was defined with the markers placed bilaterally to the iliac crests, greater trochanters, medial and lateral femoral condyles, while in the present study instead of the iliac crest the marker placed at C7 could induce greater upper body movements.

Our results are also in contrast with the values reported by Sinclair et al. (2013) who found a more flexed hip joint in the sagittal plane at touchdown in overground than in treadmill running. Although the authors did not compare the hip joint angle at all percentage points of the stance phase, according to their figure of the hip joint angle it can be speculated that the difference was present from 0 to ~70% of the stance time. Similarly, Schache et al. (2001)found that in overground running the hip joint angle remained more flexed at the initial foot contact, the loading response point and at the event of toe-off. The authors calculated the RMS differences of the hip joint angle at the three distinct points with an average of ~6 degrees. On the contrary, in the present study the mean significant difference of the hip joint was ~3 degrees throughout the stance time with a more flexed hip in treadmill running.

In contrary to the aforementioned studies Alton et al. (1998) found a trend ($p=0.019$) for the maximal hip flexion angle of a higher hip flexion in treadmill than in overground walking at a preferred speed. Similar to our study the maximal hip flexion was also significantly ($p=0.023$) greater in treadmill than in the overground modality, which was observed at 20% of the stance time (OG=32.4 ±6.3° vs. TM=34.4 ±4.3°).

Another aspect which could possibly explain the present differences in the hip joint angle between the two modalities is the review concerning the running economy by Barnes and Kilding (2015) who stated that a greater maximal angle during the hip extension could cause a better economy. This information leads to the assumption that the cohort in the present study chose a running style with a lower energy consumption in overground running. A possible reason could be, that despite the familiarization with treadmill running, the subjects are more used to overground running, which results in a better running economy. The same phenomena can be seen during the take-off for the knee joint.

6.2.2. Knee joint

There are unusual findings concerning the kinematics of the knee joint in the sagittal plane which reveals different outcomes throughout the stance phase. At the touchdown the knee joint is significantly ($p=0.024$) less extended in treadmill running. Subsequently, during the flexion of the knee a significantly ($p<0.05$) lower joint angle is present in overground running at 20%, 40%, 50% and 60%. And at the end of the stance phase (80-100%) the knee joint is again significantly ($p<0.05$) more flexed in overground running. At 10, 30 & 70% there is no significant difference between the two running conditions. Some of the results correspond, but some are also contradictory to existing literature. For example, Lee and Hidler (2008) did not find any difference in the maximal knee joint flexion between the two running conditions and similar to the present study no significant difference was found in the phase (30%) of maximal knee joint flexion. On the other hand Sinclair et al. (2013) found a significantly greater ($p=0.01$) peak knee flexion (5 degrees) in overground compared to treadmill running. It can be speculated that this finding can be transferred to the significantly more flexed knee joint at 20%, 40%, 50% and 60% of the stance phase for overground running, because this is the period of time where the maximum flexion of the knee occurs. According to the authors the movement of the COM over the stance leg, forces the proximal end of the tibia to move forward which leads to a knee flexion. The reduction of the horizontal movement of the COM in treadmill running leads to the decreased knee flexion (Sinclair et al., 2013). Based on the findings of this study we can further speculate that the two different modalities have different stiffness and the human body is attempting to adapt to the new surface (Ferris, Louie, & Farley, 1998) by modifying the leg spring stiffness. By using this strategy the human body can keep the vertical stiffness constant regardless of the surface stiffness (Ferris et al., 1998). This could partially explain the less flexed knee joint angle present at 20%, 40-60% and 80-100% of the stance phase in treadmill compared to overground running. This assumption can also be supported by the findings of the previous study (Wank et al., 1998) who found a significantly ($p<0.01$) greater centre of gravity oscillation in the overground than in the treadmill condition at two (4 and 6m/s) different running speeds. Suggestions about the role of surface stiffness are also made by Riley et al. (2008) who stated that the treadmill-based analysis can be generalized to overground running if the treadmill surface is adequately stiff and the belt speed is satisfactorily regulated. But nevertheless the lack of difference ($p>0.05$) in the joint angles at 10, 30, and 70% of the stance phase is still unclear.

In the present study we did not estimate the stiffness of the treadmill device as well as its natural frequency. The possibility exists that the aforementioned device could alter both the knee and to a greater extent the hip joint angle at the given pace through its mechanical properties. This speculation needs to be addressed in future studies incorporating not only different treadmill devices with different mechanical characteristics but examining them under various pace conditions. Previous Nigg et al. (1995) compared overground to three different treadmill devices but it was unclear how the human locomotion adapts to the different treadmill situations.

Both the collected data for the treadmill and overground locomotion at touchdown, lie within the 15-25° described as standard values in literature for the knee flexion at the foot strike for running mentioned by Buczek and Cavanagh (1990).

The significant difference at the end of the stance time (80-100%) is not concordant with present literature. It is to be noted, that numerous studies (Fellin et al., 2010; Riley et al., 2008; Sinclair et al., 2013) did not evaluate the knee joint kinematic at take-off, therefore not a lot of comparative values exist. The result of Wank et al. (1998) is in contrast to the present study, no significant difference at take-off was found in their study. Further investigation is necessary to clarify the reason for the contradictory outcomes.

Different studies discovered, that a less extended knee joint at toe-off leads to a better running economy (Cavanagh, Pollock, & Landa, 1977; Clermont et al., 2017; Moore, 2016; Moore, Jones, & Dixon, 2012) and a reduction of the energy demand by as much as 50% (Barnes & Kilding, 2015). Clermont et al. (2017) and Moore et al. (2012) mentioned as a possible explanation that the decreased knee extension at the last ground contact contributes to a reduced additional knee flexion during the swing phase. Therefore, a lower energy consumption for flexing the leg during the swing phase is necessary, which leads to a better running economy. It can be supposed that the stored energy of the treadmill is returned to the human body at the late stages (80%) of the stance phase and therefore the difference in the knee joint angle is augmented at 90 and 100% (from 2.6° to 3.9° and finally 5.0°). Additionally, this finding underlines the assumption that the cohort chose a running style with a better running economy in overground running.

6.2.3. Ankle joint

In the present study, no significant differences ($p>0.05$) were found (except at 20 and 30% of the stance phase) in the kinematic of the ankle joint between treadmill and overground locomotion, which is partially in accordance with the initial proposal of van Ingen Schenau (1980), who claimed the mechanics between the two modalities to be similar. The results are also in partial agreement with the more recent study of Riley et al. (2008), who analysed kinematic differences of the ankle joint between overground and treadmill running and found no significant difference between them. Lee and Hidler (2008) also found no significant differences in selected kinematic variables of the ankle joint between the two running modalities. In particular no differences were found at the maximum ankle extension, flexion and the range of motion. Compared to the study of Lee and Hidler (2008) we also did not find any significant difference at the instance of maximum ankle extension (100%) or the instance of maximum ankle joint flexion (40-50%). Furthermore, we have not performed an analysis of the ankle range of motion since our primary aim was to assess the joint kinematics of the two different running modalities at the different stance phases. Our approach revealed small but significant differences at 20 and 30% of the stance phase although at maximum flexion and extension no difference could be detected.

In contrast there are some studies, which revealed a significant difference between overground and treadmill running for the ankle joint at the foot strike (Fellin et al., 2010, Nigg et al., 1995, Wank et al., 1998) and others (Sinclair et al., 2013) who found a greater excursion of the ankle joint (6.0°) from touchdown to peak angle. In the study by Nigg et al. (1995) the initial shoe sole to ground angle was significantly ($p<0.01$) reduced from 15.9° in overground to 8.0° in treadmill running. This was a result of the changing landing style (rearfoot to midfoot or forefoot) of the subjects that forced the authors to examine only rearfoot landings (N=14) which revealed no significant foot angle differences between surfaces. Furthermore, Nigg and colleagues (1995) examined the effect of running experience on the two different surfaces. They showed that the non-runners exhibited a significantly decreased shoe sole angle in treadmill by 5.4° and 4.2° at 3m/s and 4.5m/s speed respectively compared to overground running. It is difficult to compare the results provided by Nigg et al. (1995) due to methodological differences in the calculation of the ankle angle. In the present study the ankle joint angle was defined by the markers placed on the 5th metatarsal, lateral malleolus and lateral epicondylous, while Nigg et al. (1995) placed two markers in the fore-, and rearfoot sole of the subjects' shoe and defined its inclination to the ground as the foot angle. Therefore, also if no differences in rearfoot strikers between surfaces existed, it is unknown how the tibia segment of the subjects in the study of Nigg et al. (1995) would have behaved at the initial contact and how the ankle angle would have developed. A similar methodological approach was also used by Wank et al. (1998) who found a decreased shoe sole to ground angle both at 4m/s ($p<0.01$) and 6m/s ($p<0.05$) (4m/s: OG=17.6±12.5° vs. TM=6.7±10.8°; 6m/s: OG=6.9±10.5° vs. TM=1.3±8.9°). As previously described the shoe sole to ground and not the centre of the ankle joint was used for describing the dorsiflexion of the foot.

Fellin et al. (2010) found a 4.5° decrease in the ankle joint dorsiflexion in treadmill compared to overground running. This result is similar to Wank et al. (1998) and Nigg et al. (1995) on the basis of the similar methodological approach in estimating the rearfoot kinematics. The authors used three markers on the sole around the rearfoot and tracked its inclination to the ground. Again, the tibia movement was not involved in the calculation of the ankle joint angle and therefore the different outcomes cannot be compared to the present study.

Nevertheless, as a possible reason for the decreased dorsiflexion of the ankle joint Fellin et al. (2010) mentioned the shortened stride length and the change of strike pattern (rearfoot to midfoot) observed in treadmill running in different studies. Moreover, Nigg et al. (1995) mentioned the smaller shoe sole angle as a strategy to reduce the time necessary to gain full contact with the treadmill, which increases the feeling of stability. Due to almost similar ankle joint kinematic waveform in the present study, we can speculate that also if the shoe sole angle at foot strike was lower in the treadmill than in the overground condition, the sense of stability would also be the case in the second situation.

Nonetheless according to Buczek and Cavanagh (1990) the general range of the ankle joint at the touchdown mentioned in literature lies between 6° plantarflexion to 13° dorsiflexion, both the values from treadmill and overground running of the present study lie within this range.

6.3. Muscular activity

It was more difficult to perform a detailed analysis of the muscular activity because no comparable literature was available, especially the division of the stance phase into more than two intervals, while comparing the overground and treadmill running locomotion, which to our knowledge has not been performed yet. Some of the results are not in line with general muscular activation patterns, and therefore for further investigations it would be necessary to validate the signals, for example by isolated contraction of the relevant muscles. Furthermore, a test of repeatability would be helpful for estimating the normal variations of the waveforms.

6.3.1. M. vastus lateralis

The results of m. vastus lateralis for both running modalities show the typical pattern of activation for running, with one period of activation during the stance as described by Montgomery, Pink, and Perry (1994). The activation of the muscle correlates with its function, the extension of the knee joint (Neumann et al., 2010, p. 58), as can be seen in the graph of the knee joint movement. The extension of the knee joint starts at 40% of the stance time and ends at about 80%, the amplitude of m. vastus lateralis has a strong increase at this period in time.

The outcomes show a significantly lower activation almost from 10%-100% of the stance period in treadmill running. This outcome corresponds with the finding of Wank et al. (1998), who found a significantly lower amplitude of m. vastus lateralis throughout the whole stance period, but they divided the whole gait into only three parts (pre-contact, ground contact and swing). It is not clear, whether a more precise division of the stance phase would reveal different results. As a possible explanation for the difference in muscular activity between overground and treadmill running, the authors named the lower vertical displacement of the centre of gravity, which can be seen in the kinematic analysis. Therefore, a lower impact force is present at the landing and only a decreased activation of the muscle is necessary to compensate this impulse. Another possible explanation for the differences found in the present study could be contributed to the significantly different knee joint angles between the two running modalities. The vastus lateralis in the overground condition has not only the role to break the downward forces acting on the human musculoskeletal system but also to propel the body forward by extending the knee joint. The aforementioned mechanism is partially present in treadmill running since the belt of the treadmill device could give energy to the runner at foot contact and the runner would pass on the energy to the belt at toe-off (Winter, 1978; Nigg et al., 1995)

6.3.2. M. biceps femoris

M. biceps femoris did not show (except at 50% of the stance phase) any significant difference between the two running modalities. Although kinematic variation in the knee joint occurred between the two running conditions, the alterations were not adequate to trigger higher activation of the biceps femoris in order to control the joint movement. At 50%

of the stance phase the activity of m.biceps femoris in the overground condition was significantly ($p<0.01$) higher compared to the treadmill condition. The point in time coincides with the higher activity of m. vastus lateralis and the lower knee joint angle exhibited in overground compared to treadmill running. As stated before probably the lack of greater kinematic differences in the knee and hip joint were possibly not an adequate stimulus to increase the activity of the m. biceps femoris in order to either extend the hip joint or to further flex the knee joint. Further research is needed to examine the behaviour of m. biceps femoris under different kinematic (Groucho running) conditions (McMahon, Valiant, & Frederick, 1987).

Another point that has to be addressed is that the m. biceps femoris revealed a different waveform of muscular activity compared to the general activation pattern for running. The curve of the present study showed a high initial activation followed by a decrease in amplitude until 30% of the stance. Afterwards an increase until 80% is visual followed by a sharp decrease until toe-off. In comparison a low initial activation followed by one peak activation during the stance and barely any activation at the take-off is described as the common waveform in literature (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006; Montgomery et al., 1994; Pinnington, Lloyd, Besier, & Dawson, 2005; Sterzing, Frommhold, & Rosenbaum, 2016; Wang et al., 2014). The discrepancy in the waveform can be explained by the different methodological approach used in the present study. We calculated the RMS value of the EMG signal and normalized it with the highest EMG activity of the respected muscle independent (overground or treadmill) of its appearance. Other studies (Wang et al., 2014) adapted the linear envelope approach and normalized the EMG activity under sub maximum voluntary contractions at given reference (squatting, lower leg raise at 90°) postures. Others (Pinnington et al., 2005) normalized the EMG activity with the maximum voluntarily isometric contraction. At this point it is not clear which method is appropriate since the aforementioned methods are all present in literature (Winter, 1990) and used in the scientific community. The development of the scientific hypothesis probably plays an important role in the selection and implementation of the appropriate method.

6.3.3. M. tibialis anterior

The waveform of the muscular activity of m. tibialis anterior, with a high activation at the beginning followed by a decrease until the lowest value is visible at take-off, is in line with present literature (Baur, Hirschmuller, Muller, Cassel, & Mayer, 2012). The graph of the kinematic movement of the ankle joint also reflects the muscular activity. A higher activation in the first half of the stance phase, as long as a dorsiflexion in the ankle joint is visible. In the second half a plantarflexion occurs, therefore the activity of the m. tibialis anterior reduces. The results of m. tibialis anterior showed a significantly higher overground activation at touchdown ($p=0.00$) in the middle of the stance time (50%, $p<0.01$), at 10% of the stance ($p<0.05$) and before the last ground contact (80-90%, $p<0.05$) compared to the treadmill condition. To our knowledge so far no studies exist, which have analysed the muscular activity of m. tibialis anterior during the stance phase for such time intervals. Hence it is not possible to compare the significant differences of the exact points in time with present literature. The study of Wang et al. (2014) found no significant difference for m. tibialis anterior for the whole stance time between treadmill running and running on different overground surfaces. Baur et al. (2007) also found no difference in the two parts (weight acceptance, push-off) the stance phase was divided into or in time domain parameters (time of on-offset, maximal activation).

The significantly lower amplitude of m. tibialis anterior at the touchdown in treadmill running might result from the reduced impact force at the touchdown in treadmill running because of the lower vertical displacement described by Wank et al. (1998) and due to the more elastic surface of the treadmill compared to running on the wooden laboratory floor mentioned by Dolenec, Stirn, and Strojnik (2015). In the study of Baur et al. (2007) the overground data was recorded in a field test on a 400m track. Therefore, the different surface hardness could explain why no significant difference was observed either at the pre-activation (right before the first ground contact) or the weight acceptance (right after the ground contact). In addition, the longer period analysed could lead to the deviating outcome.

The significant differences at the middle and the end of the stance phase are not mentioned in other literature comparing treadmill and overground running. Additionally it cannot be explained with the kinematic results, hence there are no differences between the two running modalities for the ankle joint. However, this part of the waveform shows high variations between the subjects, some show a peak at the middle or second third of the stance time and some do not, therefore the results must be treated with caution.

6.3.4. M. gastrocnemius medialis

The waveform of the muscular activity for both running modalities is in line with present literature (Chumanov, Wille, Michalski, & Heiderscheit, 2012; Wang et al., 2014; Yong, Silder, & Delp, 2014). It also corresponds with the kinematic results of the ankle joint. The amplitude of m. gastrocnemius medialis strongly increases after 30% of the stance, the time where a maximal dorsiflexion angle is expected (40-50%) in order to further plantar flex the ankle joint.

The graph of the muscular activity of m. gastrocnemius medialis for the two locomotion modalities is very uniform, the only significant difference ($p=0.003$) is present at 10% of the stance time. The high similarity is supported by the study of Wang et al. (2014) and Wank et al. (1998), who found no significant difference during the stance phase. It is to be noted, that in both studies the stance time was not divided into further intervals, therefore a more precise comparison is not possible.

The general waveform, with one peak during the stance time, corresponds with the typical activation potential described in literature. First a low activation of the muscle is apparent (Chumanov et al., 2012; Dolenec et al., 2015; Yong et al., 2014). This low activation is necessary to secure a sufficient stability of the ankle joint during the landing together with m. tibialis anterior. The low activation is reduced for a person with a rearfoot landing (Baur et al., 2012), as the running style was neither controlled nor observed, further investigations in this area are not possible. The high standard deviation at the first ground contact, especially in treadmill running could be associated with changes in the running style. The activation of m. gastrocnemius medialis afterwards increases during the weight acceptance, whereby higher values are present for people with lower weekly running mileage and is then reduced during the late stance. The less reduction occurs the more propulsion can be generated, which speaks for a higher running experience (Baur et al., 2012).

6.4. Bland & Altman analysis

The Bland & Altman analysis for the hip joint showed a systematic bias, with generally higher mean difference values for treadmill running between treadmill and overground running and significant p-values of the one sample t-test throughout the whole stance phase. From this point of view it will not be possible to use the two methods interchangeably for analysing the hip joint. Or alternatively the systematic bias can be used in order to conduct comparisons of the hip joint when using the two different running modalities.

The knee joint depicts varying discrepancies from the mean at the different points in time. Therefore it is difficult to assess kinematic differences of the knee joint by using the Bland and Altman analysis. It would probably be acceptable to use the whole kinematic curve at stance or at stride cycle instead of at specific points in time when the knee joint angle is the research question.

For the ankle joint the situation is different. The agreement between the methods is big and no systematic bias at the mean differences is visible. Furthermore, Buczek and Cavanagh (1990) quoted a general range for the ankle joint at the first ground contact mentioned in former literature from 6° plantarflexion to 13° dorsiflexion, which equals a range of 19°. The limit of agreement for the ankle joint between the two running modalities at the first ground contact has a range of 16.7° and lies within the remarked 19° from Buczek and Cavanagh (1990).

6.5. Quality of the results

The study was conducted with great care and before implementation a lot of literature research was conducted in order to avoid as much research bias as possible.

The number of subjects tested was reasonable and the cohort was homogenous according to their running experience. No professional runners joined the study, but all of them regularly participated in some running activity and it was not their first time running on a treadmill. The subjects had the recommended familiarization time according to different literature sources (Lavcanska et al., 2005; Matsas et al, 2000) a priori recording the data of the treadmill running, therefore noticeable differences cannot be blamed on temporal adaptations to the treadmill running condition. The marker placement was sufficient to generate the information needed to determine the ankle, knee and hip joint during the running movement.

Nevertheless, there were some limitations to the study, which could be improved for further investigations.

6.5.1. Limitations to the study

As mentioned in the theory part, a problem different authors already mentioned (Fellin et al., 2010; Schache et al., 2001; Sinclair et al., 2013) was to determine the exact stance time, when the treadmill has no integrated force platform. Because a separation of the swing and stance phase based on kinematic data is remarked in literature as error-prone (Sinclair et al., 2013) for this investigation the problem was tried to be solved by using the Pedar® System. Unfortunately, this system created other limitations. The Pedar® System could only record data with a maximal frequency of 100 Hz, in comparison the Vicon®- System recorded 250 frames per second, which led to the inevitable loss of precision. Furthermore, the recorded data from the Pedar® System showed lots of bias, like pressure values during time intervals, when ground contact in these frames was impossible. As aforementioned to avoid the bias the stance time was determined by analysing the visual data. Therefore, the analysis was subject dependent and misinterpretations could not be excluded.

In addition, the belt speed of the treadmill used in the study was not controlled during the running trials, which leads to the uncertainty whether there are variations in the treadmill velocity or not. According to Wank et al.(1998) it is possible, that differences in the kinematic and electromyography can be led back to variations of the belt velocity. For example, an acceleration of the speed during the push off, could explain a more forward leaning of the trunk (Wank et al., 1998). But this systematic bias was evident in all subjects and we assumed that a possible negative effect would have the same magnitude in all trials. Nevertheless, for further investigations it would be useful to test the belt speed during the running trials in order to be able to exclude cases that strongly deviate from the average speed.

Furthermore, the comparability of the overground running trials of the individual subjects was affected by different circumstances. One is specific to the laboratory, the relative short runway, with a length of approximately 13m. Riley et al. (2008) noticed in their study, that with a runway of this length it is impossible to be certain, that the parameters are measured in steady-state conditions, whereas a steady-state situation can be assumed for treadmill running. However, the laboratories from key papers like Riley et al. (2008) (15m) and Fellin et al. (2010) (25m) as well as recent publications Willy et al. (2016) (25m) also have short runways. The other aspect is specific to overground running itself, there are always slight variations in the velocity of the different trials (Riley et al., 2008). To reach a maximumuniformity the subjects had to perform practice runs on the indoor runway as long as the running was constant with no visual acceleration or deceleration in the measuring segment and the running velocity was in the accepted range a couple of times in a row.

Moreover, the cohort was asked to wear their own running shoes, which varied in style and condition. As often analysed in literature the running shoes can affect the running style (Bates, Osternig, Sawhill, & James, 1983; Murley, Landorf, Menz, & Bird, 2009; Nigg et al., 1995; Stacoff et al., 2001). In further research uniform running shoes would be preferable to reach a higher homogeneity.

7. Conclusion

This study was conducted to compare the lower leg kinematics as well as the muscular differences of four muscles of the lower extremity between overground and treadmill running. Significant differences were found both for the kinematics and muscular activity. Therefore, the use of the treadmill for clinical and research setups in terms of its ability to imitate the kinematics and muscular activity of the stance phase should be used with caution.

The innovative of this study is the segment wise separation of the stance phase into eleven points in time, thus new information about the exact time when significant differences occur can be obtained. So far most of the time the analysed parameters are limited to the foot strike, toe-off, peak values and sometimes range of motion.

Furthermore, the Bland & Altman analysis pointed out, that the kinematics of the ankle joint has a high agreement between the running modalities and it can be assumed, that the two running modalities can be used interchangeably. This assertion is not applicable for the hip and knee joint kinematic and an interchangeable use must be clarified with the specific research question.

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9. Appendix

9.1. List of tables

TABLE 1: SENSOR PLACEMENT RECOMMENDED BY THE SENIAM-PROTOCOL (PROJECT MANAGEMENT GROUP (2016, 19. DECEMBER). RECOMMENDATIONS FOR SENSOR LOCATIONS ON INDIVIDUAL MUSCLES. ACCESSED ON 19. DECEMBER 2016 UNDER HTTP://WWW.SENIAM.ORG/) 24
TABLE 2: ANTHROPOMETRIC DATA OF THE COHORT (N=14) 29
TABLE 3: RUNNING VELOCITIES FOR OVERGROUND AND TREADMILL RUNNING 49
TABLE 4: STANCE TIME IN SECONDS FOR ALL TRIALS IN OVERGROUND AND TREADMILL RUNNING........ 49
TABLE 5: TREADMILL VS. OVERGROUND RUNNING FOR THE HIP JOINT KINEMATIC FOR THE SAGITTAL PLANE (FLEXION AND EXTENSION); ANGLES ARE MEASURED IN DEGREES; STANDARD DEVIATION (SD) 50
TABLE 6: TREADMILL VS. OVERGROUND RUNNING FOR THE KNEE JOINT KINEMATIC FOR THE SAGITTAL PLANE (EXTENSION AND FLEXION); ANGLES ARE MEASURED IN DEGREES; STANDARD DEVIATION (SD) 51
TABLE 7: TREADMILL VS. OVERGROUND RUNNING FOR THE ANKLE JOINT KINEMATIC FOR THE SAGITTAL PLANE (PLANTARFLEXION AND DORSIFLEXION); ANGLES ARE MEASURED IN DEGREES; STANDARD DEVIATION (SD) 53
TABLE 8: TREADMILL VS. OVERGROUND RUNNING FOR THE MUSCULAR ACTIVITY OF M. VASTUS LATERALIS; MAGNITUDE NORMALIZED TO MAXIMAL REACHED ACTIVITY (IN PERCENT); STANDARD DEVIATION (SD) 55
TABLE 9: TREADMILL VS. OVERGROUND RUNNING FOR THE MUSCULAR ACTIVITY OF M. BICEPS FEMORIS; MAGNITUDE NORMALIZED TO MAXIMAL REACHED ACTIVITY (IN PERCENT); STANDARD DEVIATION (SD) 56
TABLE 10: TREADMILL VS. OVERGROUND RUNNING FOR THE MUSCULAR ACTIVITY OF M. TIBIALIS ANTERIOR; MAGNITUDE NORMALIZED TO MAXIMAL REACHED ACTIVITY (IN PERCENT); STANDARD DEVIATION (SD) 58
TABLE 11: TREADMILL VS. OVERGROUND RUNNING FOR THE MUSCULAR ACTIVITY OF M. GASTROCNEMIUS MEDIALIS; MAGNITUDE NORMALIZED TO MAXIMAL REACHED ACTIVITY (IN PERCENT); STANDARD DEVIATION (SD) 59
TABLE 12: BLAND-ALTMAN-ANALYSIS OF THE HIP JOINT; MEAN DIFFERENCE BETWEEN THE TWO RUNNING MODALITIES (MD) INCLUDING THE STANDARD DEVIATION (SD); LOWER AND UPPER LIMITS OF AGREEMENT REPRESENTING ±1.96 SD (LOA); P-VALUE OF ONE SAMPLE T-TEST; ALL RESULTS ARE PRESENTED IN DEGREES 61
TABLE 13: BLAND-ALTMAN-ANALYSIS OF THE KNEE JOINT; MEAN DIFFERENCE BETWEEN THE TWO RUNNING MODALITIES (MD) INCLUDING THE STANDARD DEVIATION (SD); LOWER AND UPPER LIMITS OF AGREEMENT REPRESENTING ±1.96 SD (LOA); P-VALUE OF ONE SAMPLE T-TEST; ALL RESULTS ARE PRESENTED IN DEGREES 62
TABLE 14: BLAND-ALTMAN-ANALYSIS OF THE ANKLE JOINT; MEAN DIFFERENCE BETWEEN THE TWO RUNNING MODALITIES (MD) INCLUDING THE STANDARD DEVIATION (SD); LOWER AND UPPER LIMITS OF AGREEMENT REPRESENTING ±1.96 SD (LOA); P-VALUE OF ONE SAMPLE T-TEST; ALL RESULTS ARE PRESENTED IN DEGREES 63

9.2. List of figures

Figure 1: Running gait cycle divided into the four phases (ed. by Neumann et al., 2010, p. 56) 5
Figure 2: Duration of the muscle activity and knee angle (black line)- time gradient (ISt … Initial Stance, TSt …Terminal Stance, TSw …Terminal Swing, ISw … Initial Swing) (ed. by (Neumann et al., 2010, p. 60)) 7
Figure 3: Step length, step width and stride length (ed. by Marquardt, 2012, p. 72) 8
Figure 4: Systolic blood pressure measured by observer and machine (Bland & Altman, 1999) 16
Figure 5: Systolic blood pressure: differences observer (J) – machine (S) against average (Bland & Altman, 1999). 16
Figure 6: Systolic blood pressure: differences observer (J) – machine (S) against mean with 95% limits of agreement (Bland and Altman, 1999) 17
Figure 7: Laboratory with Set Up for the Vicon® motion tracking system 22
Figure 8: Four segment marker placement on a subject 23
Figure 9: right: TrignoTM Wireless System from Delsys® left: Delsys® Sensor 24
Figure 10: Treadmill Cardiostrong TX 50 27
Figure 11: Sketch of laboratory with set up for the Vicon®-System and the light barriers 27
Figure 12: Laboratory the Vicon®-System and the light barriers 28
Figure 13: Subject preparation (EMG sensors, Markers, Pedar®-x system) 31
Figure 14: Working place with Vicon® Software 2.5 and Pedar® software 33
Figure 15: Hip movement in overground running – 3 trials of the same subject 36
Figure 16: Hip movement in treadmill running – 3 trials of the same subject 36
Figure 17: Hip joint movement - overground running (OG) vs. treadmill running (TM) 37
Figure 18: Hip movement in overground running – 3 trials of the same subject 38
Figure 19: Hip movement in treadmill running – 3 trials of the same subject 38
Figure 20: Knee joint movement - overground running (OG) vs. treadmill running (TM) 39
Figure 21: Ankle movement in overground running – 3 trials of the same subject 40
Figure 22: Ankle movement in treadmill running – 3 trials of the same subject 40
Figure 23: Knee joint movement - overground running (OG) vs. treadmill running (TM) 41
Figure 24: RMS of Sensor 1 (m. vastus lateralis), Sensor 2 (m. biceps femoris), Sensor 3 (m. tibialis anterior), Sensor 4 (m. gastrocnemius medialis) of overground running (OG). 42
Figure 25: RMS of Sensor 1 (m. vastus lateralis), Sensor 2 (m. biceps femoris), Sensor 3 (m. tibialis anterior), Sensor 4 (m. gastrocnemius medialis) of treadmill running (TM). 42
Figure 26: Muscular activity of m. vastus lateralis in overground (left) treadmill (right) running – 3 trials of the same subject 43
Figure 27: Muscular activity of m. vastus lateralis - overground running (OG) vs. treadmill running (TM) 44
Figure 28: Muscular activity of m. biceps femoris in overground (left) treadmill (right) running – 3 trials of the same subject 45
Figure 29: Muscular activity of m. vastus lateralis - overground running (OG) vs. treadmill running (TM) 45
Figure 30: Muscular activity of m. tibialis anterior in overground (left) treadmill (right) running – 3 trials of the same subject 46
Figure 31: Muscular activity of m. tibialis anterior - overground running (OG) vs. treadmill running (TM) 46
Figure 32: Muscular activity of m. gastrocnemius medialis (med.) in overground (left) treadmill (right) running – 3 trials of the same subject 47
Figure 33: Muscular activity of m. gastrocnemius medialis - overground running (OG) vs. treadmill running (TM) 48
Figure 34: Averaged hip joint movement with standard deviation - overground running (OG) vs. treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **) 51
Figure 35: Averaged knee joint movement with standard deviation - overground running (OG) vs. treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **) 52
Figure 36: Averaged ankle joint movement with standard deviation - overground running (OG) vs. treadmill running (TM) 54

Figure 37: Averaged muscular activation of m. vastus lateralis with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)........ 56
Figure 38: Averaged muscular activity of m. biceps femoris with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)57
Figure 39: Averaged muscular activation of m. tibialis anterior with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **)........ 59
Figure 40: Averaged muscular activation of m. gastrocnemius medialis with the standard deviation in overground running (OG) and treadmill running (TM), significant differences are marked with asterisks (p<0.05 *; p<0.01 **) 60
Figure 41: Bland-Altman-Plot from 10%, 30% & 70% of the stance time for the knee joint; mean of the differences (black horizontal line), upper and lower level of Agreement (dotted lines) 62
Figure 42: Bland-Altman-Plot from 0%, 10%, 40%-100% of the stance time for the ankle joint; mean of the differences (black horizontal line), upper and lower level of Agreement (dotted lines) 65

10. Declaration

I herewith declare that I have produced this paper without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This paper has not previously been presented in identical or similar form to any other German or foreign examination board.

Vienna, May 16, 2017