TECHNISCHE UNIVERSITÄT WIEN

DIPLOMA THESIS

Foot Kinematics in Healthy Adults using the Oxford Foot Model

A comparison of overground and treadmill walking at different speeds

carried out for the purpose of obtaining the degree of Diplomingenieur

submitted at TU Wien,
Faculty of Mechanical and Industrial Engineering, by

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Vienna, February the 20th, 2019

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Place, Date

Signature

Acknowledgements

This thesis has benefited greatly from the support of many people, some of whom I would sincerely like to thank here.

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"All truly great thoughts are conceived while walking."

Friedrich Nietzsche

Die aus einer Ganganalyse gewonnen Daten dienen für die Diagnostik, zur Operationsvorbereitung und zum prä- und postoperativen Vergleich. Patienten werden hierbei meistens aufgefordert in einer Ganggeschwindigkeit auf und ab zu gehen, die für sie normal ist, um zu verhindern, dass eine für sie unnatürliche Ganggeschwindigkeit ein unnatürliches Gangbild hervorruft. Die selbst gewählte Geschwindigkeit variiert jedoch von Patient zu Patient. Daher ist es Ziel dieser Studie, herauszufinden, inwieweit die Geschwindigkeit einen Einfluss auf die Gelenkswinkel des Fußes hat. Des Weiteren soll ermittelt werden, ob Gehen auf dem Laufband, das gerne zur Rehabilitation genutzt wird, mit Gehen auf der Ebene vergleichbar ist. Im Zuge dieser Studie wurden insgesamt 23 Probanden mit dem Oxford Foot Model auf der Ebene und auf dem Laufband in jeweils drei verschiedenen Ganggeschwindigkeiten (normal, langsam, schnell) mittels 3D Bewegungsanalyse vermessen. Die gesammelten Daten wurden einerseits nach der vom Probanden selbst gewählten Ganggeschwindigkeit, anderseits nach einer dimensionslosen Geschwindigkeit (siehe Schwartz et al., 2008) gruppiert und statistisch ausgewertet. Die Ergebnisse zeigen, dass eine Gruppierung nach Schwartz et al. (2008) auf Grund eines geringeren Streuungsbereiches homogenere Ergebnisse erbringt. Hier können Unterschiede in Kadenz und Schrittbreite zwischen Gehen auf der Ebene und Gehen am Laufband entdeckt werden. Weiters sind vor allem die Winkel zwischen Vorfuß und Tibia in Frontalebene und zwischen Rückfuß und Tibia in Sagittalebene von dieser Kondition abhängig. Bezüglich Ganggeschwindigkeit wurden statisch signifikante Unterschiede in Tibia, Rückfuß, Vorfuß und Hallux beobachtet. Um mögliche Fehldiagnosen zu verhindern, sollte daher zwischen Gehen am Laufband und Gehen auf einer Ebene unterschieden werden und die Ganggeschwindigkeit in die Auswertung der Ganganalyse mit einbezogen werden.

Schlagwörter: Ganganalyse, Oxford Foot Model, Laufband, Ganggeschwindigkeit

Abstract

Data obtained from gait analysis are used for diagnostic analysis, operational preparations and pre- and postsurgical comparisons. Patients are asked to walk at a self-selected speed to achieve a harmonic and natural walking pattern. The aim of the study is to figure out whether and to what extent walking speed has an effect on the joint angles of the foot. Further, it should be determined if gait patterns vary significantly between walking on the treadmill to those overground as the treadmill is popular in rehabilitation. Therefore, a 3D gait analysis with 23 subjects was conducted. The measurements were executed by using the Oxford Foot Model. The subjects walked at three different self-selected speeds (normal, slow, fast) along a walkway and on the treadmill. The data was clustered according to self-selected speed and according to Schwartz et al. (2008), who used a dimensionless velocity for classification. The results show that clustering according to Schwartz et al. (2008) leads to a lower dispersion range. Here walking condition (overground vs. treadmill) has an impact on cadence and step width as well as on motion between forefoot and tibia in frontal plane and the motion between hindfoot and tibia in sagittal plane. Concerning the influence of walking speed, similar results were obtained for both conditions as tibia, forefoot, hindfoot and hallux are affected while walking overground and while walking on the treadmill. In order to prevent misdiagnosis, the effect of walking condition and walking speed on spatiotemporal parameters and joint angles of the foot should be included in the evaluation of gait analysis.

Keywords: gait analysis, Oxford Foot Model, treadmill, walking speed

Table of Contents

1. Introduction

On average a person takes about 5,000 to 15,000 steps per day. Hence, within a year the number of steps increases to 2-5 million. Converting steps into a length scale, an average person walks about 27,000 km per year, which covers the circumference of the earth (Kirtley, 2006). No wonder that the idea of gait analysis arose in history.

The first ever gait analysis report was mentioned at the Edwin Smith Surgical Papyrus – a piece of history of the 17th century BC. It said:

> *"If thou examinest a man having a smash of his skull,… while his eye is askew because of it, on the side of him having that injury which is in his skull [and] he walks shuffling with his sole… with his sole dragging, so that it is not easy for him to walk, when it [the sole] is feeble and turned over, while the tips of his toes are contracted to the ball of his sole, and they [the toes] walk fumbling the ground."*

From then on more and more references about the history of gait analysis can be found. Aristotle was the first comparing the human gait with the gait of animals. In the 1870s the engineers Braune and Fischer and the Weber brothers analysed gait motivated by war as they wanted to make marching more efficient. In the 19^{th} century when photography was invented the first motion pictures were captured. Further, the Frenchman Etienne-Jules Marey and the American Dudley Morton built the first device with which the forces under the foot could be measured. The measurement of joint forces was first conducted by John Paul in Glasgow in the 1960s. Already 20 years later companies like Vicon (Vicon Motion System Ltd., Oxford, UK) and Codamotion (Charnwood Dynamicy Ltd., Rothley, UK) were founded. First gait analyses focused on poliomyelitis and spina bifida, but then the centre of attention moved to cerebral palsy and its treatment. Nowadays, the technology of motion capturing is not only used in a medical sense, but also in game industry for visualisation and animation (Kirtley, 2006).

To go back to the usage of motion capturing in medical sense, 500-600 3D gait analysis are conducted per year at the Laboratory for Gait and Human Motion Analysis of the Orthopaedic Hospital Speising (Vienna, Austria) according to in-house statistics. The gathered data is needed for diagnostic analysis, operational preparations and pre- and postsurgical comparisons. About one third of the patients are measured by using an additional foot model. In all cases, the patients are asked to walk at self-selected speed along a walkway, because a predefined walking speed would influence the gait patterns (Bertram & Ruina, 2001). As the self-selected speed is not equal between patients, it is important to know if and in as far this parameter has influence on the results. Further, interest revived concerning possible differences in walking overground and walking on a treadmill, as after Kirtley (2006) it is quite common to use a treadmill to improve walking skills in rehabilitation.

As this thesis focuses on the angles of the foot, it must be clarified how a foot can be represented in gait analysis as literature proposes different methods. One main reason is that there is no standard on how to measure a foot's dynamic in vivo because of its complex structure. The simplest form would be a single rigid segment, which is able to perform dorsi- and plantar flexion (Carson et al., 2001); however, nowadays it is most common to partition the foot into three segments (Saraswat et al., 2012), as more exact ankle propulsion power is gained by a multi-foot model and as it gives information about midfoot kinetics (Dixon et al, 2012). Further differences between one- and multisegment foot models were observed by Pothrat et al. (2015). Although different models segment the foot into the same parts, they are not comparable as authors use different marker positions and as anatomical axes vary (Leardini et al., 1999). For that reason, Carson et al. (2001) wanted to develop a multisegment foot model, which should be applicable to clinical daily life and further enable a comparison between studies. The Oxford Foot Model was introduced. As the reliability of this three-segment model in adults and children was not only determined by Carson et al. (2001) themselves, but also by Curtis (2009) and Wrigth (2011) in adults and children, the model becomes increasingly important in gait analysis.

As mentioned before, results yielded from gait analysis depend on the model used as well as on the present condition. Concerning the comparison between walking overground and walking on a treadmill studies focus on spatiotemporal gait parameters and stability (Hollman et al., 2016) (Yang & King, 2016). Nevertheless, no paper has been published yet, which analyses the differences in gait patterns initiated on a treadmill and overground by means of the Oxford Foot Model. Regarding the effect of walking speed on foot and ankle kinematics van Hoeve et al. (2017) must be highlighted particularly. Apart of the impact of age on kinematics, they focus on the influence of walking speed on kinematics using the Oxford Foot Model. Dubbeldam et al. (2010) also dealt with the effects of walking speed on forefoot, hindfoot and ankle joint motion; however, they used the Heidelberg Foot Model.

1.1. Aim of the Study

Due to the fact that there is interest in foot kinematics while walking in clinical respect, the aim of the study conducted was to collect spatiotemporal gait parameters as well as kinematic and kinetic data of healthy adults using the Oxford Foot Model in order to observe the possible influence of walking condition (overground vs. treadmill) and speed on gait, in particular on the joint angles of the foot.

Following research questions and their corresponding hypotheses served as guideline for this study:

Research question 1
Can any differences in foot angles and spatiotemporal parameters be observed during walking overground and walking on a treadmill?

> Hypothesis 1
> The null hypothesis states that there is no difference neither in foot angles nor in spatiotemporal parameters regarding the walking condition.

Research question 2

How do the foot kinematics and spatiotemporal parameters change with increasing walking speed?

Hypotheses 2

With respect to the null hypotheses, no change in foot kinematics and spatiotemporal parameters due to increasing walking speed is expected.

2. Present Literature (State of the Art)

The main literature research for this thesis took place in July 2018; however, during the whole project time new publications concerning the Oxford Foot Model (OFM) and gait analyses dealing with different walking speeds and the comparison between walking overground and walking on the treadmill were kept in view. Most literature was retrieved from the databases Science Direct (www.sciencedirect.com), Google Scholar (scholar.google.com) and PubMed (https://www.ncbi.nlm.nih.gov/pubmed/). Amongst others primary following keywords in different combinations were used in order to find already conducted studies focusing on a similar problem:

- Oxford Foot Model
- OFM
- OFM healthy
- Gait Treadmill
- Overground Treadmill Walk
- Walking speed
- Gait Cycle

The so found literature was used to compare results. Further, statistics about the motives to conduct a gait analysis were looked up. Keywords like "rmANOVA" or "repeated measurement ANOVA" were used to get recommendations for the statistic evaluation of the gained results. Literature research was conducted in English as well as in the German language in order to find as many appropriate studies as possible. Furthermore, research was expanded by looking at the list of references of the already found papers and books used for university and personal interest provided information especially about anatomical explanation. The results of the literature research are presented below.

According to Whittle (1993) *"gait analysis is the systematic examination of the way in which a person walks"*. Normal walk is achieved through the movement of legs, trunk and arms, whereby the most important movements are those of the hip, knee and ankle. In clinical applications gait analyses are a tool for diagnosis, decision-making and documentation. In a diagnostic sense, it is, for instance, important to know the cause of a gait abnormality in order to find the right treatment instead of impair gait patterns. It helps to plan physiotherapy or for example, in multiple joint diseases it shows which joint should be operated first. Furthermore, it is needed for the alignment and adjustment of prosthesis and orthosis. By means of documentation, changes which take place over time can be measured and improvements over possible maltreatment can be detected (Whittle, 1993).

2.2. Anatomical terminology

Before describing the anatomical structure of the human foot, the relevant terminology must first be clarified. Therefore, the anatomical standard position is used. In this position the human stands upright and palms face to the front (Zalpour, 2016).

As shown in Figure 1 the motions of the human body can be described by using three main planes and their associated axes. These axes are perpendicular to each other and indicate the spatial coordinates (Faller & Schünke, 2016). The sagittal plane splits the body into a left and a right side and is spanned by the sagittal and the longitudinal axis (Zalpour, 2016), whereby the longitudinal axis is vertical to the floor. The sagittal axis runs from the back to the front of the body and is aligned vertical to the longitudinal axis (Faller & Schünke, 2016). The second plane is the frontal plane. It divides the body into a front and a back side as it is aligned parallel to the forehead (Zalpour, 2016). The frontal plane is defined by the longitudinal and horizontal axis. The horiztonal axis passes the body from left to right and is aligned vertically to the longitudinal axis. The transversal plane, which is spanned by the horizontal and sagittal axis, cuts the body into an upper and lower half (Faller & Schünke, 2016).

In order to define the location and orientation of parts of the human body further terms are needed. The position along the longitudinal axis is described with the terms cranial/superior or caudal/inferior, which indicates a position up, closer to the skull, or down, away from the skull. The positions along the sagittal axis can be characterised as anterior (pointing to the front) or posterior (pointing to the back). Concerning the transversal plane, positions closer to the body's centre are called medial, whereas positions more distant are named lateral. Central positions are closer to the inside of the body, while peripheral positions belong to areas nearby the surface (Faller & Schünke, 2016).

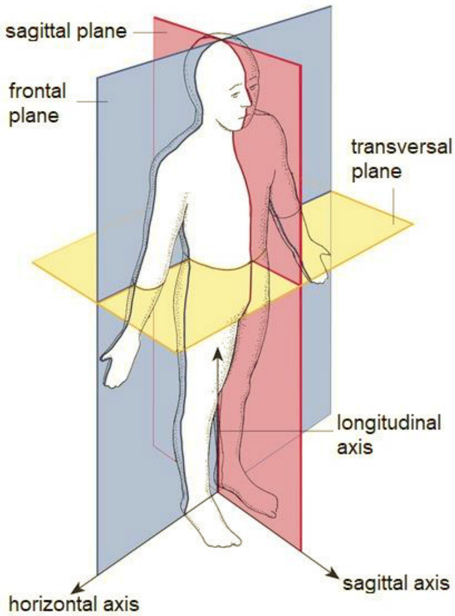

Figure 1: Main axes and planes of the human body; Adapted from: Zalpour (2016)

Furthermore, locations along the extremities can be described as proximal (closer to the body's core) or distal (nearer to the end of the extremity). Concerning the lower extremities, positions closer to the tibia are called tibial, while those nearer to the fibula are fibular. Plantar locations are closer to the sole, whereas the word dorsal describes positions facing towards the back of the foot (Faller & Schünke, 2016).

2.3. Anatomical Structure of the Human Foot

The principal functions of the human foot are bearing body weight (Chan, 2013) and acting as a lever while walking (Cheers, 2007). The human foot differs from primates' one as humans never used their feet for grabbing and therefore, need it more for stability than for mobility (Chan, 2013). The following subchapters give information about the bones of the human foot, which are partitioned into three groups – the tarsal bones, the metatarsals and the phalanges (Figure 2). Further, associated joints and ligaments are mentioned and muscles and tendons of the foot as well as its arches are described.

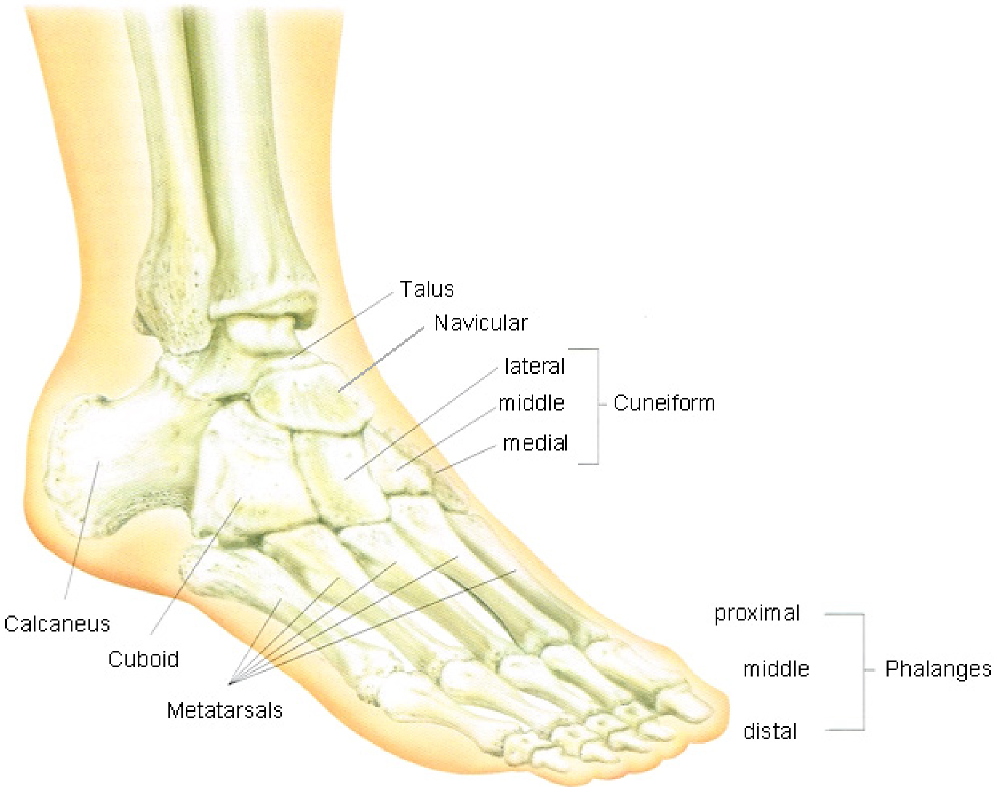

Figure 2: Bones of the foot; Adapted from: Cheers (2007)

2.3.1. The Tarsal Bones and their Joints and Ligaments

The tarsal bones are the most proximal bones of the human foot (Chan, 2013), which are connected by the ankle with the lower leg. The ankle itself is stabilised on the medial side by the ligamentum deltoideum and on the lateral side by three small ligaments. As these ligaments are much weaker than the ligamentum deltoideum, it is more common that ruptures occur there. Further ligaments between the fibula and tibia strengthen the ankle against instabilities (Cheers, 2007). In total there are seven tarsal bones – the talus, the calcaneus, the navicular, the cuboid and the three cuneiform. As shown in Figure 2 the talus is the most proximal tarsal bone and therefore bears the whole weight of the body (Chan, 2013). The talus lies in a articular cavity made by tibia and fibula (Figure 3) and forms a joint with these two bones – the talocrural joint (Cheers, 2007). The axis of this joint is presented in Figure 4.

The talus is divided into a body and a head separated by a short neck. The two large articular surfaces on the body's surface articulate with the tibia and with the calcaneus. Further, there is a groove in the body for the tendon of the flexor hallucis longus. The head of the talus has a large articular surface, which articulates with the posterior part of the navicular, the calcaneus and the sustentaculum tali, which is the protrusion of the cuboid. The calcaneonavicular ligament is situated between the navicular and the calcaneal surfaces of the talar head and closes the gap between the calcaneus and navicular (Chan, 2013).

The largest tarsal bone is the calcaneus and the only one, which establishes a connection to the ground. Hence, on the one hand body weight is transferred trough the calcaneus to the ground; on the other hand it is transmitted through tarsal bones to the metatarsals to the ground. Besides the talus, the calcaneus also articulates with the cuboid, which is positioned anterior to it. The upper surface of the sustentaculum tali supports the talus partly. The talocalcaneonavicular joint, which is a ball and socket synovial joint, articulates between the talar head, the navicular and the calcaneal body. This joint is also called Chopart's joint (Figure 4). A further joint is formed by the talus and the calcaneus, which is called the subtalar joint. The subtalar joint forms the talotarsal joint together with the talocalcaneonavicular joint. The talus and the calcaneus are connected by the talocalcaneal interosseous ligament and the cervicis tali ligament. The calcaneal tendon (Achilles tendon) is received by the posterior surface of the calcaneal tuberosity. The longer plantar ligament attaches to the calcaneal tubercle (Chan, 2013).

The navicular is covered by articular cartilage at its posterior and anterior surface, where it is connected to the head of the talus and to the three cuneiform bones. The calcaneonavicular ligament comes from the sustentaculum tali to the navicular, where the medial band of the bifurcate ligament is attached as well (Chan, 2013).

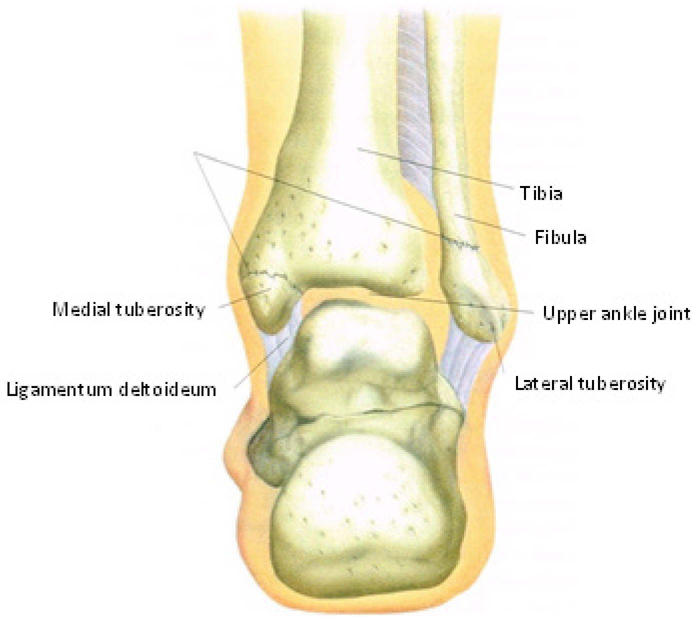

Figure 3: Ankle joint; Adapted from: Cheers (2007)

The cuboid forms with the calcaneus the calcaneocuboid joint, posteriorly. Anteriorly, it joins with the fourth and fifth metatarsals, whereas medially, it joins with the lateral cuneiform bone and the navicular. The calcaneocubiod joint is reinforced by the bifurcate ligament and the plantar ligaments (Chan, 2013).

The three cuneiform bones articulate with each other by synovial joints and ligaments. Furthermore, they join with the navicular, posteriorly, whereby they articulate with the first to the third metatarsal, anteriorly. The joints between cuneiform, calcaneus and the base of metatarsals are called tarsometatarsal joints (Figure 4). These are plane synovial joints, which do only allow minor motions. Further, they split the foot into forefoot and hindfoot (Chan, 2013).

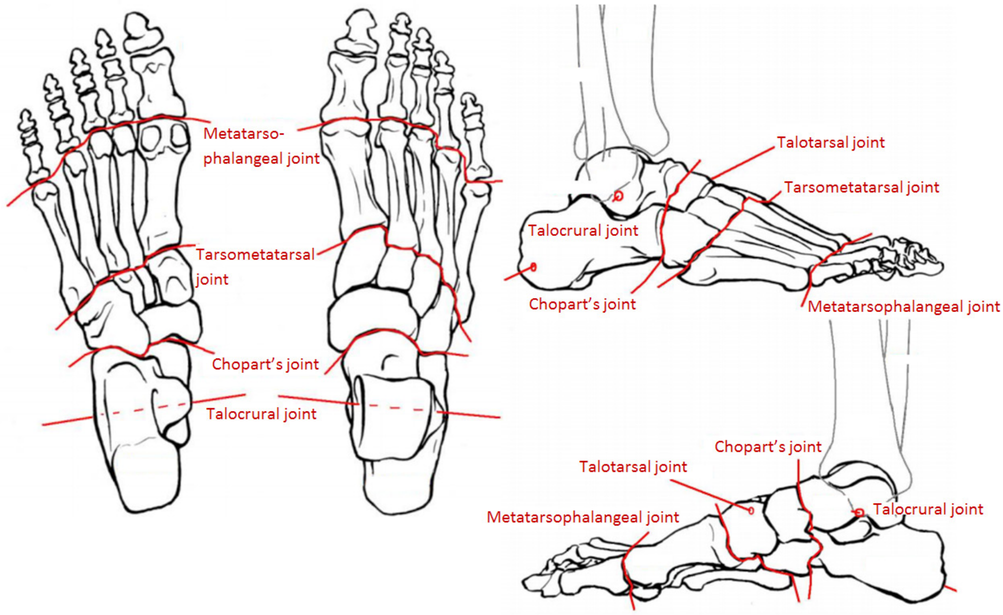

Figure 4: Bones of the foot and their joints. Major angular movement only occurs at the talocrural and talotarsal joint; Adapted from: Tittel (1990)

2.3.2. The Metatarsals and their Joints and Ligaments

The five metatarsals consist of a base, a shaft and a head each. The most medial metatarsal is the first, the most lateral one the fifth. The first to the third metatarsal articulates with the three cuneiform bones, whereas the fourth and the fifth form a joint with the cuboid. Furthermore, the bases of the metatarsals are connected with each other, except the first. On the tubercle of the fifth metatarsal the tendon of the musculus peroneus brevis attaches, whereas the tendon of musculus peroneus tertius is received by the superior surface of the fifth metatarsal (Chan, 2013).

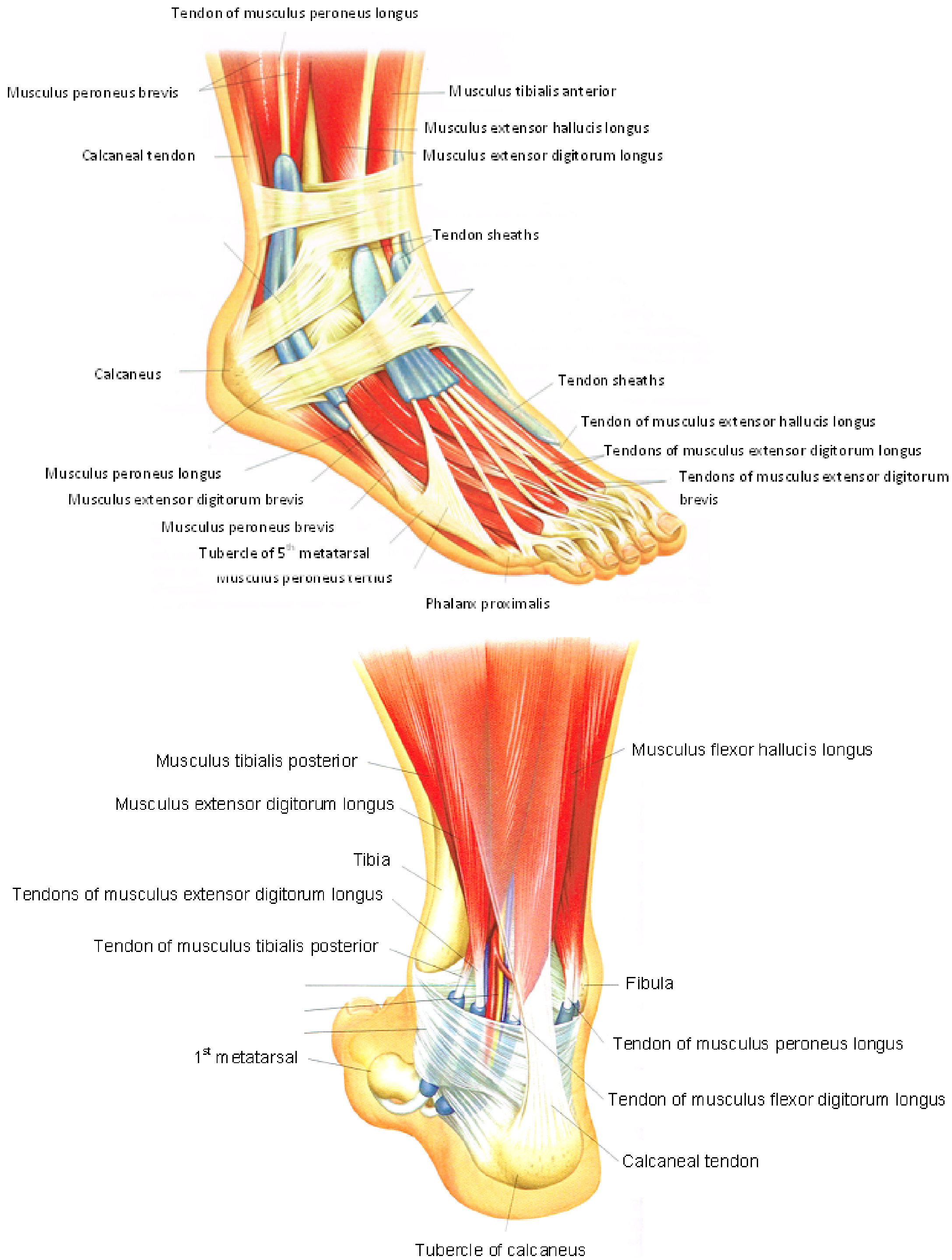

Figure 5: Muscles and tendons of the foot; Adapted from: Cheers (2007)

The head of each metatarsal articulates with their according phalanx. Further, they are connected by strong ligaments to each other. As the heads establish a connection to the ground, the metatarsals are weight-bearing (Chan, 2013).

2.3.3. The Phalanges and their Joints and Ligaments

All toes consist of three phalanges – a proximal, middle and distal one, excepting the hallux, where the middle phalanx is missing. The proximal bones form the metatarsophalangeal joints (Figure 4) with their according metatarsal. The joints are supported by collateral ligaments and the plantar ligament, which is further connected to the metatarsal ligament of each toe. The phalanges themselves are connected by hinge synovial joints – the interphalangeal joints – to each other (Chan, 2013).

2.3.4. Muscles and Tendons of the Foot

The extensor digitorum brevis (Figure 5) is the only muscle of the foot dorsum. This muscle covers the dorsum diagonally until it splits into four tendons, which stretch to the four medial toes. Further, its belly can be seen under the skin (Chan, 2013).

The sole of the human foot is divided into four layers. The first layer is the most superficial layer consisting of the abductor of the hallux, the short flexor of the lateral four toes and the abductor of the fifth toe. The abductor of the hallux forms the soft tissue of the medial side of the sole. Although, the plantar aponeurosis, a tough fibrous structure, is not part of this most superficial layer, it is connected to the muscles of this layer. It rises from the calcaneus, divides into five parts and finally attaches to each toe (Chan, 2013).

The tendons of two long flexors of the toes can be found in the second layer of the sole. The first muscle, which is to mention, is the flexor hallucis longus, which arises in the calf. Its tendon stretches from the sustentaculum tali to the hallux. The musculus flexor digitorum longus also arises from the calf and splits on its way through the sole into four parts. One part of the tendon of the flexor digitorum longus and one part of the flexor digitorum brevis attach to the lateral four toes each. The musculus quadratus plantae adheres on the tendon of the flexor digitorum longus. The whole muscle lies in the sole and functions as a flexor of the lateral four toes. Further, four lumbrical muscles attach on the flexor digitorum longus. These muscles are needed for the flexion of the metatarsophangeal joints for the extension of the interphalangeal joints (Chan, 2013).

The third layer consists of the musculus flexor hallucis brevis and musculus adductor hallucis, which are needed for the hallux. Further, the musculus flexor digit minimi brevis, which is needed for the fifth toe, is part of the third layer. The fourth layer contains the tendon of the musculus peroneus longus and the musculus tibialis posterios and two groups of small muscles. These two groups are formed by the four musculi interossei dorsales and the three musculi interossei plantares, which lay between the metatarsals (Chan, 2013).

All mentioned muscles and tendons are graphically presented in Figure 5.

2.3.5. The Arches of the Foot

As the bones of the foot do not lie horizontally they form arches (Figure 6), whereby the longitudinal arch lies in the sagittal plane and is lower on the lateral side than on the medial side. The medial part consists of the calcaneus, the talus, the navicular, the three cuneiforms and the medial three metatarsals. In healthy feet just the two ends of the arch touch the ground. However, the form of the arch is not given by the bones, but by the ligaments, tendons and muscle, especially by the plantar aponeurosis, spring ligament and the musculus tibialis anterior. Further, the tendon of the flexor hallucis longus is needed for dynamic stability.

The lateral longitudinal arch, which is represented by the line between B and C in Figure 5, is formed by the calcaneus, the cuboid and the two lateral metatarsals. As before, the shape is maintained by ligaments and muscles (Chan, 2013).

The transverse arch at the frontal plane is formed by the base of the five metatarsals, their cuneiforms and the cuboid. Like the longitudinal arch, the transverse arch is maintained by ligaments and muscles (Chan, 2013).

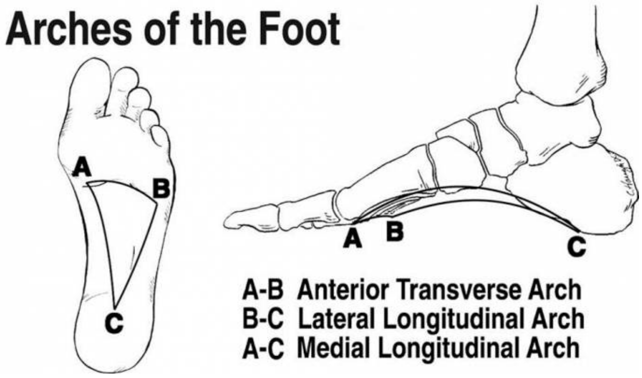

Figure 6: Schematic representation of the arches of the foot
Source: https://myphysiosa.com.au/foot-arch-pain-explained-adelaide-physiotherapist/,
Access: 29|01|20119

2.4. Possible Motions of the Foot

Major movements of the foot occur at the talocrural and talotarsal joints. In literature different approaches for the alignment of the associated axes exist (Debrunner, 1985) (von Lanz & Wachsmuth, 2003). For example, Debrunner (1985) defines an axis along the centre line, which runs from the centre of the heel and to the area between second and third toe (Figure 7). On the contrary, von Lanz & Wachsmuth (2003) lay their axis from the centre of the heel to the second toe, which leads to a difference from about 3°.

As shown in Figure 7 the axis of the talocrural joint cuts the Y axis in transversal plane at an angle of 86°, whereas the Z axis is crossed at an angle of 82°. The axis of the talotarsal joint experiences a rotation of 23° to the medial side of the foot and cuts the Y axis in sagittal plane at an angle of 42°. These values are only mean values and vary between humans (Debrunner, 1985).

The talocrural joint is needed to move the foot towards sole or to stand on tip toe. The anatomical name for this movement is plantarflexion and is conducted by muscles of the front of the shank. The opposite of plantarflexion is dorsiflexion, which occurs when toes are pulled towards tibia or while standing on heels by using the muscles of the back of the shank (Cheers, 2007). These movements are performed about the X axis presented in Figure 7 (Debrunner, 1985). A lateral movement of the foot is called eversion, whereas a medial movement is described as inversion (Cheers, 2007). Abduction and adductions are movements around the Y axis. A combination of dorsiflexion, eversion and abduction is called pronation, whereas supination is a mix of plantar flexion, inversion and adduction (Hunt et al., 2001). All movements are schematically demonstrated in Figure 8.

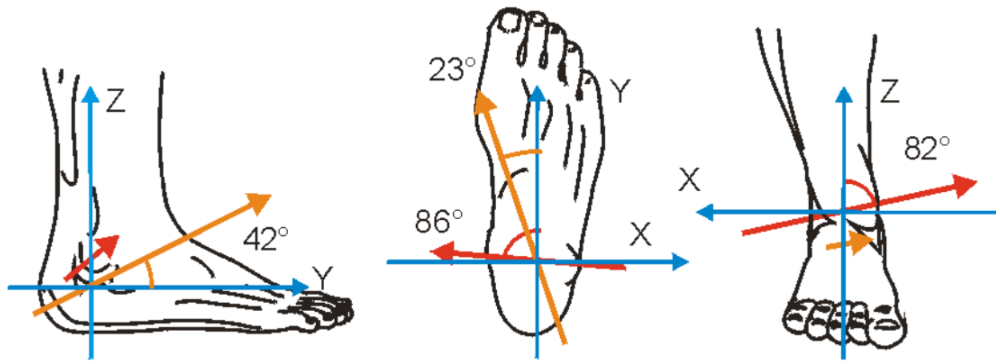

Figure 7: Alignment of axes of the talocrural (red) and talotarsal (orange) joints. The blue lines represent the clinical coordination system; X: Plantarflexion/Dorsiflexion; Y: Adduktion/Abduktion; Z: Inversion/Eversion; Adapted from: Debrunner (1985)

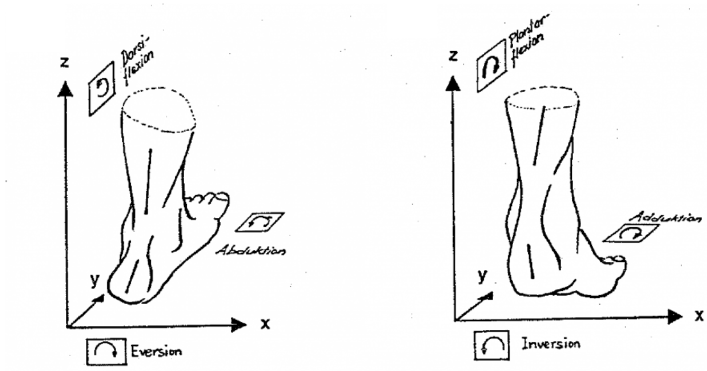

Figure 8: Possible motions of the foot;
Source: http://wiki.ifs-tud.de/biomechanik/projekte/ss2012/langstrecke, Access: 11|10|2018

2.5. Gait Cycle Characteristics

According to Whittle (1991) a *"gait cycle is defined as the interval between two successive occurrences of the same event […]"*. Every event in the gait cycle can be chosen; however, most commonly initial contact is used as shown in Figure 9. A gait cycle can be divided into a stance phase and swing phase. The stance phase is initiated by the initial contact, followed by foot flat, mid stance and heel off. Its end is signaled by toe off. Then swing phase starts. It continues with the mid-swing phase and ends again with the initial contact. Stance phase can be split into phases of double support and single support (Figure 10). During double support both feet touch the ground, whereas during single support only one foot is on the floor. A gait cycle consits of two double support phases separated by a single support phase. A single support phase of one foot correlates with the swing phase of the other foot (Whittle, 1993).

In gait analysis it is important to distinguish between a step (initial contact of one foot to initial contact of second foot) and a stride (initial contact of one foot to initial contact of the same foot). Therefore, also the terms step length and stride length differ. While step length is defined as the distance one foot moves forward, stride length is the sum of two step lengths. The number of steps walked per minute is called cadence. Velocity can be calculated according to following equation:

$$velocity\ [{}^{m}/_{s}] = stride\ length\ [m]\ \cdot cadence \left[{}^{steps}/_{minute}\right]/120 \qquad (1)$$

The division by 120 is necessary as a stride consists of two steps and because a minute equals 60 seconds (Whittle, 1993). Parameters like cadence, stride length, stride time, single and double support time are called spatiotemporal gait parameters (Hollman et al., 2016).

Concerning foot kinematics during walking, more motion takes place at the hind- and forefoot than Chopart's joint. At initial contact eversion of the subtalar joint takes places. Chopart's joint experiences dorsiflexion during mid-stance phase.

The talonavicular joint, which is a part of the Chopart's joint, locks and in late stance phase the plantar fascia is tensed by metatarsophalangeal dorsiflexion. In this phase inversion of the subtalar joint locks the foot. Plantar flexion is necessary for a successfully push-off (Kirtley, 2006).

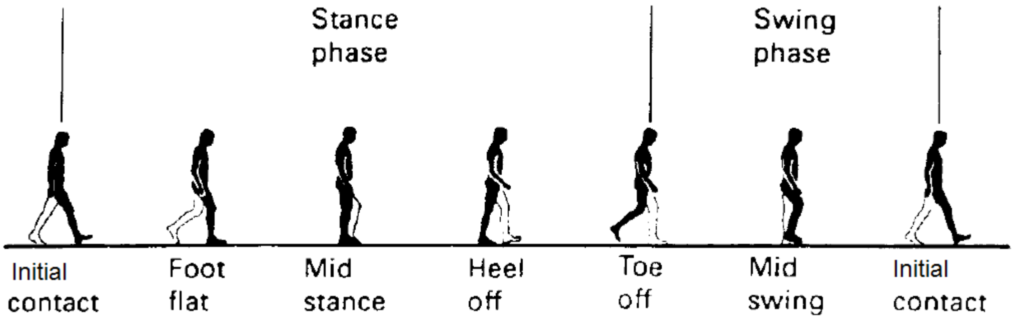

Figure 9: Single gait cycle from right inital contact to right initial contact; Adapted from: Whittle (1991)

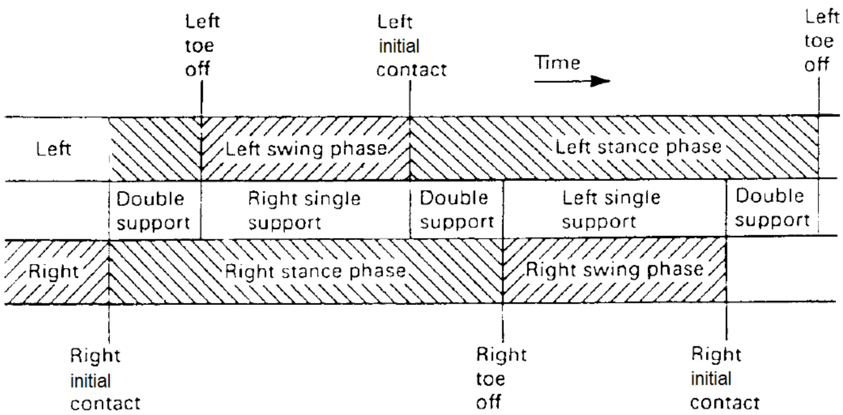

Figure 10: Single and double support during single gait cycle from right initial contact to right initial contact; Adapted from: Whittle (1991)

2.6. Foot Models

Three-dimensional multi-segmental foot models are used to analyse kinematics of the foot during gait. Although, aspects like segmentation, marker placement and anatomical coordination system differ between models (Nicholson, et al., 2018), all of them have one in common – the simplification of the complex anatomical structure of the foot (Carson et al., 2001).

In clinical gait laboratories most often skin mounted markers are used. Compared to intra-cortical pins, they are non-invasive and easier to use on a daily routine. However, the sort of foot model laboratories use vary and therefore, the obtained data is inconsistent and results are less easy to interpret. A comparison of five different models (duPont, Heidelberg, Oxford Child, Leardini and Utah), which can be applied simultaneously because of their corresponding marker sets and segmentation, showed that movement patterns differ little but offsets must be considered (Nicholson, et al., 2018).

2.6.1. The Oxford Foot Model

Carson et al. mentioned the Oxford Foot Model (OFM) for the first time in 2001. This model does not depend on x-ray information and consists of 14 non-invasive markers. More information about the marker placement is given in chapter 3.3.. The OFM divides the foot into hindfoot, forefoot and hallux. As the tibia is a further segment, the OFM is described as 3- or 4-segment foot model in literature (Carson et al., 2001) (van Hoeve et al., 2017). As shown in Figure 11 the tibia segment includes tibia and fibula. The hindfoot segment consists of calcaneus and talus, whereas the forefoot segment is the sum of all the five metatarsals. The hallux segment is formed by the hallux proximal phalanx. The reliability of the OFM in healthy adults was first tested by Carson et al. (2001). Further studies showed that this model is not only reliable during adult gait (Wright et al., 2011), but also in healthy children (Curtis et al., 2009).

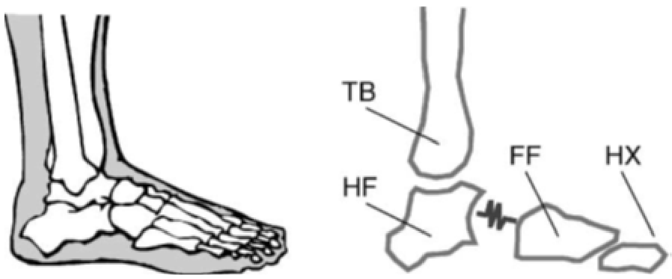

Figure 11: Segments of the OFM: TB - Tibia, HF - Hindfoot, FF - Forefoot, HX - Hallux; Source: Carson et al. (2001)

By means of the OFM, angles between the following four inter-segment pairs can be observed:

- Tibia to floor
- Hindfoot to tibia
- Forefoot to hindfoot
- Hallux to forefoot

In order to describe possible motions between these inter-segment pairs, Carson et al. (2001) introduced planes and their associated axes for each segment. These axes are presented in Figure 12. The sagittal plane of the tibia segment goes through the tuberosities of the tibia and has its midpoint between the markers ANK and ANM. The ANM marker is not shown in Figure 12, but is located at the medial distal end of malleoli (Carson et al., 2001).

For the hindfoot the sagittal plane lies in a line with the markers HEE and CPA and has its midpoint again between the malleolar markers as hwon in Figure 12. The transversal plane is laid parallel to the floor. Regarding the forefoot segment, the sagittal plane goes through the TOE and P1M marker. Its transversal plane is located in a line with the markers D1M, D5M and P5M (Carson et al., 2001)

The sagittal plane of the hallux segment is perpendicular to the floor and goes through the stick markers (HLXP, HLXD), whereas its transversal plane is parallel to the floor. These planes lead to mediolateral axes of the tibia, hindfoot and forefoot, posterior/anterior axes of the hindfoot and forefoot and a plantar dorsal axis of the hallux. Furthermore, a common perpendicular axis exists. In terms of these axes, the forefoot can perform plantar- and dorsiflexion, inversion and eversion and internal and external rotation with respect to the tibia. Possible motions of the forefoot with respect to the hindfoot are plantar- and dorsiflexion, supination and pronation and ab- and adduction. The hallux can conduct motion with respect to the forefoot as plantar- and dorsiflexion, ab- and adduction and axial rotation (Carson et al., 2001).

Carty et al. (2015) analysed how sensitive the OFM is to marker misplacement. Their study showed that during stance phase a misplaced marker of the heel-wand complex had the greatest impact on the kinematic profile in all directions. An error in placement of the P5M marker lead to wrong results in the vertical direction (Carty et al., 2015). However, even a correct marker placement does not promise a correct result. Skin movement pointed out as a problem in motion analysis, particularly for small movements of small segments. Further, the thickness of the layer of soft tissue between skin and the bony landmark influences the occurring error (Birch & Deschamps, 2011).

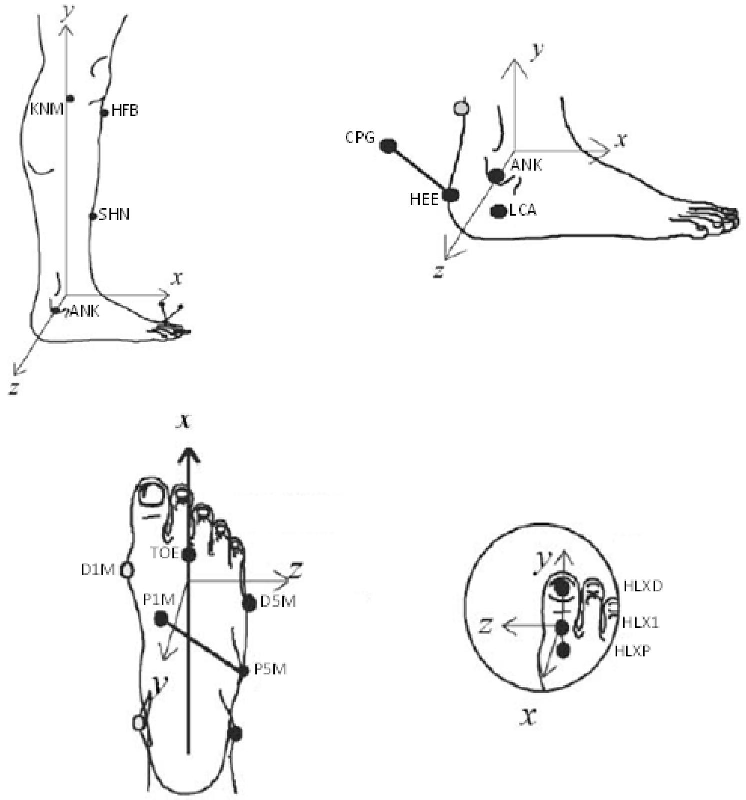

Figure 12: Coordination systems of each segment of the Oxford Foot Model; top left: tibia; top right: hindfoot; bottom left: forefoot; bottom right: hallux; Adapted from: Carson et al. (2001)

2.7. Influence of Walking Condition

Overground walking is compared to treadmill walking using different approaches and models (Alto et al., 1998) (Matsas et al., 2000) (Riley et al., 2007) (Lee & Hidler, 2008) (Chiu et al., 2015) (Hollman et al., 2016). It was observed that spatiotemporal gait parameters like stance time and cadence are different between these two walking conditions (Alton et al., 1998); however, according to Matsas et al. (2000) and Lavcanska et al. (2005) gait parameters stabilise after 6 minutes on the treadmill. Furthermore, walking on a treadmill seems to reduce the variability of gait characteristics (Chiu et al., 2015) (Hollman et al., 2016). Nevertheless, this variability is an indicator for health (Hollman et al., 2016).

Alton et al. (1998) observed a greater Range of Motion (ROM) of the hip joint at the treadmill; however, there were no differences in ROM of the knee or ankle joint. As a totally different marker set was used and motion of the hip was calculated using markers placed at the shoulder, the credibility of these results is limited. Riley et al. (2007) used a different marker set and detected the opposite – while walking on the treadmill the peak hip flexion and extension decreased. Furthermore, a reduction of the knee flexion and extension was determined. As the dynamics of both conditions are similar, similar Ground Reaction Forces (GRF) were observed (Riley et al., 2007). Lee & Hidler (2008) found differences at braking GRF at heel contact. These forces were higher at overground walking and led to greater moments of the ankle dorsiflexior and knee extensor. Further, they observed different joint moments and powers in sagittal plane, which caused differences in muscle activation patterns. According to Riley et al. (2007) all moments of the hip, knee and ankle show similar patterns in all three planes, excluding inversion and eversion moments of the ankle. Chiu et al. (2015) came to the conclusion that walking on the treadmill produce similar inter-joint coordination as walking overground if walking speed is similar. All in all, opinions split as Riley et al. (2007) said that overground walking and walking on a treadmill are qualitatively and quantitatively very similar, whereas according to Kirtley walking on the treadmill cannot replace overground walking as there are too many differences.

2.8. Influence of Walking Speed

Concerning walking speed, studies show that it has an impact on various parameters of the gait cycle. Van Hoeve et al. (2017) used the OFM in his study and showed that during loading phase the ROM between forefoot and hindfoot and between hindfoot and tibia differs significantly at slow and fast walking speed concerning the sagittal plane. Further, ROM is significantly higher between forefoot and hindfoot in the sagittal plane during push-off phase. Regarding the ROM between hindfoot and tibia significant results are observed in frontal and transversal plane during loading and push-off phases. A higher ROM, especially at the ankle joint, could be detected at higher walking speeds with the OFM (van Hoeve et al., 2017) and with the Heidelberg Foot Model (Dubbeldam, et al., 2010). Further, the study conducted with the Heidelberg Foot Model showed that the lower the walking speed is, the lower is the stride length, but stride time and double support time increases. This can be associated with the observed later toe off. Concerning the motion of the segments, the plantar flexion of the tibio-talar joint showed a decrease in its peak value at lower walking speed. Also the dorsiflexion and abduction of the hallux was lower. At mid stance pronation of the midfoot and hindfoot increased. The medial arch was observed to be flatter the slower the walking speed is, but the joint angles of the five metatarsals increased. Furthermore, an increase of speed leads to an increase in stride length, which further has a positive impact on hallux adduction and leg rotation. (Dubbeldam, et al., 2010).

3. Methods

The measurements for this study were conducted at the Laboratory for Gait and Human Motion Analysis at the Orthopaedic Hospital Speising in October 2018. In order to compare the joint angles of the foot at different walking conditions and walking speeds the OFM was used.

3.1. Study Population

The participants of this study were university colleagues, co-workers and friends. Following criteria must be fulfilled to be approved to the study:

- Aged older than 18
- Physically fit
- No injuries of the foot within the last year
- No foot deformities
- No perspiring foot

In total, data of 20 healthy subjects was collected. Data of three additional subjects, which fit to the study conducted, were found in the database of the labatory. The average age of the subjects was 25.17 ± 2.58 years (♀: 24.50 ± 2.75 years; ♂: 26.22 ± 1.87 years). Furthermore, in average subjects weighted 64.51 ± 12.36 kg (♀: 57.81 ± 5.89 kg; ♂: 74.93 ± 12.56 kg) and are 173.26 ± 10.08 cm (♀: 168.53 ± 7.22 cm; ♂: 181.83 ± 8.15 cm) tall. Detailed information to each subject can be found in Table 1.

All subjects participated voluntarily and were not paid for their attendance.

Subject	Sex	Height [cm]	Weight [kg]	Age [years]
1	♀	171.0	54.4	25
2	♀	167.0	59.0	23
3	♂	178.0	74.1	26
4	♂	185.0	80.0	30
5	♀	164.0	61.8	30
6	♀	163.0	48.2	27
7	♀	177.0	63.8	23
8	♀	167.0	55.0	25
9	♂	194.0	97.7	24
10	♂	173.0	57.0	25
11	♀	167.0	58.4	24
12	♂	168.0	54.6	27
13	♂	187.0	75.5	24
14	♀	157.5	54.6	24
15	♀	186.0	69.2	24
16	♀	167.0	64.8	27
17	♂	181.0	81.0	28
18	♀	161.0	50.2	19
19	♀	163.0	51.0	21
20	♀	167.0	56.0	28
21	♂	192.5	84.0	25
22	♂	178.0	70.5	27
23	♂	171.0	62.8	23

Table 1: Detailed information about the study population

3.2. Equipment

The walkway used for the overground measurements is 12 m long and 1.2 m wide; however, only 6 m are detected by 12 Vicon cameras. The cameras record with a frequency of 150 Hz and their resolution amounts 4 megapixels. The not detected area of the walkway is necessary to guarantee normal walking without stopping and turning within the measuring area. Three strain-gauge force plates from AMTI (Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA) are embedded in the middle of the walkway. The force plates record with 1,500 Hz.

For the treadmill measurements a quasar treadmill from h/p/cosmos (h/p/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany) was used. A zebris system (zebris Medical GmbH, Isny, Germany) with integrated capacitive sensors is imbedded in the surface, which makes it possible to measure pressure and/or force distribution while walking. Data is collected at a frequency of 75 Hz. Further, 10 Vicon cameras with a resolution of 1 megapixel are installed in the room in order to capture the motion of the whole body.

For both measurement setups the Vicon system, force plates and pressure plates are calibrated, regularly. Data was gathered and processed by using the software Vicon Nexus 2.6.1., Vicon Polygon and zebris FDM. Further information about the data processing is given in chapter 3.5..

3.3. Marker Setup

The used marker positions are a combination of the Cleveland Clinic Marker Set and the modified OFM. The static measurements were conducted with a total of 74 markers. The markers are placed at anatomical landmarks as shown in Figures 13 and 14 and described in Table 2. For the dynamic measurements 12 markers, which are highlighted in red, were removed (KNE, KNM, ANK, ANM, CPA, D1M). The combination of these marker sets do not only allow analysing gait in general, but also deliver more precise data about the movements of the foot.

The markers are reflecting spheres with different diameters according to their position. Further, the base of some markers of the OFM is cut in order to prevent its dragging on the floor and its consequential loosing. The CPG marker is attached by means of a pole, whereas the markers T1-T3 and S1-S3 are placed on each end of a T-shaped framework and form a triangle. Each marker must be captured by at least two cameras at any time in order to be able to reconstruct its 3D-trajcectory.

<table>
<tr><th rowspan="2">Segment</th><th colspan="2">Marker name</th><th rowspan="2">Anatomical position of the marker</th></tr>
<tr><th>right</th><th>left</th></tr>
<tr><td rowspan="2">Head</td><td>RFHD</td><td>LFHD</td><td>front head above the temple</td></tr>
<tr><td>RBHD</td><td>LBHD</td><td>back head in horizontal plane of FHD</td></tr>
<tr><td rowspan="5">Torso</td><td colspan="2">CLAV</td><td>incisura jugularis</td></tr>
<tr><td colspan="2">STRN</td><td>3 cm caudal of CLAV</td></tr>
<tr><td colspan="2">C7</td><td>processus spinosus of 7th cervical vertebra</td></tr>
<tr><td colspan="2">T10</td><td>connecting line of anguli inferiori at vertebra</td></tr>
<tr><td colspan="2">RBAK</td><td>right scapula</td></tr>
<tr><td rowspan="2">Pelvis</td><td colspan="2">SACR</td><td>connecting line of spinae illiacae posterior</td></tr>
<tr><td>RASI</td><td>LASI</td><td>lateral of spina illiaca anterior superior</td></tr>
<tr><td rowspan="7">Upper extremities</td><td>LSHO</td><td>RSHO</td><td>acromion</td></tr>
<tr><td>RUPA</td><td>LUPA</td><td>upper arm proximal/distal of articulation cubiti</td></tr>
<tr><td>RELB</td><td>LELB</td><td>epicondylus lateralis</td></tr>
<tr><td>RFRA</td><td>LFRA</td><td>lower arm proximal/distal of articulation cubiti</td></tr>
<tr><td>RWRA</td><td>LWRA</td><td>processus styloideus radii</td></tr>
<tr><td>RWRB</td><td>LWRB</td><td>processus styloideus ulnae</td></tr>
<tr><td>RFIN</td><td>LFIN</td><td>2nd caput ossis metacarpalis</td></tr>
<tr><td rowspan="13">Lower extremities</td><td>RKNE</td><td>LKNE</td><td>epicondylus lateralis humeri</td></tr>
<tr><td>RKNM</td><td>LKNM</td><td>epicondylus medialis humeri</td></tr>
<tr><td>RT1</td><td>LT1</td><td rowspan="3">marker-triangle at distal third of upper leg (long side towards posterior)</td></tr>
<tr><td>RT2</td><td>LT2</td></tr>
<tr><td>RT3</td><td>LT3</td></tr>
<tr><td>RS1</td><td>LS1</td><td rowspan="3">marker-triangle at distal third of lower leg (long side towards posterior)</td></tr>
<tr><td>RS2</td><td>LS2</td></tr>
<tr><td>RS3</td><td>LS3</td></tr>
<tr><td>RANK</td><td>LANK</td><td>lateral distal end of malleoli</td></tr>
<tr><td>RANM</td><td>LANM</td><td>medial distal end of malleoli</td></tr>
<tr><td>RHFB</td><td>LHFB</td><td>head of fibula</td></tr>
<tr><td>RTTB</td><td>LTTB</td><td>distal end of tuberosity tibia</td></tr>
<tr><td>RSHN</td><td>LSHN</td><td>distal third of the front of tibia</td></tr>
</table>

Segment	Marker name right	Marker name left	Anatomical position of the marker
Foot	RHEE	LHEE	distal end of calcaneus posterior
	RCPA	LCPA	proximal end of calcaneus posterior
	RCPG	LCPG	marker basis between HEE and CPA (along longitudinal axis of calcaneus)
	RSTL	LSTL	sustentaculum tali
	RLCA	LLCA	calcaneus lateralis
	RP5M	LP5M	lateral of proximal head of 5th metatarsus
	RD1M	LD1M	medial of distal head of 1st metatarsus
	RD5M	RD5M	lateral of distal head of 5th metatarsus
	RTOE	LTOE	proximal of connecting line of articulation metacarpophalangealis I-VI
	RHLX	LHLX	medial side 1st phalanx
	RP1M	LP1M	proximal head of 1st metatarsus (medial of musculus extensor hallucis)

Table 2: Used markers and their anatomical position

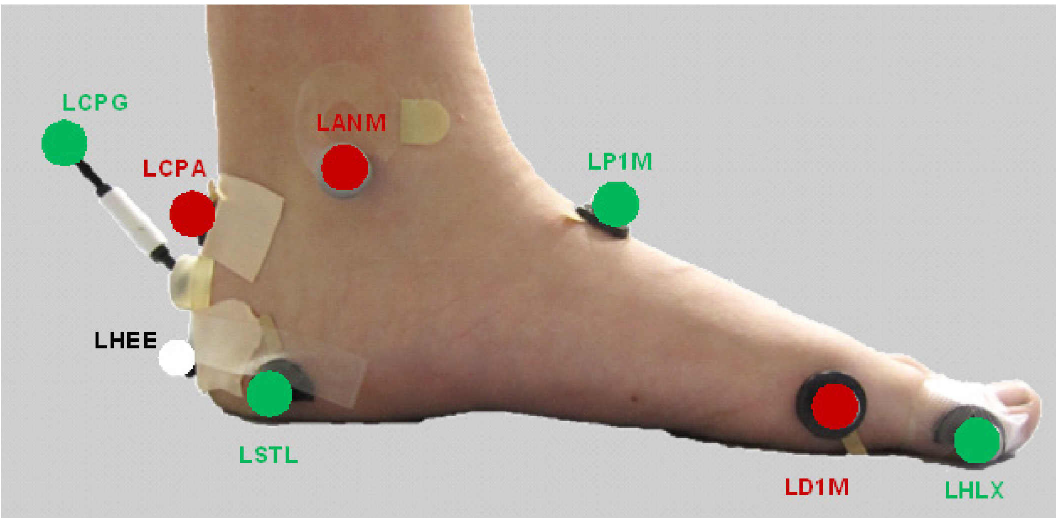

Figure 13: Marker setup at the medial side of the foot; White markers: Cleveland Clinic; Green markers: Oxford Foot Model; Red Markers: removed after static measurement

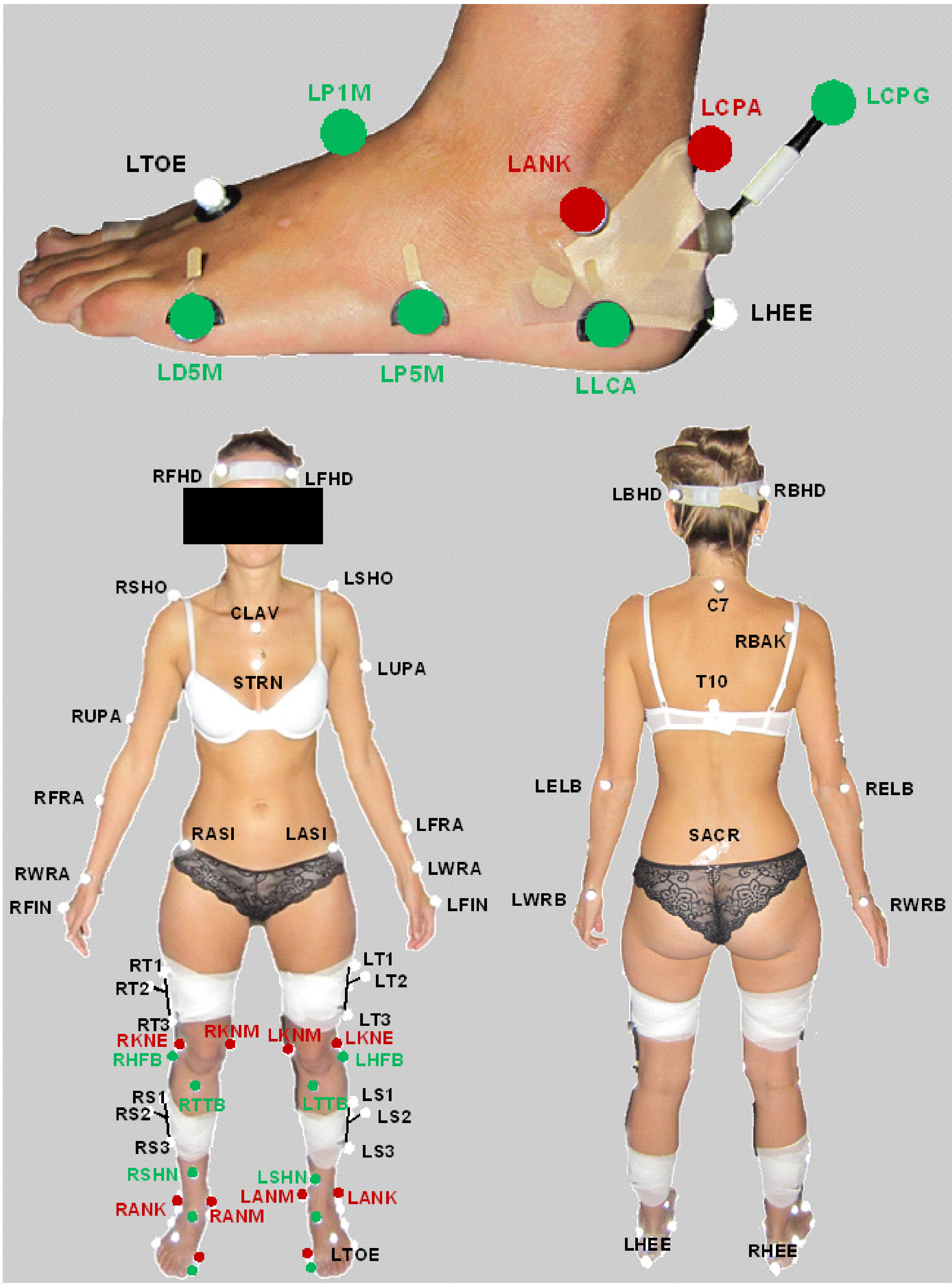

Figure 14: Marker setup at the lateral side of the foot (top) and at the whole body (bottom); White markers: Cleveland Clinic; Green markers: Oxford Foot Model; Red Markers: removed after static measurement

3.4. Protocol

Each measurement was conducted with the same equipment using the same procedure. The applied measurement report can be found in the appendix (A).

In advance of each measurement all necessary equipment was prepared. First of all, anthropometric data of the subjects was gathered, which was further implemented in Vicon Nexus. Beside height and weight, the width of the pelvis, elbow and hand were measured. Next, markers were applied with skin-compatible tape. As the markers were placed directly on the skin measurements were conducted barefoot and subjects were requested to wear underwear. The markers of the OFM were positioned by two testers experienced in marker placement in order to minimise variance. Once all markers were applied, two static recordings were captured. For this the subjects were asked to stand normally with slightly raised arms first and then to bend their knees a bit. The collected data was used to create the model in Vicon Nexus, which was necessary for the dynamic measurements.

The first condition observed was walking overground. The participant was requested to walk along the walkway at a self-selected speed, which felt like a "normal" walking speed for them. At least 5 proper trials were recorded, in which the subjects hit the force plate with the whole foot. Each foot had to hit the plate for at least 5 times. After trials at "normal" speed were captured successfully, the subjects were first requested to walk slower than normal and then faster than normal.

The measurements on the treadmill were conducted after the overground walking measurements. Firstly, subjects had to walk for about 5 minutes on the treadmill in order that spatiotemporal gait parameters could stabilise. Then the speed of the treadmill was set according to the average speed of overground walking measurements. The order of the measurements was again normal – slow – fast walking speed. At least three measurements of the duration of 15 seconds were captured per walking speed.

3.5. Data Processing

Vicon Nexus 2.6.1. was used to process raw data. Markers were labelled and possible gaps were filled in order that every marker was visible during the whole trail. Furthermore, raw data was cut and the relevant models were calculated. The Plug-In Gait model compared the relative orientation of the segments proximal and distal of the joint, whereas the Oxford Foot Model delivered more detailed information about joint angles between foot segments.

Regarding the measurements conducted overground the offset of the force plates was reset and initial contact as well as toe off are allocated. Concerning data gathered on the treadmill, initial contact and toe off were calculated by the data of the pressure plate. Finally, Vicon Nexus 2.6.1. calculated joint angle trajectories. By means of the created report the processed data could be graphically illustrated and labelling errors, outliers or other errors could be identified and corrected.

For further evaluation the Laboratory for Gait and Human Motion Analysis provided a tool written in Matlab R2018b (Mathworks, Natick, Massachusetts, USA). After the import of single trials, the trials were cut into gait cycles, which were further time normalised. Single gait cycles were laid on top of each other and the mean value of each parameter was formed. Further, the computed data was saved as a Matlab File.

In order to be able to compare measurements according to the walking speed, data had to be clustered. Two different methods were used:

- Clustering according to the self-selected speed into:
  slow – normal – fast
- Clustering according to Schwartz et al. (2008) into:
  very slow – slow – normal – fast – very fast

Schwartz et al. (2008) used the following formulas, which were published by Hof in 1996, in order to convert spatiotemporal parameters into dimensionless parameters.

$$stride\ length_{dimensionless} = stride\ length\ [m] /\ leg\ length\ [m] \tag{2}$$

$$cadence_{dimensionless} = cadence\ \left[{}^{steps}/_{minute}\right] / \sqrt{g\ \left[{}^{m}/_{s^2}\right] / leg\ length\ [m]} \tag{3}$$

$$velocity_{dimensionless} = velocity\ [{}^{m}/_{s}] / \sqrt{g\ \left[{}^{m}/_{s^2}\right] \cdot leg\ length\ [m]} \tag{4}$$

whereby g = 9.81 m/s^2 and velocity was calculated by using equation (1). Although, Schwartz et al. (2008) analysed children, this method can be used for adults as well, because most gait parameters are not affected by age (Ganley & Powers, 2006) (Ganley & Powers, 2005).

Mean value and standard deviation of the dimensionless velocity was calculated for the measurements conducted at normal walking speed. These values served as a basis for classification of the five different speed categories. Values ± 1 standard deviation away from the mean value referred to the categories "slow" or "fast", whereas values with a distance of ± 2 standard deviations belonged to "very slow" or "very fast" walking. Table 3 presents the calculated norm data for clustering used at the Laboratory for Gait and Human Motion Analysis.

This form of clustering led to unbalanced groups as not all subjects attained all speeds. As no measurement belonged to the category "very slow" and the category "very fast" included only two measurements, these categories were excluded from statistical analysis. The remaining groups contained enough trials to be statistically relevant ($N_{slow} = 14$, $N_{normal} = 23$, $N_{fast} = 17$).

Velocity	Minimum	Maximum
Very slow	0	0.227
Slow	0.227	0.363
Normal	0.363	0.500
Fast	0.500	0.636
Very fast	0.636	∞

Table 3: Clustering according to Schwartz et al. (2008) using dimensionless speed

3.6. Statistical Analysis

As the same dependent variable was measured repeatedly a repeated measures Analysis of Variance (rmANOVA) was conducted. Regarding this study the dependent variables were the kinematic and kinetic data. The within-subject factor was the walking speed.

First of all, the data had to be checked whether the data showed a normal distribution. Therefore, the Shapiro-Wilk test was conducted. If the result was significant ($p < 5\,\%$), the data was not normally distributed. According to literature, rmANOVA is robust towards normal distribution (Glass et al., 1972) (Harwell et al., 1992) (Lix et al., 1996) (Salkind, 2010). Furthermore, it is mentioned that data does not need to be checked on normal distribution if the sample size is larger than 30 (Kähler, 2004) (Bortz & Schuster, 2010) (Tavakoli, 2013). Therefore, data was not changed, even if no normal distribution was given..

Further, it had to be controlled if the data included outliners. Boxplots supported the calculated results graphically. Slight outliners were a distance of more than 1.5 standard deviations away of the mean value; extreme outliners were more than 3 standard deviations. For further processing extreme outliners were deleted.

Before the rmANOVA could be conducted, data was analysed according its sphericity. This was done by the Mauchy-test. If $p < 5\,\%$, sphericity was not present and an epsilon ε correction had to be conducted. According to Girden (1992) the Greenhouse-Geisser correction should be conducted if $\varepsilon < 0.75$. If ε

> 0.75, the Huynh-Feldt correction should be used. With the corrected data the rmANOVA could be conducted. A significant result ($p < 5$ %) indicated that at least two groups differed from each other statistically. However, post-hoc tests were needed in order to determine these groups.

As the influence of walking speed could not be excluded while comparing overground walking to walking on the treadmill a two-way repeated measures ANOVA was used. The prerequisite were similar to those of the rmANOVA. In case of unbalanced data, it was not possible to use a rmANOVA; therefore, a one- and two-way ANOVA was conducted. Therefore, after checking normal distribution and outliners variances were compared by the Levene's test. If the result was not significant, the ANOVA and further post-hoc tests were conducted.

The most important parts of the used Matlab functions are presented in the appendix (B).

4. Results

Due to the vast number of statistical and graphical outcomes, only the most significant and important results are presented in this chapter. All results can be looked up in the appendix (C).

Concerning the evaluation, the most crucial values of the gait cycle are used. In case of this study the following parameters (all measured in degrees) are analysed:

- Snapshot at 80 % of the gait cycle (80Prz)
- Maximum value during the gait cycle (max)
- Minimum value during the gait cycle (min)
- ROM during the gait cycle (rom)

The snapshot at 80 % of the gait cycle is important as it is a good indicator for supination during swing phase. This snapshot can also be replaced by the mean value calculated from data gathered between 75-85 % of the gait cycle. The analysed parameters are inspected in all planes (sag, front, trans) and for the movements between the following segments:

- Forefoot to hindfoot (FFHF)
- Forefoot to tibia (FFTB)
- Hindfoot to tibia (HFTB)
- Hallux to forefoot (HXFF)

Although this thesis focuses on the OFM, parameters like the motion of the hip and knee in sagittal plane as well as GRF and Foot GPS (a parameter, which indicates the deviation of the Root Mean Square from standard data) are included in the evaluation. Regarding spatiotemporal parameters, cadence, walking speed and step width are considered. Gender related differences between the parameters are not taken into account and are not evaluated.

4.1. Effect of Walking Condition

In order to answer the first hypotheses, if any differences in foot angles and spatiotemporal parameters can be observed between walking conditions (overground vs. treadmill), measurements conducted overground were compared to those walking on the treadmill. As an interaction with speed could not be excluded a two-way ANOVA used for this analysis. The results are split according to the two types of clustering – according to self-selected speed and according to Schwartz et al. (2008).

The tables of the following subchapters show parts of the outcome of the comparison of the different walking conditions. Concerning tables including results of statistical analyses, the first column names the analysed parameter. The second column gives information about the normal distribution (ND) of each examined dataset. If the result is significant ($p < 0.05$), the data is not normally distributed. The dataset is always structured the same way:

- First row: Walking overground at normal speed
- Second row: Walking overground at slow speed
- Third row: Walking overground at fast speed
- Fourth row: Walking on the treadmill at normal speed
- Fifth row: Walking on the treadmill at slow speed
- Sixth row: Walking on the treadmill at fast speed

The third column of the results table includes the mean value (MV) and standard deviation (SD) of each data group. The fourth and fifth column presents the significance level of tests of the between-subject effects, which are split into influence of walking condition (cond.) and interaction of speed and walking condition (speed x cond.). The last two columns contain information about the comparison of the walking condition for normal (n), slow (s) and fast (f) walking speed.

Concerning tables comparing the mean values between the walking conditions, the first column contains again the name of the parameter. The second column tells what speed category (normal, slow, fast) was analysed, whereas the third and fourth columns present the associated mean value (MV) and standard deviation (SD) of each category.

Regarding to the boxplots of the following subchapters, abbreviation O stands for overground, whereas T means treadmill. In total, this leads to six boxes per graph – three different speeds per walking condition. All boxes have the same structure. The tops and bottoms of each box represent the 25th and 75th percentiles of the samples. The red line in the middle of each box demonstrates the median of the sample. Lines, which extend the box above and below, are called whiskers. These whiskers reach from the 25th and 75th percentiles to the adjacent values. Observations beyond the whiskers length are outliners and are marked with a red +.

Regarding figures showing the joint angle trajectories, X axis represents the timeline of the gait cycle expressed as a percentage. 0 % represents initial contact of one foot. The vertical line at around 60 % of the gait cycle shows, when the "toe off" event happens. At 100 % the gait cycle ends with the initial contact of the same foot. The Y axis gives information about the angle specified as degrees. Furthermore, the name of the motion is given as a shortcut, whereby pronation/supination is written as Pro/Sup, abduction/abbduction as Abd/Add, dorsiflexion/plantarflexion as PF/DF, external/internal rotation as Ext/Int, Extension/Flexion as Ext/Flex and eversion/inversion as Ever/Inve. The titel includes the name of the two analysed segments and the plane, in which they are presented. Attention must be taken that if no plane is mentioned, the demonstrated joint angle trajectory is shown in frontal plane.

4.1.1. Clustering according to self-selected speed

Spatiotemporal parameters do significantly differ between walking overground and walking on the treadmill ($p_{ANOVA} < 0.05$). Speed influences the results for cadence ($p_{speed\ x\ cond.} = 0.001$) and step width ($p_{speed\ x\ cond.} = 0.026$). For these parameters p-values are significant ($p < 0.05$) for all speeds except the p-value of cadence for normal speed (p_{normal} = 0.206). The results are graphically presented as boxplots in Figure 15. A comparison of mean values presented in Table 4 indicates that cadence is higher while walking on the treadmill, whereas step width is lower. Regarding walking speed, the result of the ANOVA was significant (p_{ANOVA} = 0.015); however, post-hoc tests do not support this outcome ($p_{post\text{-}hoc}$ > 0.05).

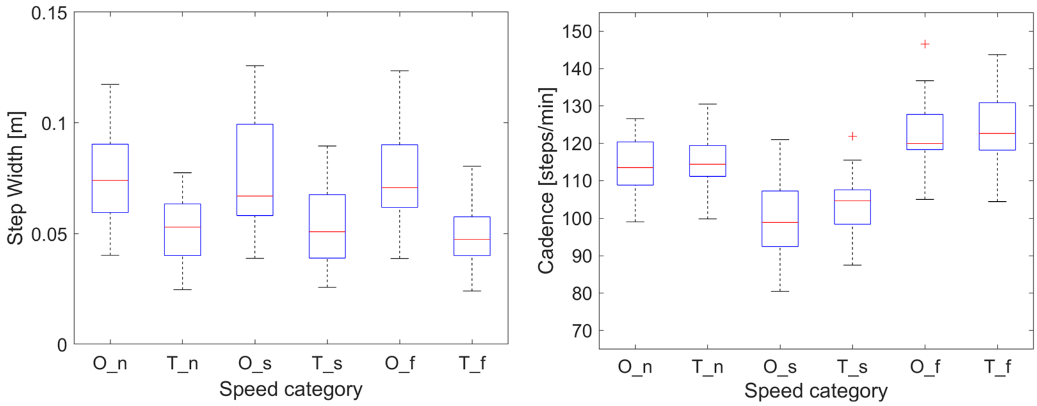

Figure 15: Comparison of overground (O) and treadmill (T) measurements conducted at normal (n), slow (s) and fast (f) walking speed for the parameters step width (left) and cadence (right); Data is clustered according to self-selected speed; The red line indicates the median of the sample. The tops and bottoms of the blue box represent 25th and 75th percentiles of the sample. The lines above and below of the box (whiskers) reach from the percentiles to the adjacent values. Outliners are marked with a red +;

Concerning the OFM, the null hypotheses cannot be rejected for the maximum value of FFHF in frontal and transversal plane (p_{ANOVA} > 0.05); nevertheless, it can be rejected for the minimum value (p_{front} = 0.006; p_{trans} = 0.005) and ROM (p_{front} = 0.000; p_{trans} = 0.000) for both planes in all speeds ($p_{post\text{-}hoc}$ < 0.05). In all cases, speed does not affect the result. In order to illustrate the difference better, FFHF in frontal and transversal plane at normal speed are graphically presented in Figure 16 a-b. Values of Table 4 show that pronation of FFHF is less while walking overground compared to walking on the treadmill, whereas supination remains unchanged. Furthermore, ROM in frontal plane increases. Concerning ROM in transversal plane, data shows an decrease as FFHF abducts less while walking on the treadmill

FFTB differs significantly at 80 % of the gait cycle in all three planes. However, in

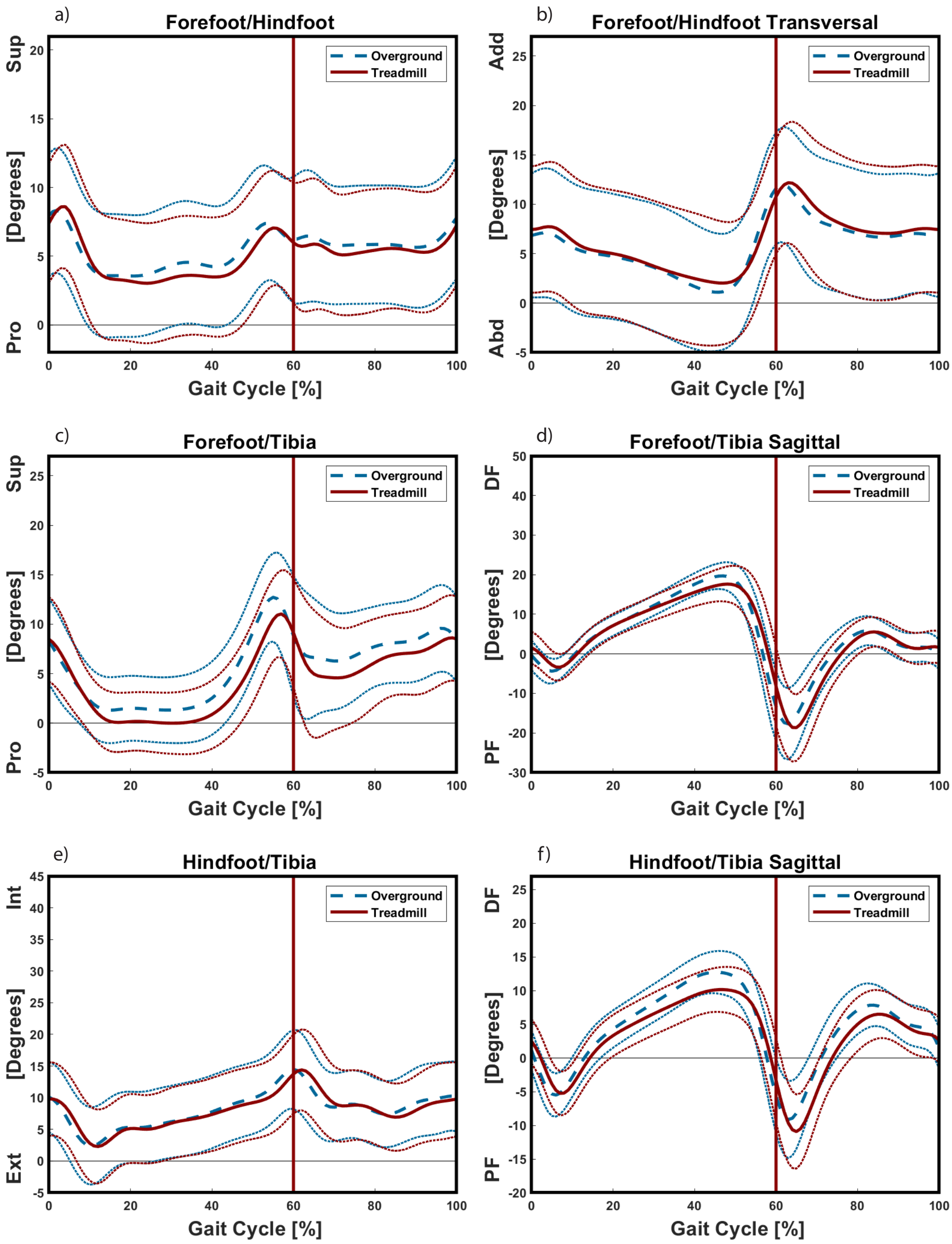

Figure 16: Angle trajectories between different segments in different planes at normal speed showing the difference between overground (blue dashed line) and treadmill (red solid line) walking. Data is clustered according to self-selected speed.

a) FFHF front; b) FFHF trans; c) FFTB front; d) FFTB sag; e) HFTB front; f) HFTB sag frontal plane the result is not independent of speed as shown in Table 5. The null hypothesis cannot be rejected for FFTB in transversal plane for the remaining analysed data. In frontal plane FFTB differs significantly for maximum value, minimum value and ROM, but for the minimum value an interaction between speed and surface takes place. Concerning the sagittal plane of FFTB a significant difference can be observed at maximum and minimum value, whereby the outcome of the maximum value is not independent of walking speed. The angle movement of FFTB in frontal and sagittal plane is shown in Figure 16 c-d. Regarding the movement of FFTB, results presented in Table 4 demonstrate that ROM in frontal plane rises while walking overground as supination increases, but pronation decreases. Further, FFTB dorsi and plantar flexes more while walking overground. At 80 % of the gait cycle FFTB supinates, dorsi flexes and adducts more while walking overground.

Regarding HFTB significant results without interactions with speed can be observed in frontal plane for the maximum value ($p_{ANOVA} = 0.000$) and ROM ($p_{ANOVA} = 0.001$) as graphically illustrated in Figure 16 e. In sagittal plane (Figure 16 f) the maximum value ($p_{ANOVA} = 0.000$) and minimum value ($p_{ANOVA} = 0.000$) differ significantly. These parameters are also not influenced by speed. Further a significant outcome can be detected at 80 % of the gait cycle in frontal plane ($p_{ANOVA} = 000$) for all speeds ($p_{post\text{-}hoc} < 0.05$). However, in this case the result is not independent of speed ($p_{speed\ x\ cond.} = 0.019$). A comparison of mean values presented in Table 4 shows that HFTB rotates less internal and has a lower ROM in frontal plane while walking on the treadmill. Furthermore, less dorsi but more plantar flexion are indicated while walking on the treadmill.

For HXFF (Figure 17 a) the null hypotheses can be rejected for the minimum and maximum value in sagittal plane ($p_{ANOVA}= 0.000$). Mean values (Table 4) detected an increase in dorsi flexion, but a decrease in plantar flexion are while walking on the treadmill.

In order to get a better overview about the data and the influence of different walking conditions hip and knee motion in sagittal plane as well as the Foot GPS were analysed. ROM and maximum value of the hip and knee are statistically influenced by the walking condition (Figure 17 b-c); however, the walking speed has an effect on the result as well (excluding ROM of the hip). This means that the knee flexes statistically more on the treadmill; whereas no explicit statement about extension can be made (Table 4). Regarding the motion of the hip, a higher flexion and a greater ROM in sagittal plane were observed while walking on the treadmill (Table 4). Post-hoc tests detected differences for these parameters in all speeds ($p_{post\text{-}hoc} = 0.000$). Concerning the Foot GPS, statistically significant differences are observed between walking overground and walking on the treadmill for all three speeds ($p_{post\text{-}hoc} = 0.000$), but the walking condition interacts with the speed.

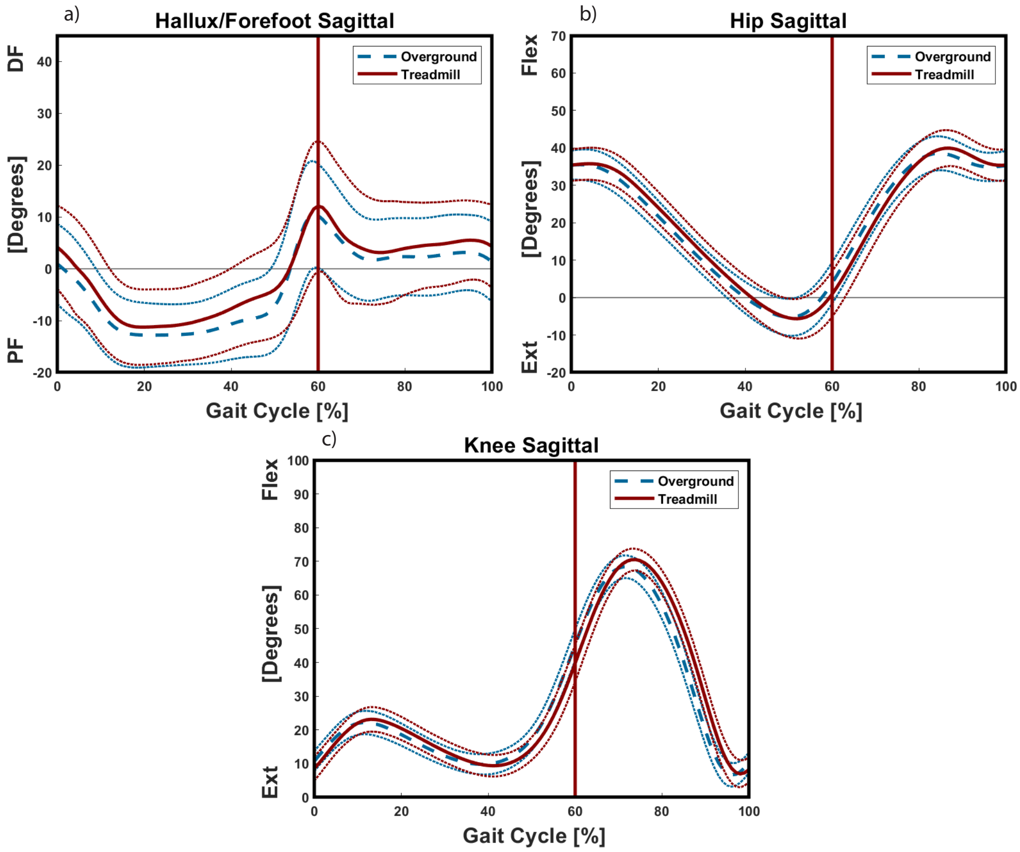

Figure 17: Angle trajectories between different segments in different planes at normal speed showing the difference between overground (blue dashed line) and treadmill (red solid line) walking. Data is clustered according to self-selected speed.
a) HXFF sag; b) Hip sag; c) Knee sag

Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD	Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD
Cadence	normal	114.0327 ± 7.5388	114.6616 ± 7.4666	**FFTB_front_max**	normal	13.8912 ± 4.2828	12.3612 ± 4.1497
	slow	99.4908 ± 9.7929	102.9401 ± 8.7758		slow	13.7535 ± 3.9718	12.3323 ± 3.8752
	fast	122.4217 ± 9.7135	123.8600 ± 9.6817		fast	13.2186 ± 4.1654	11.7898 ± 4.3989
Walking Speed	normal	1.2851 ± 0.1176	1.1731 ± 0.3223	**FFTB_front_min**	normal	0.0281 ± 3.6327	-1.2818 ± 3.6511
	slow	0.9889 ± 0.1377	0.9438 ± 0.1938		slow	-0.0426 ± 3.1489	-1.2872 ± 3.2780
	fast	1.5277 ± 0.1492	1.4276 ± 0.2700		fast	-0.4761 ± 3.9142	-1.2375 ± 3.6840
Step Width	normal	0.0761 ± 0.0218	0.0518 ± 0.0140	**FFTB_front_rom**	normal	13.8631 ± 2.9317	13.6430 ± 2.9895
	slow	0.0742 ± 0.0250	0.0540 ± 0.0189		slow	13.7961 ± 2.6912	13.6195 ± 2.7095
	fast	0.0756 ± 0.0229	0.0487 ± 0.0139		fast	13.6947 ± 3.1854	13.0272 ± 3.3440
FFHF_front_min	normal	2.5346 ± 4.3685	1.9396 ± 4.2595	**FFTB_sag_80Prz**	normal	4.6686 ± 4.0204	3.1985 ± 4.3584
	slow	2.2216 ± 4.3629	1.5436 ± 4.2023		slow	5.4950 ± 3.8100	3.9645 ± 4.5291
	fast	2.6205 ± 4.3678	1.9360 ± 4.2049		fast	5.3740 ± 3.3655	3.9275 ± 4.0670
FFHF_front_rom	normal	7.0375 ± 1.6614	7.5990 ± 1.6255	**FFTB_sag_max**	normal	20.1541 ± 3.3979	18.1916 ± 4.5869
	slow	6.7598 ± 1.7865	7.2773 ± 1.6181		slow	20.7344 ± 3.3646	19.2212 ± 4.4510
	fast	7.4494 ± 1.8167	7.8813 ± 1.9415		fast	18.9814 ± 4.3650	16.2930 ± 5.4818
FFHF_trans_min	normal	0.8192 ± 5.8863	1.6342 ± 6.1083	**FFTB_sag_min**	normal	-18.4861 ± 8.9023	-19.6278 ± 8.5652
	slow	1.1418 ± 6.0909	1.7903 ± 6.0949		slow	-13.9535 ± 7.4984	-15.8007 ± 9.4098
	fast	1.0120 ± 6.1046	1.6550 ± 6.0722		fast	-20.6159 ± 8.5495	-22.7248 ± 8.9049
FFHF_trans_rom	normal	11.4784 ± 2.1113	10.8784 ± 2.0248	**FFTB_trans_80Prz**	normal	15.2895 ± 6.7304	15.9006 ± 6.7678
	slow	11.0102 ± 2.0475	10.5862 ± 1.9574		slow	15.6547 ± 6.9004	16.2325 ± 6.8024
	fast	11.3916 ± 2.2283	10.9177 ± 2.0151		fast	14.3180 ± 6.8937	15.2283 ± 6.7035
FFTB_front_80Prz	normal	7.5894 ± 4.1053	5.8873 ± 4.5197	**HFTB_front_80Prz**	normal	1.9377 ± 4.0843	0.5971 ± 4.5969
	slow	7.9865 ± 3.7672	6.4615 ± 4.3319		slow	2.0583 ± 4.0786	1.0675 ± 4.4885
	fast	7.1055 ± 4.0902	6.0716 ± 4.2602		fast	1.3870 ± 4.3606	0.5703 ± 4.6393

Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD	Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD
HFTB_front_max	normal	6.4386 ± 4.3076	5.2913 ± 4.6071	**HXFF_sag_min**	normal	-14.1360 ± 6.3598	-14.4402 ± 7.5236
	slow	6.3554 ± 4.2834	5.3754 ± 4.6654		slow	-14.2553 ± 6.2635	-12.7298 ± 7.2206
	fast	5.5748 ± 4.5510	4.8880 ± 4.8436		fast	-12.4722 ± 7.5393	-11.4506 ± 7.6181
HFTB_front_rom	normal	10.9055 ± 2.0891	10.4955 ± 2.1905	**Hip_sag_max**	normal	38.7650 ± 4.5532	40.0716 ± 4.8144
	slow	10.5406 ± 1.8692	9.9502 ± 1.9572		slow	36.4555 ± 4.6635	38.5644 ± 4.6950
	fast	10.5184 ± 2.1982	10.0781 ± 2.1832		fast	40.5556 ± 5.3347	42.0447 ± 5.4753
HFTB_sag_max	normal	13.0266 ± 3.0840	10.5727 ± 3.3840	**Hip_sag_rom**	normal	44.1806 ± 4.2910	45.9434 ± 4.9130
	slow	13.5505 ± 3.2495	11.4334 ± 3.6065		slow	39.9498 ± 4.2257	51.9460 ± 4.3131
	fast	11.5189 ± 3.4152	9.4109 ± 3.4551		fast	48.6817 ± 5.3248	50.2648 ± 5.6981
HFTB_sag_min	normal	-10.0259 ± 5.2832	-11.7949 ± 5.4714	**Knee_sag_max**	normal	68.6812 ± 3.3481	70.7665 ± 3.2274
	slow	-7.7646 ± 4.3423	-9.8474 ± 5.5944		slow	66.3208 ± 4.1079	69.4689 ± 4.0990
	fast	-11.2435 ± 4.8914	-13.7834 ± 5.1918		fast	68.4882 ± 2.7565	70.6956 ± 2.8935
HXFF_sag_max	normal	13.1872 ± 9.9229	15.9553 ± 11.2017	**Knee_sag_rom**	normal	62.6456 ± 4.8228	64.9070 ± 4.3201
	slow	11.7681 ± 9.7728	14.2468 ± 11.1636		slow	60.0509 ± 5.6541	63.0928 ± 5.1820
	fast	15.0529 ± 11.3918	17.1456 ± 11.5843		fast	63.1193 ± 3.6849	65.1480 ± 3.8070

Table 4: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected significant differences. Data is gathered while overground walking and while walking on the treadmill. Further it is clustered according to self-selected speed.

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2">ND</th><th rowspan="2">MV ± SD</th><th colspan="2">Sig. Between-subject</th><th rowspan="2" colspan="2">p-value</th></tr>
<tr><th>cond.</th><th>speed x cond.</th></tr>
<tr><td rowspan="6">FFTB_ front_80Prz</td><td>0.07</td><td>7.5894 ± 4.1053</td><td rowspan="6">0.000</td><td rowspan="6">0.006</td><td rowspan="2">n</td><td rowspan="2">0.000</td></tr>
<tr><td>0.00</td><td>7.9865 ± 3.7672</td></tr>
<tr><td>0.02</td><td>7.1055 ± 4.0902</td><td rowspan="2">s</td><td rowspan="2">0.000</td></tr>
<tr><td>0.45</td><td>5.8873 ± 4.5197</td></tr>
<tr><td>0.02</td><td>6.4615 ± 4.3319</td><td rowspan="2">f</td><td rowspan="2">0.000</td></tr>
<tr><td>0.34</td><td>6.0716 ± 4.2602</td></tr>
<tr><td rowspan="6">FFTB_ sag_80Prz</td><td>0.51</td><td>4.6686 ± 4.0204</td><td rowspan="6">0.000</td><td rowspan="6">0.957</td><td rowspan="2">n</td><td rowspan="2">0.000</td></tr>
<tr><td>0.80</td><td>5.4950 ± 3.8100</td></tr>
<tr><td>0.60</td><td>5.3740 ± 3.3655</td><td rowspan="2">s</td><td rowspan="2">0.000</td></tr>
<tr><td>0.16</td><td>3.1985 ± 4.3584</td></tr>
<tr><td>0.57</td><td>3.9645 ± 4.5291</td><td rowspan="2">f</td><td rowspan="2">0.000</td></tr>
<tr><td>0.54</td><td>3.9275 ± 4.0670</td></tr>
<tr><td rowspan="6">FFTB_ trans_80Prz</td><td>0.14</td><td>15.2895 ± 6.7304</td><td rowspan="6">0.000</td><td rowspan="6">0.106</td><td rowspan="2">n</td><td rowspan="2">0.006</td></tr>
<tr><td>0.18</td><td>15.6547 ± 6.9004</td></tr>
<tr><td>0.40</td><td>14.3180 ± 6.8937</td><td rowspan="2">s</td><td rowspan="2">0.006</td></tr>
<tr><td>0.50</td><td>15.9006 ± 6.7678</td></tr>
<tr><td>0.47</td><td>16.2325 ± 6.8024</td><td rowspan="2">f</td><td rowspan="2">0.000</td></tr>
<tr><td>0.54</td><td>15.2283 ± 6.7035</td></tr>
</table>

Table 5: Outcome of the statistical analysis for FFTB at 80% of the gait cycle clustered according to self-selected speed. The second and third columns give information about the normal distirbution (ND) and the mean value (MV) and standard deviation (SD) of the dataset. If the value for ND is smaller than 0.05 the data is not normally distributed. The first three rows of each parameters for the columns ND and MV ± SD belong to the measurements conducted overground in the order normal - slow - fast walking speed. Rows 4 - 6 present the data of measurements conducted on the treadmill in the order normal - slow - fast walking speed. The fourth and fifth columns give information if the walking condition (cond.) does have a significant influence ($p < 0.05$) on the result and if there is an interaction with walking speed (speed x cond.). An interaction is indicated by a value smaller than 0.05. The last two columns show if the difference occur at normal (n), slow (s) or fast (f) walking speed. Results are significant if the value is smaller than 0.05.

4.1.2. Clustering according to Schwartz et al. (2008)

Clustering according to Schwartz et al. (2008) leads to no interaction of speed while comparing walking conditions. Walking condition has a statistically relevant influence on cadence ($p_{ANOVA} = 0.047$) and step width ($p_{ANOVA} = 0.000$). The results are graphically presented in Figure 18. Concerning cadence, differences were observed for slow ($p_{slow} = 0.000$) and fast ($p_{fast} = 0.012$) walking speed, whereas step width differs in all three speeds ($p_{post\text{-}hoc} = 0.000$). A comparison of mean values (Table 6) indicates an increase of cadence and a decrease of step width while walking on the treadmill. Regarding walking speed, ANOVA detected a significant difference; however, post-hoc tests do not support this result ($p_{post\text{-}hoc} > 0.05$).

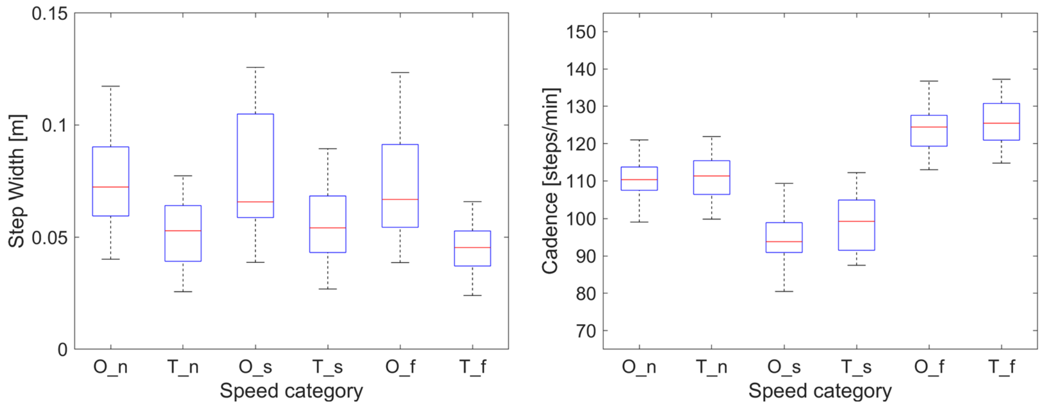

Figure 18: Comparison of overground (O) and treadmill (T) measurements conducted at normal (n), slow (s) and fast (f) walking speed for the parameters step width (left) and cadence (right); Data is clustered according to Schwartz et al. (2008).

Further, the null hypotheses that there is no difference between the analysed data can be rejected for ROM of FFHF in frontal plane for all three speeds. This means pronation and supination of FFHF increases while walking on the treadmill (Table 6).

Concerning frontal plane of FFTB (Figure 19 a) statistically significant results were obtained for 80% of the gait cycle, maximum value and minimum value. In all cases, the p-value of the post-hoc tests amounts 0.000 for all speeds. In sagittal plane ANOVA for the parameter FFTB at 80 % of the gait cycle could not be conducted as Levene's test detected unequal variances. Nevertheless, for the maximum value ANOVA was valid and observed a significant difference (p_{ANOVA} = 0.000). Post-hoc tests detected these differences in normal (p_{normal} = 0.000), slow (p_{slow} = 0.018) and fast (p_{fast} = 0.000) walking speed. A comparison of mean values of these significant parameters shows that FFTB supinates less but pronates more while walking on the treadmill. This leads to a downwards shifting of the angle trajectory (Figure 19 a). Further, dorsi flexion is significantly greater for walking overground than for walking on the treadmill.

Regarding HFTB, the variances of ROM in frontal plane were not equal and therefore, ANOVA could not be conducted. Figure 19 b shows the motion of HFTB in sagittal plane at normal speed. In this plane statistically significant results could be obtained for maximum value (p_{ANOVA} = 0.000) and minimum value (p_{ANOVA} = 0.002), whereby post-hoc tests observed the differences in all three walking speeds ($p_{post\text{-}hoc} < 0.05$). This means dorsi flexion of HFTB increases and plantar flexion decreases while walking overground(Table 6).

Concerning the motion of HXFF in sagittal plane, no statistically relevant outcomes were obtained by ANOVA ($p_{ANOVA} > 0.05$) and therefore, the null hypotheses cannot be rejected.

Hip and knee motion (Figure 19 c-d) show significant differences for their maximum value and ROM ($p_{ANOVA} < 0.05$) for all three walking speeds ($p_{post\text{-}hoc}$ = 0.000). The walking condition does not interact with speed. A comparison of mean values (Table 6) lead to the result that flexion and ROM of the hip increases while walking on the treadmill. Concerning knee motion, similar outcomes were obtained – greater ROM and more flexion while walking on the treadmill. In regard to Foot GPS, no statistical differences could be observed.

Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD	Parameter	Compared Speed	Overground MV ± SD	Treadmill MV ± SD
Cadence	normal	110.4985 ± 5.6180	111.4024 ± 5.5261	**FFTB_sag_max**	normal	20.5120 ± 3.2608	18.6506 ± 4.4300
	slow	94.3572 ± 7.8827	99.2189 ± 8.0967		slow	20.9591 ± 3.4591	19.6768 ± 4.7814
	fast	123.7818 ± 5.8612	125.7181 ± 6.4502		fast	18.6634 ± 3.8198	15.6978 ± 4.4127
Walking Speed	normal	1.2093 ± 0.0897	1.0836 ± 0.2916	**HFTB_sag_max**	normal	13.2416 ± 3.0274	10.8893 ± 3.4427
	slow	0.8998 ± 0.0880	0.8464 ± 0.1514		slow	14.7118 ± 2.8880	12.4547 ± 3.2285
	fast	1.5345 ± 0.0970	1.4154 ± 0.2237		fast	11.5528 ± 3.2894	9.1242 ± 3.3922
Step Width	normal	0.0754 ± 0.0224	0.0522 ± 0.0140	**HFTB_sag_min**	normal	-9.5620 ± 4.8465	-11.5316 ± 5.4199
	slow	0.0739 ± 0.0274	0.0561 ± 0.0203		slow	-6.0014 ± 3.6768	-7.7438 ± 5.2071
	fast	0.0729 ± 0.0241	0.0447 ± 0.0119		fast	-11.4888 ± 5.5095	-14.5598 ± 5.4165
FFHF_front_rom	normal	7.0211 ± 1.6501	7.4402 ± 1.5651	**Hip_sag_max**	normal	38.1200 ± 3.9953	39.5227 ± 4.3518
	slow	6.5482 ± 1.9781	7.1592 ± 1.7703		slow	34.4154 ± 4.0307	36.6709 ± 4.1725
	fast	7.3314 ± 1.6594	8.0035 ± 1.8919		fast	41.5023 ± 5.0756	42.9547 ± 4.8703
FFTB_front_80Prz	normal	7.4966 ± 4.0518	5.9634 ± 4.3888	**Hip_sag_rom**	normal	42.9928 ± 3.4096	44.6876 ± 3.9656
	slow	8.2526 ± 4.3301	6.7401 ± 5.0690		slow	37.6533 ± 3.1608	39.7529 ± 3.2707
	fast	6.7074 ± 3.6421	5.5340 ± 4.1522		fast	49.8150 ± 4.1056	51.2100 ± 4.1387
FFTB_front_max	normal	13.9015 ± 4.2336	12.4728 ± 4.1239	**Knee_sag_max**	normal	68.3754 ± 3.3393	70.6597 ± 3.3014
	slow	13.9075 ± 4.5894	12.3221 ± 4.4681		slow	64.5634 ± 3.9326	67.9471 ± 4.0985
	fast	13.0635 ± 3.9540	11.5906 ± 4.3401		fast	69.0146 ± 2.7983	71.0990 ± 3.0682
FFTB_front_min	normal	-0.1024 ± 3.5859	-1.3286 ± 3.6558	**Knee_sag_rom**	normal	62.2286 ± 4.7242	64.6756 ± 4.5354
	slow	-0.3508 ± 3.7710	-1.6691 ± 3.9262		slow	57.4342 ± 4.9072	60.8424 ± 4.6289
	fast	-0.4330 ± 3.7308	-1.4394 ± 3.5476		fast	63.8194 ± 3.8077	65.7613 ± 3.6030

Table 6: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected significant differences. Data is gathered while walking overground and while walking on the treadmill Further, data is clustered according to Schwartz et al. (2008).

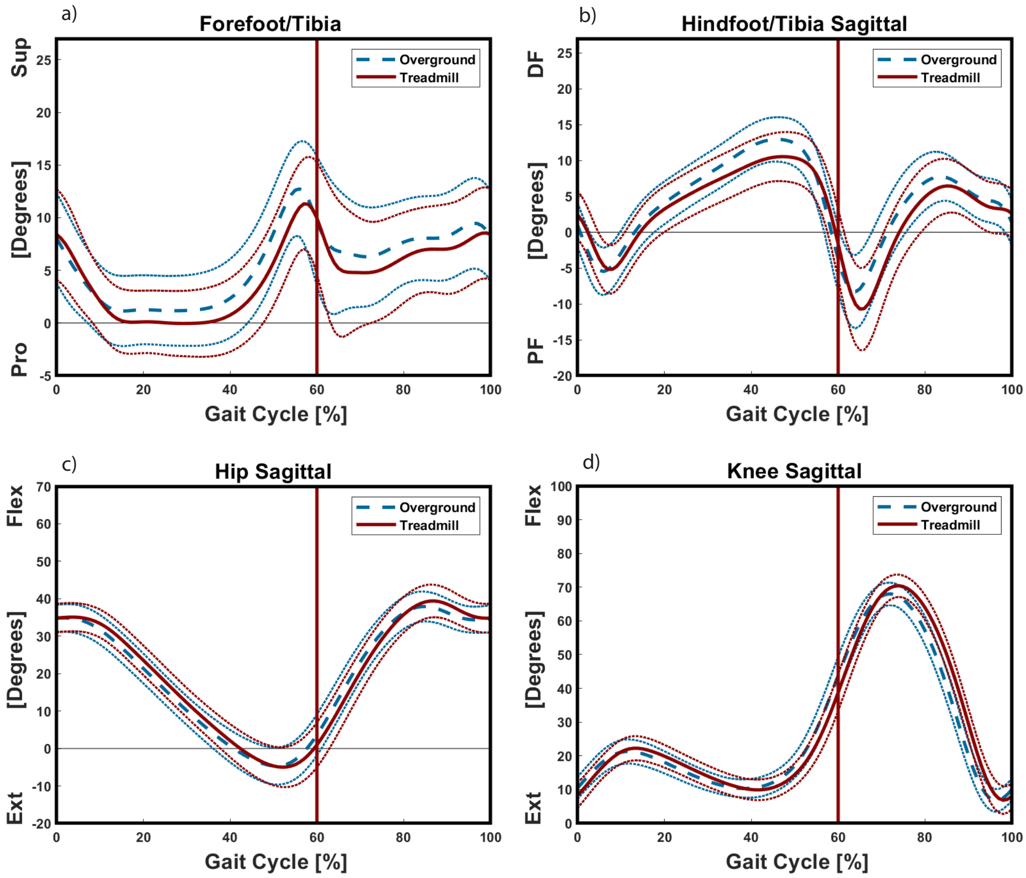

Figure 19: Angle trajectories between different segments in different planes at normal speed showing the difference between overground (blue dashed line) and treadmill (red solid line) walking. Data is clustered according to Schwartz et al. (2008).
a) FFTB front; b) HFTB sag; c) Hip sag; d) Knee sag

4.2. Effect of Speed

Results presented in this chapter are used to answer the second hypotheses, if any differences in foot angles and spatiotemporal parameters occur because of the walking speed. For the analysis, a one-way ANOVA was conducted. The subchapters are split into the different forms of clustering as well as into the two walking conditions (overground and treadmill).

Tables, which present statistical outcome in the subchapters below, are strucured as follows. The first column includes the name of the analysed parameter. The second and third column gives information about the normal distribution (ND), mean value (MV) and standard deviation (SD) of each examined dataset, whereby the first row contains data of the measurements at normal walking speed and the following two rows the data of slow and fast walking speed. If the result is significant ($p < 0.05$), the data is not normally distributed. The values of the fourth column represent the ourcome of the conducted ANOVA (sig.), whereas the last columns show the p-value of the post-hoc tests. Concerning this comparison, 1 refers to normal, 2 to slow and 3 to fast walking speed. Further, it is to mention that the significance level α of the ANOVA amounts 0.05 but for the comparison the conducted Bonferroni correction reduces α to 0.017. In addition, post-hoc tests are only valid if the result of the ANOVA is significant. Furthermore, the following subchapters include tables, which enable the comparison of mean values and standard deviations for each speed category.

4.2.1. Clustering according to self-selected speed

Overground

As presented in Table 7 ANOVA shows significant differences in both cadence and walking speed ($p_{ANOVA} < 0.05$). Based on results of the post-hoc tests the null hypotheses can be rejected as in all possible combinations of comparison p-value is smaller than 0.017. A comparison of mean values (Table 8) shows that cadence increases with increasing walking speed. Concerning step width, no significant differences could be observed. The results for cadence and walking speeds are also presented graphically in Figure 20. This figure contains the same data as Figure 15, but data, which is irrelevant for this comparison, is not presented.

The significant influence ($p_{ANOVA} < 0.05$) of speed on the motion in all three planes between FFHF are charted in Figure 21 a-c. At 80 % of the gate cycle significant differences are only detected in transversal plane ($p_{ANOVA} = 0.004$) between normal and slow ($p_{1:2} = 0.002$) and slow and fast ($p_{2:3} = 0.000$) walking speed concerning these segments. This means that the higher the walking speed, the more FFHF supinates and plantar flexes, but the less FFHF pronates and adducts

(Table 8), which leads to a downwards shifting of the angle trajectory (Figure 21 a). Futhermore, ROM in all planes is greater at higher walking speeds.

Parameter	ND	MV ± SD	sig.	p-value	
Cadence [steps/min]	0.58	114.0327 ± 7.5388	0.000	1:2	0.000
	0.99	99.4908 ± 9.7929		1:3	0.000
	0.51	122.4217 ± 9.7135		2:3	0.000
Walking Speed [m/s]	0.51	1.2851 ± 0.1176	0.000	1:2	0.000
	0.55	0.9889 ± 0.1377		1:3	0.000
	0.85	1.5277 ± 0.1492		2:3	0.000
Step Width [m]	0.56	0.0761 ± 0.0218	0.612	1:2	0.095
	0.13	0.0742 ± 0.0250		1:3	0.264
	0.53	0.0756 ± 0.0229		2:3	0.179
FFTB_front_80Prz	0.07	7.5894 ± 4.1053	0.001	1:2	0.026
	0.00	7.9865 ± 3.7672		1:3	0.001
	0.02	7.1055 ± 4.0902		2:3	0.000
FFTB_sag_80Prz	0.51	4.6686 ± 4.0204	0.008	1:2	0.001
	0.80	5.4950 ± 3.8100		1:3	0.002
	0.60	5.3740 ± 3.3655		2:3	0.235
FFTB_trans_80Prz	0.14	15.2895 ± 6.7304	0.000	1:2	0.009
	0.18	15.6547 ± 6.9004		1:3	0.000
	0.40	14.3180 ± 6.8937		2:3	0.000

Table 7: Statistical outcome for spatiotemporal parameters and FFTB at 80% of the gait cycle. The data is gathered while walking overground and is clustered according to self-selected speed. The second and third columns give information about the normal distirbution (ND) and the mean value (MV) and standard deviation (SD) of the dataset. If the value for ND is smaller than 0.05 the data is not normally distributed. The first row of each parameter for the columns ND and MV ± SD belong to the measurements conducted at normal speed. The following two rows contain information about measurements conducted at slow and fast walking speed. The fourth column presents the outcome of the ANOVA. If Sig. is smaller than 0.05 the analysed data show somewhere a significant difference. The last two columns give the p-value of the post-hoc tests for the comparisons normal to slow (1:2), normal to fast (1:3) and slow to fast (2:3) walking speed. If the p-value is smaller than 0.017 a significant difference is detected.

Regarding the motion between FFTB significant differences are observed at 80 % of the gait cycle in all three planes (Table 7). Data presented in Table 8 shows that FFTB supinates, dorsi flexes and adducts more, but plantar flexes less at higher walking speed. Further, speed affects the remaining evaluated parameters in sagittal and transversal plane, but not in frontal plane (Figure 21 d-f).

Besides the ROM of HFTB in frontal plane, all other parameters concerning entire gait cycle are significant different ($p_{ANOVA} < 0.05$) as presented in Figure 22 a-c. Furthermore, HFTB at 80 % of the gait cycle differs significantly between normal and fast ($p_{1:3} = 0.000$) and slow and fast ($p_{2:3} = 0.005$) walking speed. A comparison of mean values (Table 8) shows that internal rotation decreases and external rotation increases with increasing walking speed.

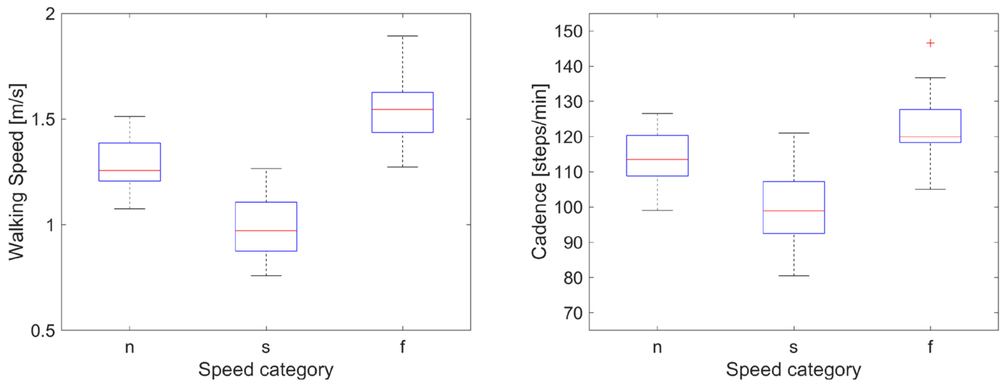

Figure 20: Comparison of measurements conducted overground at normal (n), slow (s) and fast (f) walking speed for the parameters walking speed (left) and cadence (right); Data is clustered according to self-selected speed.

The statistical significant angle trajectories for the motion between HXFF are demonstrated graphically in Figure 22 d and numerically in Table 8. The results show that HXFH dorsi flexes and plantar flexes more at higher walking speed.

For Foot GPS it is not possible to make a clear statement about the impact of speed, as its mean values are the lowest for normal speed, followed by fast and slow speed. Data used for this comparisons can be found in Table 8.

Regarding GRF (Figure 22 f), statistically relevant results were obtained for all possible comparisons ($p_{post\text{-}hoc} = 0.000$). The same outcome was received for the hip and knee motion in sagittal plane for all analysed parameters. The angle trajectory of the knee is presented in Figure 22 e. A look at Table 8 shows that flexion and extension of the hip increases with increasing walking speed. Concerning Foot GPS, measurements differ significantly for all possible comparisons ($p_{post\text{-}hoc} < 0.05$).

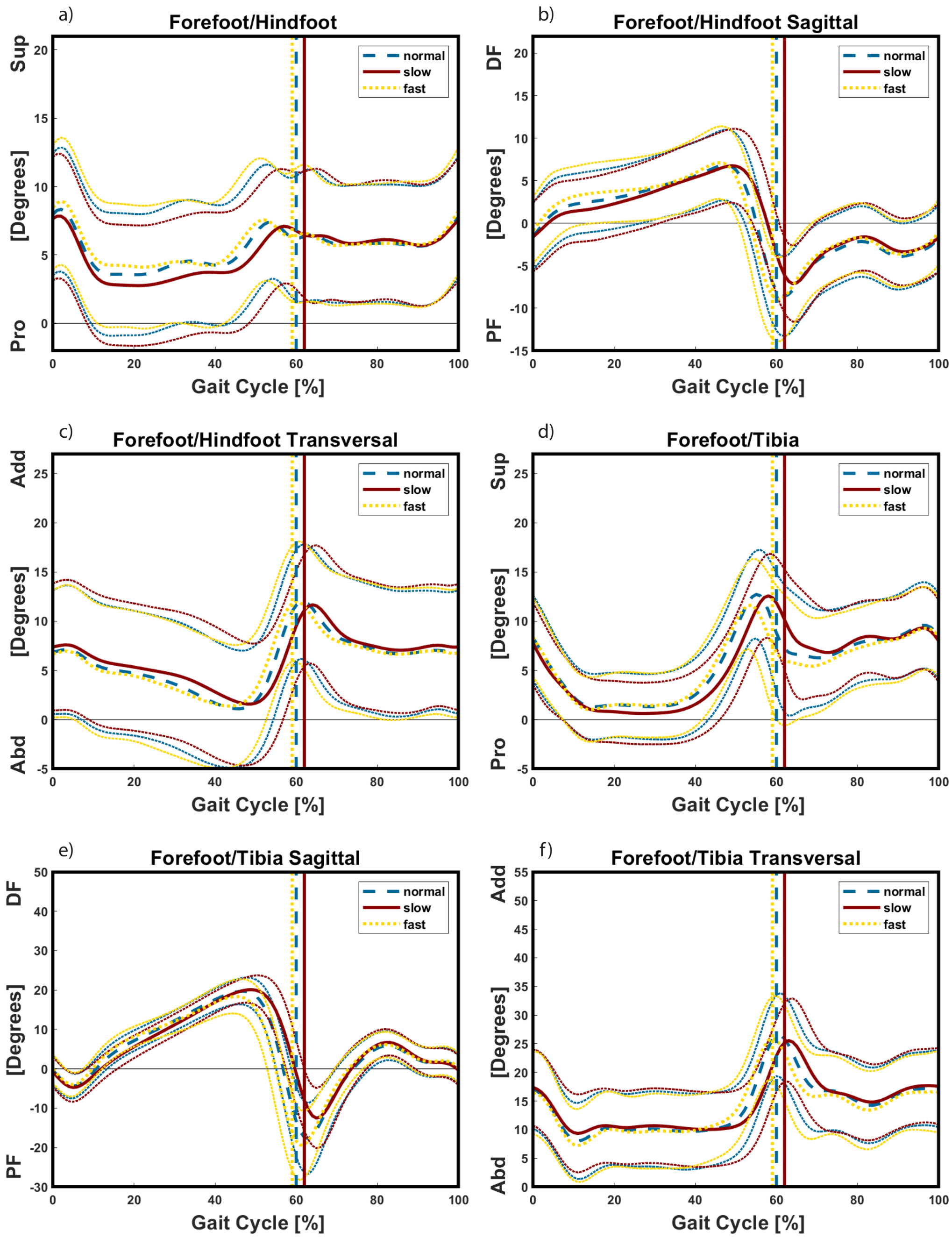

Figure 21: Angle trajectories between different segments in different planes while walking overground showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to self-selected speed.
a) FFHF front; b) FFHF sag; c) FFHF trans; d) FFTB front; e) FFTB sag; f) FFTB trans

Parameter	MV ± SD			Parameter	MV ± SD		
	slow	normal	fast		slow	normal	fast
Cadence	99.4908 ± 9.7929	114.0327 ± 7.5388	122.4217 ± 9.7135	**HFTB_front_max**	6.3554 ± 4.2834	6.4386 ± 4.3076	5.5748 ± 4.5510
Walking Speed	0.9889 ± 0.1377	1.2851 ± 0.1176	1.5277 ± 0.1492	**HFTB_front_min**	-4.1851 ± 3.8968	-4.4669 ± 4.1267	-4.9436 ± 4.5028
FFHF_front_max	8.9814 ± 4.4006	9.5720 ± 4.2546	10.0699 ± 4.5106	**HFTB_sag_max**	13.5505 ± 3.2495	13.0266 ± 3.0840	11.5189 ± 3.4152
FFHF_front_min	2.2216 ± 4.3629	2.5346 ± 4.3685	2.6205 ± 4.3678	**HFTB_sag_min**	-7.7646 ± 4.3426	-10.0259 ± 5.2832	-11.2435 ± 4.8914
FFHF_front_rom	6.7598 ± 1.7865	7.0375 ± 1.6614	7.4494 ± 1.8167	**HFTB_sag_rom**	21.3151 ± 4.2933	23.0525 ± 5.2518	22.7624 ± 4.9130
FFHF_sag_min	-7.7232 ± 4.5125	-9.0519 ± 4.6532	-9.6383 ± 4.8292	**HFTB_trans_max**	14.5844 ± 6.2246	15.1831 ± 6.2861	15.0053 ± 6.4514
FFHF_sag_rom	14.8070 ± 3.4230	16.1567 ± 3.8428	17.1754 ± 3.9242	**HFTB_trans_min**	2.5478 ± 5.7002	1.8941 ± 5.9492	1.2725 ± 5.9508
FFHF_trans_80Prz	7.4737 ± 6.4834	7.1616 ± 6.4617	6.9959 ± 6.7813	**HFTB_trans_rom**	12.0366 ± 3.2878	13.2889 ± 3.5941	13.7328 ± 3.6356
FFHF_trans_min	1.1418 ± 6.0909	0.8192 ± 5.8830	1.0120 ± 6.1046	**HXFF_sag_max**	11.7681 ± 9.7728	13.1872 ± 9.9229	15.0529 ± 11.3918
FFHF_trans_rom	11.0102 ± 2.0475	11.4784 ± 2.1113	11.3916 ± 2.2283	**HXFF_sag_min**	-14.2553 ± 6.2635	-14.1360 ± 6.3598	-14.4722 ± 7.5393
FFTB_front_80Prz	7.9865 ± 3.7672	7.5894 ± 4.1053	7.1055 ± 4.0902	**HXFF_sag_rom**	26.0234 ± 7.1021	27.3232 ± 8.0009	27.5251 ± 7.9363
FFTB_front_max	13.7535 ± 3.9718	13.8912 ± 4.2828	13.2186 ± 4.1654	**GRF_x_max**	16.1256 ± 2.9250	21.5722 ± 2.5866	25.3876 ± 3.1798
FFTB_sag_80Prz	5.4950 ± 3.8100	4.6686 ± 4.0204	5.3740 ± 3.3655	**GRF_x_min**	-12.5571 ± 2.1857	-17.6175 ± 2.7163	-21.9286 ± 3.9523
FFTB_sag_max	20.7344 ± 3.3646	20.1541 ± 3.3979	18.9814 ± 4.3650	**Hip_sag_max**	36.4555 ± 4.6635	38.7650 ± 4.5532	40.5556 ± 5.3347
FFTB_sag_min	-13.9535 ± 7.4984	-18.4861 ± 8.9023	-20.6159 ± 8.5495	**Hip_sag_min**	-3.4943 ± 4.8542	-5.4156 ± 4.9559	-8.1261 ± 5.2153
FFTB_sag_rom	34.6879 ± 7.3437	38.6402 ± 8.4659	39.5972 ± 8.0569	**Hip_sag_rom**	39.9498 ± 4.2257	44.1806 ± 4.2910	48.6817 ± 5.3248
FFTB_trans_80Prz	15.6547 ± 6.9004	15.2895 ± 6.7304	14.3180 ± 6.8937	**Knee_sag_max**	66.3208 ± 4.1079	68.6812 ± 3.3481	68.4882 ± 2.7565
FFTB_trans_min	8.0001 ± 6.3684	7.0033 ± 6.2775	6.3715 ± 6.1017	**Knee_sag_min**	6.2699 ± 3.3254	6.0356 ± 3.2027	5.3689 ± 2.8171
FFTB_trans_rom	18.7558 ± 3.9678	20.4236 ± 4.1718	20.7793 ± 4.3871	**Knee_sag_rom**	60.0509 ± 5.6541	62.6456 ± 4.8228	63.1193 ± 3.6849
HFTB_front_80Prz	2.0583 ± 4.0786	1.9377 ± 4.0843	1.3870 ± 4.3606	**Foot_GPS**	6.4850 ± 1.5636	6.0923 ± 1.5138	6.1702 ± 1.6460

Table 8: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected significant differences. Data is gathered while walking overground and clustered according to self-selected speed.

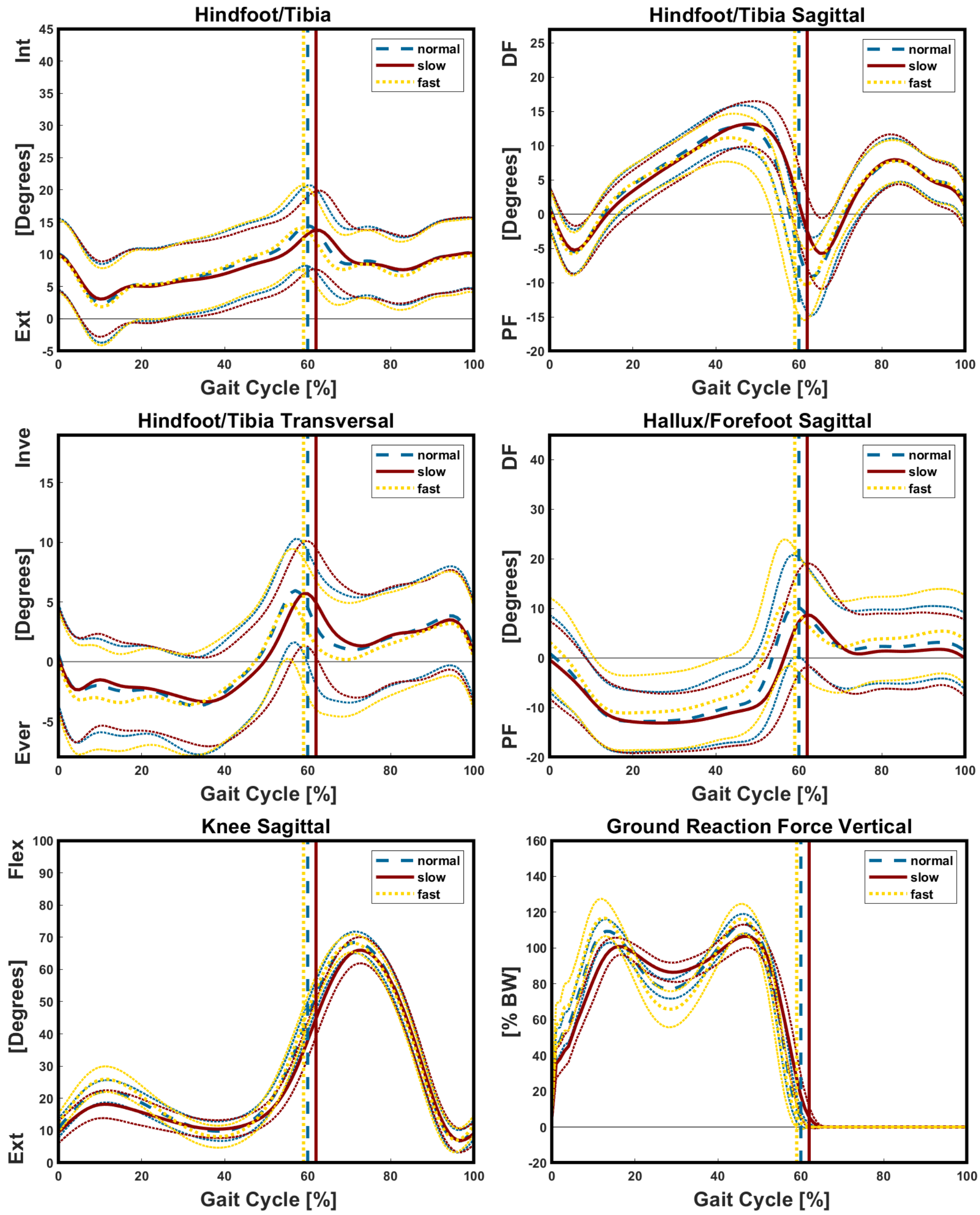

Figure 22: Angle trajectories between different segments in different planes and vertical GRF while walking overground showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to self-selected speed.
a) FFTB front; b) FFTB sag; c) FFTB trans; d) HXFF sag; e) Knee sag, f) GRF vertical

Treadmill

Concerning spatiotemporal parameters cadence and walking speed differ for all three possible comparisons significantly as shown in Table 10. Mean values (Table 11) show that cadence increases with increasing walking speed, whereas step width decreases. The significant differences are presented graphically in Figure 23. This figure contains the same data as Figure 15, but only relevant data is shown.

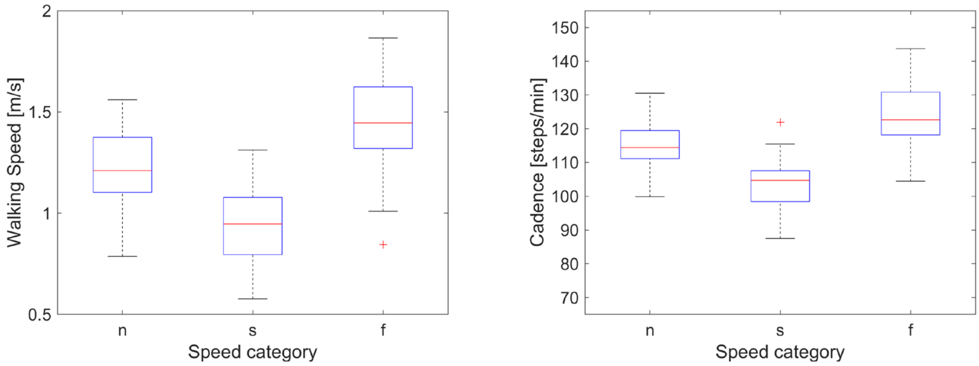

Figure 23: Comparison of measurements conducted on the treadmill at normal (n), slow (s) and fast (f) walking speed for the parameters walking speed (left) and cadence (right); Data is clustered according to self-selected speed.

Regarding the OFM, the angle between FFHF is significantly influenced by speed in the frontal and sagittal plane (Figure 24 a-b), but not in transversal plane (Figure 24 c). Based on the data given in Table 11, this means that FFHF supinates and pronates more at higher walking speed, which leads to a greater ROM in frontal plane. Furthermore, ROM increases in sagittal plane as well as FFHF plantar flexes more.

A look at the data at 80 % of the gait cycle demonstrates that significant values can be found in each possible segment combination; however in different planes. Detailed information about the statistical outcome is given in Table 10. Regarding the snapshot at 80 % of the gait cylce, less adduction at higher speeds were detected for FFHF (Table 11). Further, data of Table 11 shows that FFTB supinates less at higher speeds at 80 % of the gait cycle, whereas internal rotation of HFTB decreases and external rotation increases.

Regarding the entire gait cycle, significant results could only be observed in the frontal plane between normal and fast walking speed at the maximum value ($p_{1:3} = 0.002$) and ROM ($p_{1:3} = 0.002$) for FFTB (Figure 24 d). In case of the motion between FFTB in sagittal plane (Figure 24 e), all values are significant ($p_{post\text{-}hoc} < 0.017$). Considering the movement between FFTB in transversal plane (Figure 24 f), significant differences are detected for the minimum value for all three combinations and for ROM. However, ROM is not significantly affected by speed for the comparison normal to fast walking speed. Furthermore, the maximum value of FFTB in transversal plane differs significantly ($p_{ANOVA} = 0.089$). The mean values (Table 11) show that FFTB supinates less at higher speeds, which further leads to a lower ROM. Furthermore, a higher walking speed leads to a decrease in dorsiflexion and an increase in plantarflexion, which results in a shifting of the angle trajectory and in a greater ROM in sagittal plane. ROM also increases in transversal plane at higher walking speed as FFTB shows less abduction.

Concerning the movement between HFTB, outcome is in all planes for all values significantly different, excluding the in Table 9 presented combinations. The according data is presented in Figure 25 a-c. Data given in Table 11 shows that internal rotation of HFTB increases, but external rotation decreases with decreasing walking. Furthermore, HFTB dorsi flexes less but plantar flexes more at higher walking speed, which leads to a greater ROM in sagittal plane. In transversal an increase in ROM can also be observed with increasing walking speed as inversion and eversion increases.

The motion between HXFF in sagittal plane shows for all values in most combinations significant results. The differences can be observed graphically in Figure 25 d. A comparison of the mean values given in Table 11 shows that dorsiflexion and plantarflexion increase with increasing walking speeds, which further results in a greater ROM.

Regarding the motion of the hip and knee, angle trajectories are shown in Figures 25 e-f. For the hip statistical analysis obtained significant results for all parameters and all possible combinations ($p_{post\text{-}hoc} = 000$). Concerning the knee, no statistical relevant outcome was received for the comparison normal to fast speed for the parameters maxium value, minimum value and ROM. Mean values (Table 11) detected an more flexion and extension of the hip and knee at higher walking speed compared to lower speed. Furthermore, greater ROM was detected.

Regarding the Foot GPS, a statistical difference could be observed between normal and slow and slow and fast walking speed ($p_{1:2;2:3}$ = 0.000).Concerning Foot GPS, an increase caused by decreasing walking speed is implied.

Parameter	Sig.	p - Value	
HFTB_front_max	0.021	1:2	0.215
HFTB_front_min	0.000	1:3	0.311
HFTB_front_rom	0.048	2:3	0.289
HFTB_sag_rom	0.000	1:3	0.018
HFTB_trans_max	0.023	1:3	0.197
		2:3	0.023

Table 9: Comparison of walking speed for different parameters, wich do not show significant difference. Data is gathered while walking on the treadmill and clustered according to self-selected speed.

Parameter	ND	MV ± SD	Sig.	p-Value	
Cadence [steps/min]	0.97	114.6616 ± 7.4666	0.000	1:2	0.000
	0.72	102.9401 ± 8.7758		1:3	0.000
	1.00	123.8600 ± 9.6817		2:3	0.000
Walking Speed [m/s]	0.00	1.1731 ± 0.3223	0.000	1:2	0.000
	0.75	0.9438 ± 0.1938		1:3	0.001
	0.50	1.4276 ± 0.2700		2:3	0.000
Step Width [m]	0.89	0.0518 ± 0.0140	0.037	1:2	0.101
	0.48	0.0540 ± 0.0189		1:3	0.031
	0.96	0.0487 ± 0.0139		2:3	0.007
FFHF_trans_80Prz	0.23	7.5400 ± 6.8699	0.014	1:2	0.000
	0.43	7.8598 ± 6.7356		1:3	0.083
	0.06	7.3067 ± 7.0289		2:3	0.002
FFTB_front_80Prz	0.45	5.8873 ± 4.5197	0.018	1:2	0.003
	0.02	6.4615 ± 4.3319		1:3	0.081
	0.34	6.0716 ± 4.2602		2:3	0.032
FFTB_sag_80Prz	0.16	3.1985 ± 4.3584	0.049	1:2	0.006
	0.57	3.9645 ± 4.5291		1:3	0.006
	0.54	3.9275 ± 4.0670		2:3	0.309
FFTB_trans_80Prz	0.50	15.9006 ± 6.7678	0.000	1:2	0.015
	0.47	16.2325 ± 6.8024		1:3	0.000
	0.54	15.2283 ± 6.7035		2:3	0.000
HFTB_front_80Prz	0.59	0.5971 ± 4.5969	0.002	1:2	0.001
	0.62	1.0675 ± 4.4885		1:3	0.288
	0.44	0.5703 ± 4.6393		2:3	0.001

Table 10: Statistical outcome for spatiotemporal parameters and FFTB and HFTB at 80% of the gait cycle . Data is gathered while walking on the treadmill and clustered according to self-selected speed .

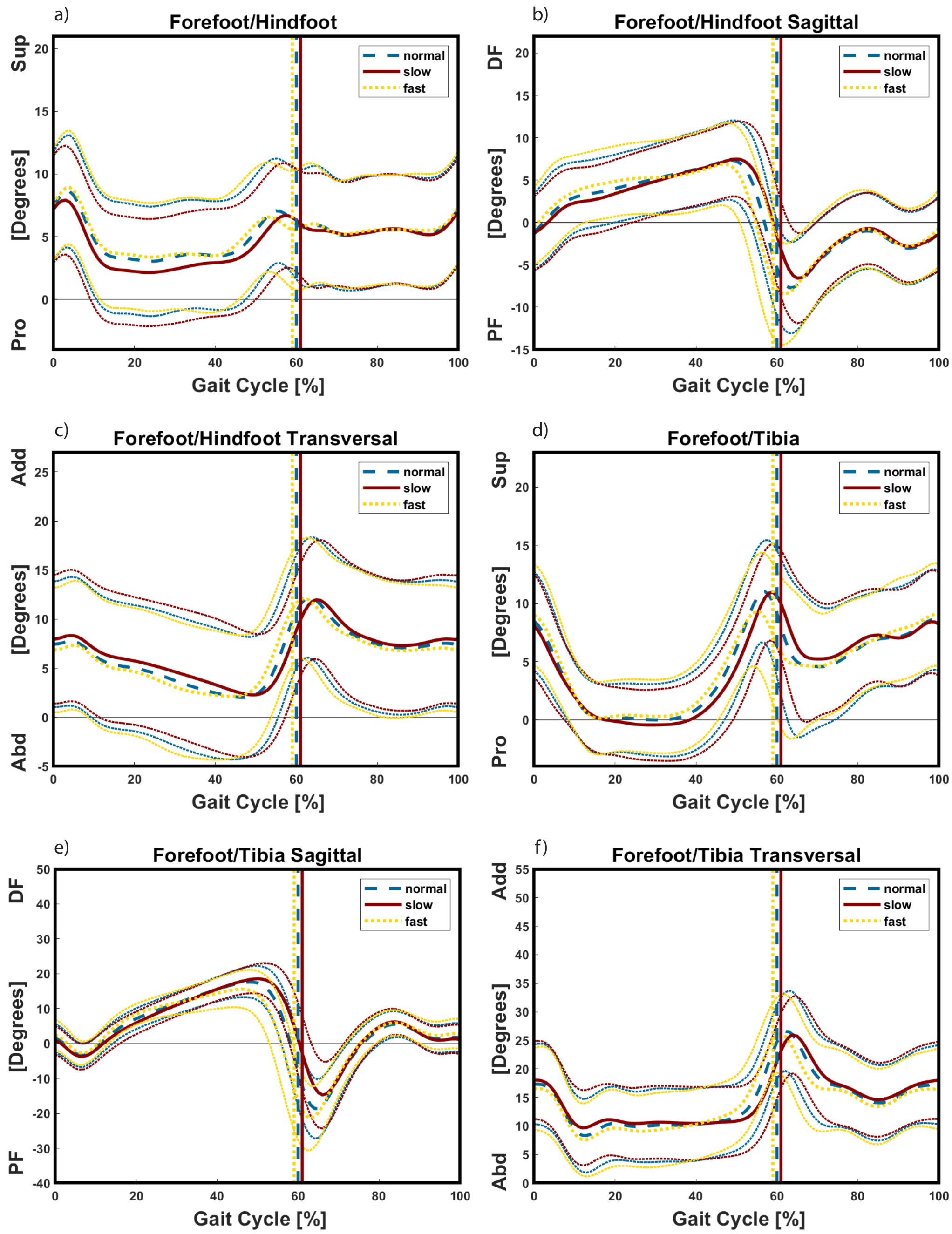

Figure 24: Angle trajectories between different segments in different planes while walking on the treadmill showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to self-selected speed.
a) FFHF front; b) FFHF sag; c) FFHF trans; d) FFTB front; e) FFTB sag; f) FFTB trans

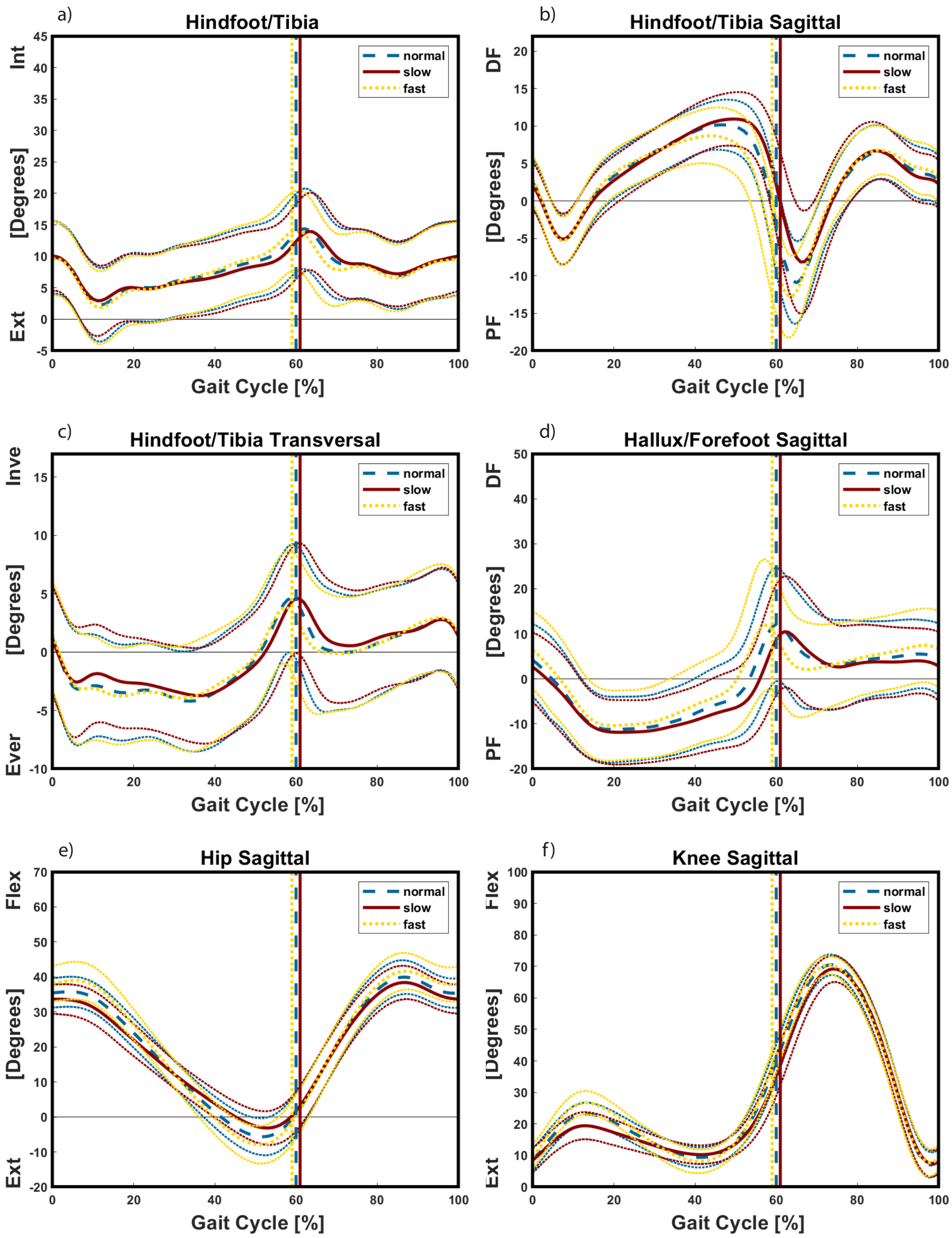

Figure 25: Angle trajectories between different segments in different planes while walking on the treadmill showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to self-selected speed.
a) FFTB front; b) FFTB sag; c) FFTB trans; d) HXFF sag; e) Hip sag; f) Knee sag

Parameter	MV ± SD			Parameter	MV ± SD		
	slow	normal	fast		slow	normal	fast
Cadence	102.9401 ± 8.7758	114.6616 ± 7.4666	123.8600 ± 9.6817	**HFTB_front_max**	5.3754 ± 4.6654	5.2913 ± 4.6071	4.8880 ± 4.8436
Walking Speed	0.9438 ± 0.1938	1.1731 ± 0.3223	1.4276 ± 0.2700	**HFTB_front_min**	-4.5749 ± 4.2919	-5.2043 ± 4.6396	-5.1901 ± 4.7292
Step Width	0.0540 ± 0.0189	0.0518 ± 0.0140	0.0487 ± 0.0139	**HFTB_front_rom**	9.9502 ± 1.9572	10.4955 ± 2.1905	10.0781 ± 2.1832
FFHF_front_max	8.8210 ± 4.1102	9.5386 ± 4.3249	9.8174 ± 4.5105	**HFTB_sag_max**	11.4334 ± 3.6065	10.5727 ± 3.3840	9.4109 ± 3.4551
FFHF_front_min	1.5436 ± 4.2023	1.9396 ± 4.2595	1.9360 ± 4.2049	**HFTB_sag_min**	-9.8474 ± 5.9544	-11.7947 ± 5.4714	-13.7834 ± 5.1918
FFHF_front_rom	7.2773 ± 1.6181	7.5990 ± 1.6255	7.8813 ± 1.9415	**HFTB_sag_rom**	21.2808 ± 5.4076	22.3674 ± 5.3248	23.1943 ± 4.6907
FFHF_sag_min	-7.0866 ± 5.1549	-8.2655 ± 5.3192	-9.3310 ± 5.6985	**HFTB_trans_max**	14.6212 ± 6.2058	15.2506 ± 6.3884	15.1442 ± 6.3918
FFHF_sag_rom	14.8555 ± 3.5555	15.9202 ± 3.7019	16.7815 ± 3.7801	**HFTB_trans_min**	2.4213 ± 5.4093	1.7814 ± 5.7937	1.1941 ± 5.8615
FFHF_trans_80Prz	7.8598 ± 6.7356	7.5400 ± 6.8699	7.3067 ± 7.0289	**HFTB_trans_rom**	12.1999 ± 3.4670	13.4692 ± 3.6735	13.9501 ± 3.5040
FFTB_front_80Prz	6.4615 ± 4.3319	5.8873 ± 4.5197	6.0716 ± 4.2602	**HXFF_sag_max.**	14.2468 ± 11.1636	15.9553 ± 11.2017	17.1456 ± 11.5843
FFTB_front_max	12.3323 ± 3.8752	12.3612 ± 4.1497	11.7897 ± 4.3989	**HXFF_sag_min**	-12.7298 ± 7.2206	-12.4402 ± 7.4236	-11.4506 ± 7.6181
FFTB_front_rom	13.6195 ± 2.7095	13.6430 ± 2.9895	13.0272 ± 3.3440	**HXFF_sag_rom**	26.9766 ± 9.4440	28.3955 ± 9.4232	28.5962 ± 9.2084
FFTB_sag_80Prz	3.9645 ±4.5291	3.1985 ± 4.3584	3.9275 ± 4.0670	**Hip_sag_max**	38.5644 ± 4.6950	40.0716 ± 4.8144	52.0447 ± 5.4753
FFTB_sag_max	19.2212 ± 4.4510	18.1916 ± 4.5869	16.2930 ± 5.4818	**Hip_sag_min**	-3.3816 ± 4.8465	-5.8718 ± 5.2937	-8.2200 ± 5.3892
FFTB_sag_min	-15.8007 ± 9.4098	-19.6278 ± 8.5652	-22.7248 ± 8.9049	**Hip_sag_rom**	41.9460 ± 4.3131	45.9434 ± 4.9130	50.2648 ± 5.6981
FFTB_sag_rom	35.0219 ± 8.5404	37.8194 ± 7.6403	39.0178 ± 7.0981	**Knee_sag_max**	69.4689 ± 4.0990	70.7665 ± 3.2274	70.6956 ± 2.8935
FFTB_trans_80Prz	16.2325 ± 6.8024	15.9006 ± 6.7678	15.2283 ± 6.7035	**Knee_sag_min**	6.3761 ± 3.3776	5.8594 ± 3.2243	5.5476 ± 3.2603
FFTB_trans_min	8.2822 ± 6.0274	7.2964 ± 6.0839	6.6396 ± 6.1909	**Knee_sag_rom**	63.0928 ± 5.1820	64.9070 ± 4.3201	65.1480 ± 3.8070
FFTB_trans_rom	18.5326 ± 4.3860	20.2856 ± 4.2878	20.7976 ± 4.1282	**Foot_GPS**	6.6844 ± 1.8431	6.4078 ± 1.7694	6.3278 ± 1.8431
HFTB_front_80Prz	1.0675 ± 4.4885	0.5971 ± 4.5969	0.5703 ± 4.6393				

Table 11: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected significant differences. Data is gathered while walking on the treadmill and clustered according to self-selected speed.

4.2.2. Clustering according to Schwartz et al. (2008)

Overground

Regarding spatiotemporal parameters, ANOVA shows significant results for cadence and walking speed (p_{ANOVA} = 0.000). The post-hoc tests detected differences between all possible combinations for both parameters ($p_{post\text{-}hoc}$ = 0.000). For better representation, the results are shown as boxplots in Figure 26. The graphically illustrated data includes data used for Figure 18, but only contains information relevant to the comparison of this chapter. Data presented in Table 12 shows that cadence increases with increasing walking speed. Regarding step width, ANOVA did not detect any significant differences.

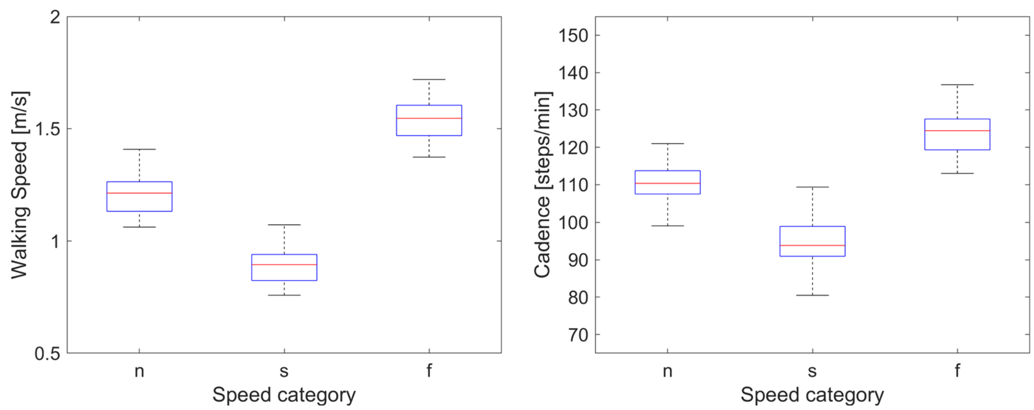

Figure 26: Comparison of measurements conducted overground at normal (n), slow (s) and fast (f) walking speed for the parameters walking speed (left) and cadence (right); Data is clustered according to Schwartz et al. (2008).

At 80% of the gait cycle statistically significant results were obtained for FFTB in transverse plane ($p_{2:3}$ = 0.044) and HFTB in frontal plane ($p_{2:3}$ = 0.040) between slow and fast walking speed. Concerning FFTB, this means that dorsiflexion decreases with higher walking speed (Table 12). Furthermore, internal rotation of HFTB decreases.

Differences were observed for the minimum value of FFHF in transversal plane between slow and fast walking speed ($p_{2:3}$ = 0.029). Data presented in Table 12 shows that abduction as well as ROM increases with increasing walking speed.

Concerning FFTB, minimum value ($p_{2:3}$ = 0.000), maximum value ($p_{2:3}$ = 0.031) and ROM ($p_{2:3}$ = 0.006) differ significantly for the comparison of slow to fast walking speed in sagittal plane. In transversal plane the null hypotheses can only be rejected for the minimum value (p_{ANOVA} = 0.022) and for ROM (p_{ANOVA} = 0.044). For both values post-hoc tests observed the differences between slow and fast walking speed, whereby the p-value for minimum value amounts 0.036 and for ROM 0.040. The angle movement between FFTB is graphically presented in Figure 27 a-b and numerically in Table 12. Obtained data shows that FFTB dorsi flexes less, whereas plantar flexion and abduction increases with increasing walking speed. Furthermore ROM is greater in sagittal and transversal plane at higher walking speed.

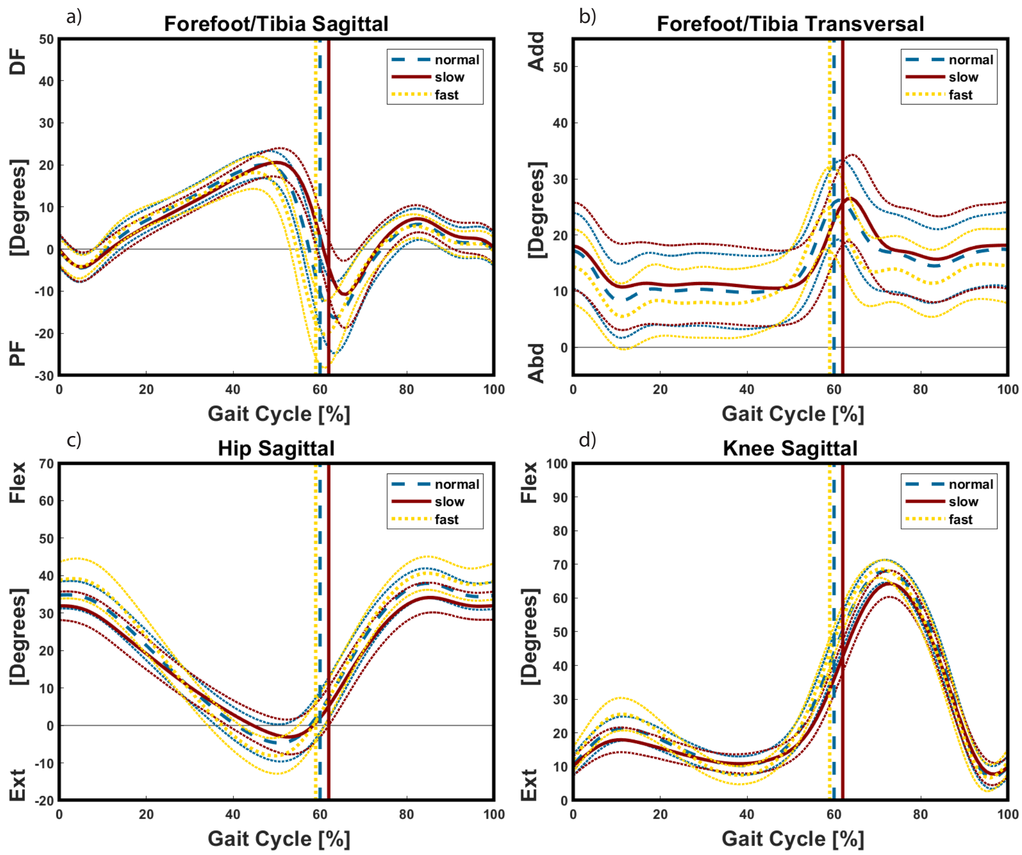

Figure 27: Angle trajectories between different segments in different planes while overground walking showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to Schwartz et al. (2008).
a) FFTB sag; b) FFTB trans; c) Hip sag; d) Knee sag

In regard to the motion between HFTB, it was not possible to conduct the ANOVA in sagittal plane for the minimum value as Levene's test observed unequal variances ($p_{Levene} = 0.034$). However, for the maximum value in sagittal plane the ANOVA was valid and observed a statistically relevant difference ($p_{ANOVA} = 0.001$). The difference was detected between normal and fast ($p_{1:3} = 0.044$) and between slow and fast ($p_{2:3} = 0.000$) walking speed. Concerning the transversal plane, null hypotheses can only be rejected for ROM between slow and fast walking speed ($p_{2:3} = 0.013$). Regarding mean values presented in Table 12, an decrease of dorsi flexion at higher walking speed can be observed, whereas in transversal plane ROM increases.

Furthermore, it was not possible to conduct ANOVA for the GRF parameters as in both cases the p-value of the Levene's test is lower than its significance level. Regarding the motion of the hip in sagittal plane (Figure 27 c) significant differences are observed for maximum value, minimum value and ROM for all combinations excluding the comparison of normal and slow speed for the minimum value. Concerning the motion of the knee (Figure 27 d), statistically relevant differences are obtained for its maximum and minimum value ($p_{ANOVA} = 0.000$). In both cases post-hoc tests observed the differences between normal to slow and slow to fast walking speed. A look at the mean values (Table 12), indicates a reduction in flexion and extension for the knee and the hip, which finally leads to a lower ROM, is observed for lower walking speeds. The Foot GPS is significantly influenced by speed concerning the comparison slow to fast ($p_{2:3} = 0.045$) as mean value decreases with increasing walking speed (Table 12).

Parameter	MV ± SD		
	slow	normal	fast
Cadence	94.3572 ± 7.8827	110.4985 ± 5.6180	123.7818 ± 5.8612
Walking Speed	0.8998 ± 0.0880	1.2093 ± 0.0897	1.5345 ± 0.0970
FFHF_trans_min	2.8133 ± 6.3881	0.8764 ± 5.8455	-0.9322 ± 4.5447
FFTB_sag_max	20.9591 ± 3.4591	20.5120 ± 3.2608	19.6634 ± 3.8198
FFTB_sag_min	-11.9675 ± 7.6932	-17.4075 ± 8.5183	-21.0820 ± 8.0862
FFTB_sag_rom	32.9266 ± 8.3236	37.9195 ± 8.2794	39.7454 ± 8.8629
FFTB_trans_80Prz	16.5543 ± 7.8036	15.3833 ± 6.8182	12.2971 ± 6.0466
FFTB_trans_min	9.0358 ± 7.1052	7.2704 ± 6.2494	4.6002 ± 5.5539
FFTB_trans_rom	18.3818 ± 3.8528	20.1589 ± 4.0765	21.1217 ± 4.8279
HFTB_front_80Prz	2.9826 ± 4.2557	1.9281 ± 4.0891	0.3872 ± 4.0241
HFTB_sag_max	14.7118 ± 2.8880	13.2416 ± 3.0274	11.5528 ± 3.2894
HFTB_trans_rom	11.4357 ± 2.8224	13.1619 ± 3.4189	13.9679 ± 3.8812
Hip_sag_max	34.4154 ± 4.0307	38.1200 ± 3.9953	41.5023 ± 5.0756
Hip_sag_min	-3.2378 ± 4.6537	-4.8728 ± 4.9583	-8.3082 ± 4.7645
Hip_sag_rom	37.6533 ± 3.1608	42.9928 ± 3.4096	49.8105 ± 4.1056
Knee_sag_max	64.5634 ± 3.9326	68.3754 ± 3.3393	69.0146 ± 2.7983
Knee_sag_rom	57.4342 ± 4.9072	62.2286 ± 4.7242	63.8194 ± 3.8077
Foot_GPS	6.8918 ± 1.6412	6.1475 ± 1.4962	5.9801 ± 1.2874

Table 12: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected signifant differences. Data is gathered while overground walking and clustered according to Schwartz et al. (2008).

Treadmill

Concerning spatiotemporal parameters, ANOVA detected significant differences in cadence ($p_{ANOVA} = 0.000$) and walking speed ($p_{ANOVA} = 0.000$) (Figure 25). Post-hoc tests showed that differences occur in all three possible combinations ($p_{post-hoc} < 0.000$). Data presented in Table 13 indicates that cadence increases with increasing walking speed.

Concerning the OFM, no significant differences were observed at 80 % of the gait cycle. Regarding the other analysed parameters, a significant difference was detected in the maximum value of FFHF in frontal plane for the comparison of slow to fast walking speed ($p_{2:3} = 0.043$), which can be observed as an increase in supination with increasing walking speed (Table 13).

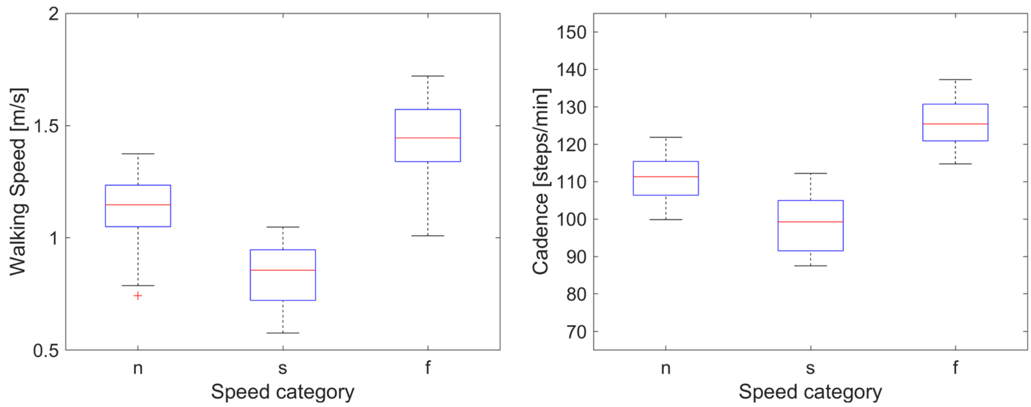

Figure 28: Comparison of overground measurements conducted at normal (n), slow (s) and fast (f) walking speed for the parameters walking speed (left) and cadence (right); Data is clustered according to Schwartz et al. (2008).

In regard to FFTB, maximal value, minimum value and ROM are affected by speed significantly in sagittal plane as shown in Figure 29 a. Maximum value differs for the comparisons of normal to fast ($p_{1:3} = 0.013$) and slow to fast walking speed ($p_{2:3} = 0.002$). The minimum value shows significant values for all three possible comparisons, whereas ROM only differs for the comparison slow to fast walking speed ($p_{2:3} = 0.008$). In transversal plane (Figure 29 b) the results are significantly different for the comparison fast to slow walking speed for the minimum value ($p_{2:3} = 0.020$) and for ROM ($p_{2:3} = 0.003$). A comparison of mean values (Table 13) shows, that FFTB dorsi flexes less but plantar flexes more at higher walking speed and further has a greater ROM in sagittal plane. In transversal plane ROM increases but adduction is reduced.

HFTB is significantly influenced by speed in sagittal plane as graphically presented in Figure 29 c. The minimum value shows significant differences for all three comparisons, whereas the maximum value and ROM just differ between slow and fast walking speed. Concerning the transversal plane, significant differences were observed for ROM between slow and fast walking speed. Mean values (Table 13) show that dorsi flexion increases but plantar flexion decreases at higher walking speed, which leads to a greater ROM in sagittal plane. This increase can also be observed for ROM in transversal plane.

Regarding motion of the hip (Figure 29 d), all parameters are significantly different for all combinations besides the minimum value for the comparison of normal to slow walking speed ($p_{1:2} = 0.194$). The hip motion obtained significant results for maximum value and ROM for the comparisons normal to slow and slow to fast walking speed. In regard to mean values (Table 13), this means that the hip flexes and extenses more at faster walking speed. The Foot GPS is not statistically influenced by walking speed ($p_{ANOVA} = 0.068$).

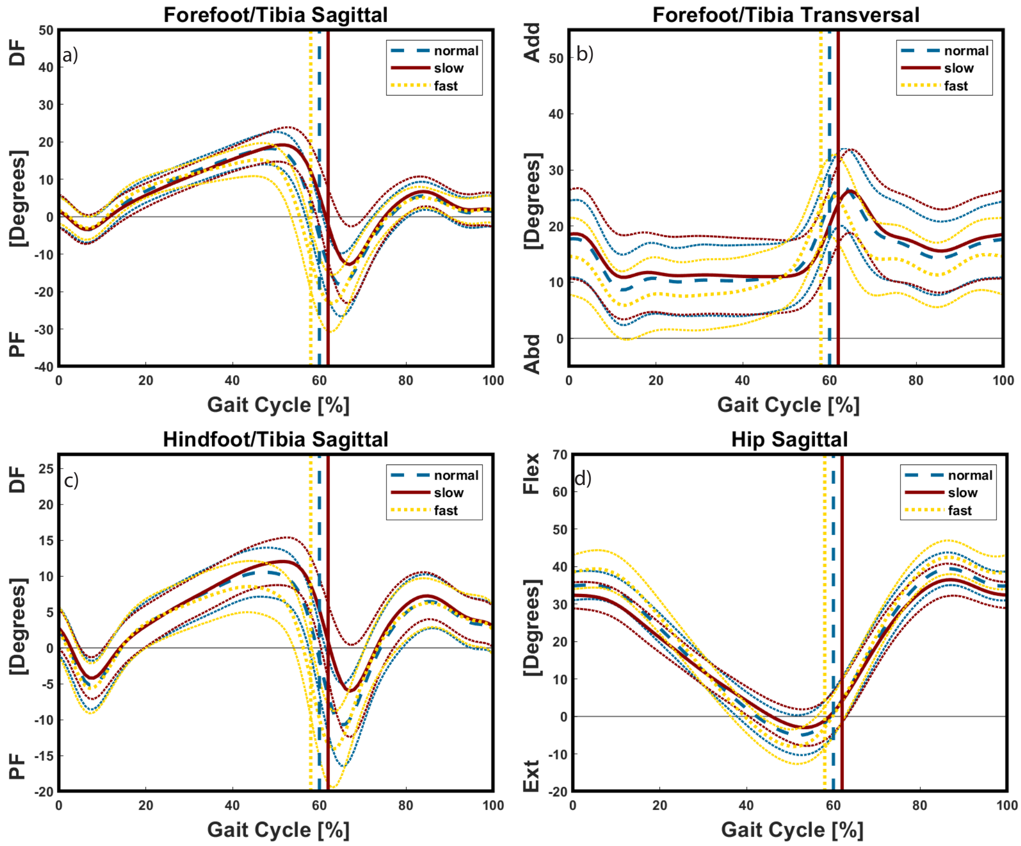

Figure 29: Angle trajectories between different segments in different planes while walking on the treadmill showing the difference between normal (blue dashed line), slow (red solid line) and fast (yellow dotted line) walking speed. Data is clustered according to Schwartz et al. (2008).
a) FFTB sag; b) FFTB trans; c) HFTB sag; d) Hip sag

Parameter	MV ± SD		
	slow	normal	fast
Cadence	99.21889 ± 8.0967	111.4024 ± 5.8261	125.7181 ± 6.4502
Walking Speed	0.8464 ± 0.1514	1.0836 ± 0.2916	1.4154 ± 0.2237
FFHF_front_max	8.1457 ± 4.2334	9.1705 ± 4.1809	10.1327 ± 4.0616
FFTB_sag_max	19.6768 ± 4.7814	18.6506 ± 4.4300	15.6978 ± 4.4127
FFTB_sag_min	-13.4331 ± 9.8467	-18.9106 ± 8.5183	-23.8739 ± 7.6960
FFTB_sag_rom	33.1099 ± 9.3701	37.5612 ± 7.8419	39.5716 ± 7.8815
FFTB_trans_min	9.0845 ± 6.7474	7.5797 ± 5.9793	4.8331 ± 5.7008
FFTB_trans_rom	17.7373 ± 4.2147	20.1744 ± 4.1491	21.4140 ± 4.5565
HFTB_sag_max	12.4547 ± 3.2285	10.8893 ± 3.4427	9.1242 ± 3.3922
HFTB_sag_min	-7.7438 ± 5.2071	-11.5316 ± 5.4199	-14.5598 ± 5.4165
HFTB_sag_rom	20.1958 ± 5.2059	22.4209 ± 5.4350	23.6840 ± 5.1923
HFTB_trans_rom	11.4145 ± 3.2355	13.3604 ± 3.5316	14.5055 ± 3.4404
Hip_sag_max	36.6709 ± 4.1725	39.5227 ± 4.3518	42.9547 ± 4.8703
Hip_sag_min	-3.0819 ± 4.8876	-5.1649 ± 5.3228	-8.2552 ± 4.5740
Hip_sag_rom	39.7529 ± 3.2707	44.6876 ± 3.9656	51.2100 ± 4.1387
Knee_sag_max	67.9471 ± 4.0985	70.6597 ± 3.3014	71.0990 ± 3.0682
Knee_sag_rom	60.8424 ± 4.6289	64.6756 ± 4.5354	65.7613 ± 3.6030

Table 13: Mean value (MV) ± standard deviation (SD) of parameters, for which ANOVA detected significant differences. Data is gathered while walking on the treadmill and clustered according to Schwartz et al. (2008)

5. Discussion and Interpretation

The chapter “Discussion and Interpretation” is divided according to the two research question of this study - the effect of walking condition and the effect of walking speed on gait patterns.

5.1. Effect of Walking Condition

As subjects had to walk at least for 5 minutes on the treadmill before measurements were conducted, gait patterns should have stabilised according to Matsas et al. (2000) and Lavcanska et al. (2005). However, in this study significant differences were still observed.

All in all similar results were obtained for clustering according to self-selected speed and for clustering according to Schwartz et al. (2008). However, in total, less significant differences were detected, when data was clustered according to Schwartz et al. (2008). A possible reason for that could be the lower dispersion range compared to the clustering according to self-selected speed. The lower dispersion range is achieved by excluding subjects who walked very slow or very fast and is a result of not overlapping data sets. A additional advantage of clustering according to Schwartz et al. (2008) was that no interaction with speed was detected while analysing the influence of walking condition.

Independend of the type of clustering, an increase of cadence while walking on the treadmill was detected (Table 4 and 6). This outcome is supported by Alton et al. (1998) as they observed a statistically significant result as well. A decrease in stance time, which Alton et al. (1998) found, could be noticed graphically in this study as shown in Figure 30. Concerning joint angle motion, the outcome of this study shows that the knee flexes more on the treadmill (Table 4). This result conflicts with the outcome of the study conducted by Riley et al. (2007) as they detected a reduction of the knee flexion and extension.

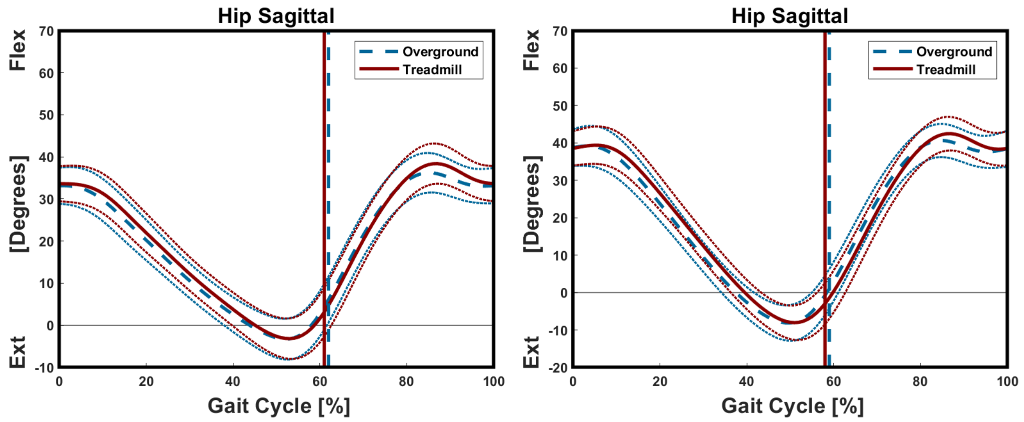

Figure 30: Decrease of stance time on the treadmill for clustering according to self-selected speed at slow walking speed (left) and for clustering according to Schwartz et al. at fast walking speed (right) in the form of earlier toe off (here in the example for the motion of the hip in sagittal plane).

5.2. Effect of Speed

This chapter concentrates on the impact of speed on various parameters. Again clustering had little influence on the results, excluding the lower number of statistically significant outcomes for the clustering according to Schwartz et al. (2008). As mentioned before, a reason could be a lower dispersion range at this form of clustering.

For comparison the studies by van Hoeve et al. (2017) and Dubbeldam et al. (2010) are used. As these study just analyse walking overground at different speeds, they cannot be used for results obtained from measurements on the treadmill. For this walking condition, no comparable study was found.

In regards to spatiotemporal parameters, a shortening of stance time at higher walking speed can be observed graphically as toe off occurs earlier, as, for example, shown in Figure 21-22.This result corresponds to the findings of Dubbeldam et al. (2010). Further, this shortening was detected for both types of clustering and for both walking conditions.

Regarding FFHF, greater ROM at higher walking speed was observed in all planes for walking overground and for data clustered according to self-selected speed (Table 8). This result corresponds partly with the outcome of the study conducted by van Hoeve et al. (2017) as they detected a significant increase in ROM in sagittal plane.

Concerning the snapshot of FFTB in sagittal plane at 80 % of the gait cycle, same inconsistencies were observed for data of overground measurements (Table 8)and of measurements conducted on the treadmill (Table 11), which was clustered according to self-selected speed. Here post-hoc tests only detected statistically significant differences between normal and slow and normal and fast walking speed. This should follow logically a significant difference between slow and fast walking speed, but post-hoc tests do not confirm this conclusion. A look at the mean values explains the inconsistencies as they do only differ little between walking at slow and fast speed. Reason for that could be outliners, which influence the result.

Concerning HFTB, no change of ROM in frontal plane could be detected in contrast to van Hoeve et al. (2017), who detected a significant increase during loading and push-off phase at higher walking speed. Nevertheless, the obtained results regarding the increase of ROM in sagittal and transversal plane with increasing walking speed correspond to the findings of van Hoeve et al. (2017). These results could only be observed for data clustered according to self-selected speed (Table 8 and 11).

In regard to HXFH, an increase dorsi flexion could be observed at higher walking speed (Table 8). The same result was obtained by Dubbeldam et al. (2010).

5.3. Limitations of the Study

All in all, the conducted study gives a good first impression of how walking condition and walking speed influence spatiotemporal parameters and joint angles of the foot; however, some improvements can be made in future. First of all, a greater number of subjects should be observed, as, especially for the clustering according to Schwartz et al. (2008), data amount is shrinking and almost too low for a reliable statistical statement.

Concerning the measuring procedure, mean walking speed, which is used for investigations on the treadmill, should be computed from all overground trials. This may lead to less interaction of walking speed for the comparison of walking condition. Further, a consistent measurement order might give rise to suspicion of bias. Therefore, a variation of the recording order is suggested for future measurements. In addition, in this study two persons placed the markers of the OFM, which may result in a higher variation. Regarding to marker placement, it must be stated that some markers did not adhere on the foot throughout the entire measurements, but were positioned again during the analysis. As this may lead to a change in position, results may be affected as well.

Regarding the evaluation, the statistical tool should be upgraded as some inconsistencies may origin from there. Further, mean value and standard deviation after deletion of outliners would be of interest. In case of the analysed parameters, an inclusion of ankle movement and anthropometric data would complete the research.

6. CONCLUSION

Gait analyses are part of daily life in the Laboratory for Gait and Human Motion Analysis of the Orthopaedic Hospital Speising. As part of the analyses patients are asked to walk at self-selected speed, because otherwise gait pattern would be falsified (Bertram & Ruina, 2001). Doctors are supplied with gathered and further processed data, which supports their diagnosis and is needed for operational preparations and pre- and postsurgical comparisons. Regarding rehabilitation, it is quite popular to use a treadmill for the improvement of walking skills as sometimes space is limited and for safety reasons (Kirtley, 2006).

In order to impede possible misdiagnosis, this study should clarify whether and to what extent the walking condition and walking speed have an impact on spatiotemporal parameters and the joint angles of the foot. Therefore, gait analyses with 23 healthy adults were conducted overground and on the treadmill at three different speed categories (normal, slow, fast) at the Laboratory for Gait and Human Motion Analysis of the Orthopaedic Hospital Speising. For the analyses Vicon cameras, strain-gauge force plates and a quasar treadmill with imbedded capacitive sensors were used. In order to gain more detailed data about the foot angles, the Oxford Foot Model (first presented by Carson et al. in 2001) is used additionally to the Cleveland Clinic Marker Set. For data processing a Vicon system and in-house Matlab programs are utilized. The code for the statistical tests, which were relevant for further analysis, was written in course of this study in Matlab. Finally, data was clustered according to the self-selected speed and according to Schwartz et al. (2008), who used a dimensionless velocity for classification.

Results show that a clustering according to Schwartz et al. (2008) leads to a lower number of significant differences. A reason for that could be the lower dispersion range, which is achieved by excluding subjects who walked very slow or very fast and by elimination of overlapping datasets. As this type of clustering is more homogenous the conclusion is based on these outcomes. Furthermore, it must be mentioned that appearing differences are due to the influence of the different examined conditions as variations are higher than the fluctuations emerging between trials or between testers observed by Carson et al. (2001).

In order to answer the first research question, if differences occur in spatiotemporal parameters and in the joint angles of the foot because of the walking condition, results of the two-way ANOVA are used. Regarding spatiotemporal parameters, a significant influence is observed for cadence, step width and walking speed. Care must be taken as for walking speed the impact was only observed by ANOVA but not by post-hoc tests. Concerning foot angles, most differences occur in the forefoot in frontal plane and in the tibia in sagittal plane, whereby minimum and maximum values are particularly affected. A view at the motion of the hip and the knee indicates that the influence of the walking condition on the angles of the foot can be already observed there.

In conclusion, a 5 minute warm-up as recommended by Matsas et al. (2000) and Lavcanska et al. (2005) may support a stabilisation of gait pattern, but differences still occur. Therefore, I cannot admit to the statement of Riley et al. (2007), who stated that walking on a treadmill is qualitatively and quantitatively very similar to walking overground, but I am in agreement with Kirtley (2006), who is of the opinion that walking on the treadmill cannot replace overground walking.

Concerning the second research question, whether and to what extent walking speed has an impact on joint angles of the foot and spatiotemporal parameters each walking condition is evaluated separately, whereby again the results obtained from clustering according to Schwartz et al. (2008) serve as a basis. For both walking conditions an increase in cadence with increasing walking speed could be observed. Further, the null hypothesis that there is no difference in foot kinematics must be rejected as significant results were obtained especially for FFTB and HFTB. This outcome corresponds partly with findings of van Hoeve et al. (2017). Regarding these segments a greater ROM at higher walking speed could be determined. Walking speed seems to have less impact on the movements between FFHF. All in all, results of overground measurements are very similar to those conducted while walking on the treadmill. The suspicion that occurring differences are a result of the walking condition cannot be confirmed by checking the inconsistencies with the outcome of the analysis of walking condition.

All in all, this study should provide an impetus to consider walking condition or speed as reason for possible discrepancies instead of making a misdiagnosis. Therefore, the dimensionless velocity, which Schwartz et al. (2008) used for categorising, should be included into the evaluation of gait analyses in future.

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Abd	Abduction
Add	Adduction
ANOVA	Analysis of Variances
cond.	Walking condition
DF	Dorsiflexion
DOF	Degree of Freedom
ε	Epsilon
Ever	Eversion
Ext	Extension
Ext	External rotaion
f	fast
FF	Forefoot
FFHF	Forefoot to hindfoot
FFTB	Forefoot to tibia
Flex	Flexion
front	frontal
GRF	Ground Reaction Force
HF	Hindfoot
HFTB	Hindfoot to tibia
HX	Hallux
HXFF	Hallux to forefoot
Inv	Inversion
Int	Internal rotation
max	Maximum value during the gait cycle
min	Minimum value during the gait cycle
MV	Mean Value
n	normal
O	Overground
OFM	Oxford Foot Model
PF	Plantarflexion

Pro	Pronation
rmANOVA	repeated measures Analysis of Variances
ROM	Range of Motion
rom	Range of Motion during the gait cycle
s	slow
sag	sagittal
SD	Standard Deviation
speed x cond.	Interaction of speed and walking condition
Sup	Supination
T	Treadmill
TB	Tibia
trans	transversal
1	normal
2	slow
3	fast
80Prz	Snapshot at 80 % of the gait cycle

Bewegungsanalyselabor OSS 1130 Wien, Speisingerstr. 109	Protokoll Ganganalyse Normdaten 3D	Orthopädisches Spital Speising Wien
VOR - ISO: 7.5 Dokumentierte Information Version:5.0 **BAL09**	Qualitätsmanagement pCC inkl. ISO	

Nachname ______________ **Vorname** ________________

Geburtsdatum: ______________ **Untersuchungsdatum:** ______________

Größe [cm]: _________ **Altersdekade:**

Gewicht [kg]: _________ **Kommentar:** **NORMDATEN**

Zusatzaufnahmen	*Modell*	*Daten*
Aufnahme mit EMG □	**Cleveland Full** □	Beckenbreite: ________mm
Aufnahme mit PEDO □	**Cleve Full + Spine** □	Ellbogen: ________mm
Aufnahme mit Video □	**Oxford Full** □	Hand: ________mm

Marker:

	Andreas	Bernhard		
Knie rechts				
SPG rechts				
Knie links				
SPG links				

Static:

Regression	durchgeführt	bearbeitet
Static1		
Static2		
Static3		
Stand1		
Stand2		

Funktionell	Seite	bearbeitet	übernommen
HJC01	□ LI □ RE		
HJC02	□ LI □ RE		
KJC01	□ LI □ RE		
KJC02	□ LI □ RE		

Walk:

	Trial	Speed	Stiege	Laufband	KMP1	KMP2	KMP3	Auswertung
Dynamic		normal						
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic		slow						
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic		fast						
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic								
Dynamic			AUF links		R	L		

Figure 31: Report used for the measurements conducted overground. Date of the measurement, name and anthropometric data and applied marker set were recorded. Further name of the person, who applied the markers was written down. Boxes for checking if static measurements were conducted were available as well as boxes for writing down at which dynamic trial which foot hits which force plate.

The following pages present the most essential parts of the Matlab code used for statistical analyses. The descriptions of the conducted functions are written in green above each function. Furthermore, the code is split into single chapters according to the function. The function "Daten_bearbeiten" is called if outliners should be deleted. The code of "Daten_bearbeiten" differs between rmANOVA and analysis conducted with unbalanced dataset.

Function rmANOVA

```
% Conducting Shapiro-Wilk Test by using swtest function
% https://de.mathworks.com/matlabcentral/fileexchange/13964-shapiro-wilk-
and-shapiro-francia-normality-tests
[H(1,1), pValue(1,1), W(1,1)] = swtest(RawData(:,1), 0.05)
[H(1,2), pValue(1,2), W(1,2)] = swtest(RawData(:,2), 0.05)
[H(1,3), pValue(1,3), W(1,3)] = swtest(RawData(:,3), 0.05)

% Boxplot of Data
boxplot(RawData)

% 4th and 5th column are filled with NaNs
RawData(1:size(RawData,1),4:5)=NaN;
clear STD MW

% Looking for slight and extreme outliners and marking these
for i=1:3
MW(1,i)=mean(RawData(:,i));
STD(1,i) = std(RawData(:,i));
[row,col] = find((RawData(:,i)<=MW(1,i)-(1.5*STD(1,i))) |
(RawData(:,i)>=MW(1,i)+(1.5*STD(1,i))));
RawData(row,4)=1;

clear row col

[row,col] = find((RawData(:,i)<=MW(1,i)-(3*STD(1,i))) |
(RawData(:,i)>=MW(1,i)+(3*STD(1,i))));
RawData(row,5)=1;
end

clear row col

% In case of edting Rawdata the function "Daten_Bearbeiten" is accessed
RawData=Daten_Bearbeiten(RawData);

% Computing of the rm object
species(1:size(RawData,1),1)={'Messung'};

t = table(species,RawData(:,1),RawData(:,2),RawData(:,3),...
'VariableNames',{'species','meas1','meas2','meas3'});

Meas = table([1 2 3]','VariableNames',{'Measurements'});

rm = fitrm(t,'meas1-meas3~1','WithinDesign',Meas)

% Conducting MauchlyTest
mauch=mauchly(rm);

Mauch=table2array(mauch);
```

```
% Conducting Epsilon Correction
epsi=epsilon(rm);

% Conducting Innersubject Test
rm = fitrm(t,'meas1-meas3~1','WithinDesign',Meas);
ranovatbl = ranova(rm);

statistikData=table2array(ranovatbl);
Epsilon=table2array(epsi);
Innersubjekt=nan(8,6);
Innersubjekt(1,:)=statistikData(1,1:6);
Innersubjekt(2:4,1)=statistikData(1);
Innersubjekt(5:8,1)=statistikData(2,1);
Innersubjekt(2:4,4)=statistikData(1,4);
Innersubjekt(5,2:3)=statistikData(2,2:3);
Innersubjekt(2:4,5)=statistikData(1,6:8)';

for i=1:3
    Innersubjekt(1+i,2)=Innersubjekt(1,2)*Epsilon(1,1+i);
    Innersubjekt(1+i,3)=Innersubjekt(1,3)/Epsilon(1,1+i);

    Innersubjekt(5+i,2)=Innersubjekt(5,2)*Epsilon(1,1+i);
    Innersubjekt(5+i,3)=Innersubjekt(5,3)/Epsilon(1,1+i);
end

% Computing squared partial eta
for i=1:4
Innersubjekt(i,6)=Innersubjekt(i,1)/((Innersubjekt(4+1)+Innersubjekt(i,1)))
;
end

% Conducting PostHoc Tests including Bonferroni Correction
[h,p]=ttest(RawData(:,1),RawData(:,2));
p1=p/3;
clear p h

[h,p]=ttest(RawData(:,1),RawData(:,3));
p2=p/3;
clear p h

[h,p]=ttest(RawData(:,2),RawData(:,3));
p3=p/3;
clear p h
```

Function Daten_bearbeiten

```
function bea_RawData = Daten_Bearbeiten(RawData)
switch answer
    case 'extreme Ausreißer entfernen'
        [row,col] = find(RawData(:,5)==1);
        RawData(row,:)=[];
        bea_RawData=RawData;
    case 'leichte + extreme Ausreißer entfernen'
        [row,col] = find(RawData(:,4)==1);
        RawData(row,:)=[];
        bea_RawData=RawData;

end
clear answer
end
```

Function 2-way ANOVA with repeated measurements

```
% Conducting Innersubject Tests
rm = fitrm(t,'Speed1-Speed3~1','WithinDesign',Meas);
ranovatbl = ranova(rm);

table2 =
table(RawData(:,1),RawData(:,2),RawData(:,3),RawData(:,4),RawData(:,5),RawD
ata(:,6),'VariableNames',{'Y1','Y2','Y3','Y4','Y5','Y6'});
within2 =
table({'S1';'S2';'S3';'S1';'S2';'S3'},{'O1';'O1';'O1';'O2';'O2';'O2';},'Var
iableNames',{'Speed','Surface'});
rm2 = fitrm(table2,'Y1-Y6~1','WithinDesign',within2);
ranovatbl2 = ranova(rm2,'WithinModel','Speed*Surface');

ranova1=table2array(ranovatbl);
ranova2=table2array(ranovatbl2);
Epsilon=table2array(epsi);

Anova(1,1:5)=ranova1(1,1:5);
Anova(2,1:5)=[ranova1(1,1) ranova1(1,2)*Epsilon(2) ranova1(1,3)/Epsilon(2)
ranova1(1,4) ranova1(1,6)];
Anova(3,1:5)=[ranova1(1,1) ranova1(1,2)*Epsilon(3) ranova1(1,3)/Epsilon(3)
ranova1(1,4) ranova1(1,7)];
Anova(4,1:5)=[ranova1(1,1) ranova1(1,2)*Epsilon(4) ranova1(1,3)/Epsilon(4)
ranova1(1,4) ranova1(1,8)];
Anova(5,1:5)=[ranova2(7,1:3) ranova2(8,4) ranova2(5,5)+ranova2(7,5)];
Anova(6,1:5)=[ranova2(7,1) ranova2(7,2)*Epsilon(2) ranova2(7,3)/Epsilon(2)
ranova2(8,4) ranova2(5,6)+ranova2(7,6)];
Anova(7,1:5)=[ranova2(7,1) ranova2(7,2)*Epsilon(3) ranova2(7,3)/Epsilon(3)
ranova2(8,4) ranova2(5,7)+ranova2(7,7)];
Anova(8,1:5)=[ranova2(7,1) ranova2(7,2)*Epsilon(4) ranova2(7,3)/Epsilon(4)
ranova2(8,4) ranova2(5,8)+ranova2(7,8)];
Anova(9,1:5)=[ranova2(8,1)+ranova2(4,1) ranova2(8,2)+ranova2(4,2)
(ranova2(8,3)+ranova2(4,3))/2 NaN NaN];
Anova(10,1:5)=[ranova2(8,1)+ranova2(4,1) Anova(9,2)*Epsilon(2)
Anova(9,3)/Epsilon(2) NaN NaN];
Anova(11,1:5)=[ranova2(8,1)+ranova2(4,1) Anova(9,2)*Epsilon(3)
Anova(9,3)/Epsilon(3) NaN NaN];
Anova(12,1:5)=[ranova2(8,1)+ranova2(4,1) Anova(9,2)*Epsilon(4)
Anova(9,3)/Epsilon(4) NaN NaN];

% Betweensubject Tests
pSpeed=ranovatbl2(3,5);
pSurf=ranovatbl2(5,5);
pZw=ranovatbl2(7,5);

ZST(1,1)=pSpeed;
ZST(2,1)=pSurf;
ZST(3,1)=pZw;

% Conducting PostHoc Tests
[h,p1]=ttest(RawData(:,1),RawData(:,4));
clear h

[h,p2]=ttest(RawData(:,2),RawData(:,5));;
clear h

[h,p3]=ttest(RawData(:,3),RawData(:,6));
clear h
```

Function 1-way ANOVA for unbalanced dataset

```
% Looking for slight and extreme outliners
for i=1:3
     MW(i)=nanmean (RawData(:,i));
     STD(i) = nanstd(RawData(:,i));
    [idleicht] = find((RawData(:,i)<=MW(1,i)-(1.5*STD(1,i))) |
(RawData(:,i)>=MW(1,i)+(1.5*STD(1,i))));

    [idextrem] = find((RawData(:,i)<=MW(1,i)-(3*STD(1,i))) |
(RawData(:,i)>=MW(1,i)+(3*STD(1,i))));

end


% In case of edting Rawdata the function "Daten_Bearbeiten" is accessed
RawData=Daten_Bearbeiten_onewANOVA(RawData);


% Restructuring and grouping of Data
tmp=RawData(:,1);
Data=tmp(~isnan(tmp));
tmp=(~isnan(tmp)*1);
Group=tmp(tmp==1);
tmp=RawData(:,2);
Data=vertcat(Data,tmp(~isnan(tmp)));
tmp=(~isnan(tmp)*2);
Group=vertcat(Group,tmp(tmp==2));
tmp=RawData(:,3);
Data=vertcat(Data,tmp(~isnan(tmp)));
tmp=(~isnan(tmp)*3);
Group=vertcat(Group,tmp(tmp==3));

% Levene Test for equal variances
pLevene = vartestn(Data,Group,'TestType','LeveneAbsolute');

%Mauch
mauch=mauchly(rm);
Mauch=table2array(mauch);

% Anova
[pANOVA,anova1tbl,stats]  = anova1(Data,Group,'off');

epsi=epsilon(rm);
Epsilon=table2array(epsi);

pGreen=pANOVA*Epsilon(1,2);
pHuynh=pANOVA/Epsilon(1,3);

% Conducting PostHoc Test
PostHoc = multcompare(stats,'Display','off');
Spaltenvergleich=PostHoc(:,1:2);
DiffGrupMittel=PostHoc(:,4);
Unter95Proz=PostHoc(:,3);
Ober95Proz=PostHoc(:,5);
pPost=PostHoc(:,6);
PostHocTable(:,1:2)=Spaltenvergleich;
PostHocTable(:,3)=DiffGrupMittel;
PostHocTable(:,4)=Unter95Proz;
PostHocTable(:,5)=Ober95Proz;
PostHocTable(:,6)=pPost
```

Function Daten_bearbeiten_onewANOVA

```
function RawData=Daten_Bearbeiten_onewANOVA(RawData)
switch answer
    case 'extreme Ausreißer entfernen'
        RawData(idextrem)=NaN;

    case 'leichte + extreme Ausreißer entfernen'
        RawData(idleicht)=NaN;

end
clear answer
end
```

Function 2-way ANOVA for unbalanced dataset

```
% Restructuring and grouping of Data
a1=RawData(:,1);
a1(:,2)=1;
a1(:,3)=1;
a2=RawData(:,2);
a2(:,2)=2;
a2(:,3)=1;
a3=RawData(:,3);
a3(:,2)=3;
a3(:,3)=1;
a4=RawData(:,4);
a4(:,2)=1;
a4(:,3)=2;
a5=RawData(:,5);
a5(:,2)=2;
a5(:,3)=2;
a6=RawData(:,6);
a6(:,2)=3;
a6(:,3)=2;

RawData_group=vertcat(a1,a2,a3,a4,a5,a6);

% ANOVA
[pANOVA,anovantbl,stats] = anovan(RawData_group(:,1),{RawData_group(:,2)
RawData_group(:,3)},'model','interaction','varnames',{'Speed','Surface'});

epsi=epsilon(rm);
Epsilon=table2array(epsi);

pGreen=pANOVA*Epsilon(1,2);
pHuynh=pANOVA/Epsilon(1,3);


%% Conducting PostHoc Tests
[h,p1]=ttest(RawData(:,1),RawData(:,4));
clear h

[h,p2]=ttest(RawData(:,2),RawData(:,5));;
clear h

[h,p3]=ttest(RawData(:,3),RawData(:,6));
clear h
```

Two-way ANOVA with repeated measurements

Parameter	Normal Distribution	Mean Value	Standard Deviation	Between-subject p-Value		Comparison p-Value	
				Condition	Speed x Cond.		
Cadence	0.58	114.0327	7.5388	0.000	0.001	normal	0.206
	0.99	99.4908	9.7929				
	0.51	122.4217	9.7135			slow	0.000
	0.97	114.6616	7.4666				
	0.72	102.9401	8.7758			fast	0.015
	1.00	123.8600	9.6817				
Walking Speed	0.51	1.2851	0.1176	0.015	0.534	normal	0.064
	0.55	0.9889	0.1377				
	0.85	1.5277	0.1492			slow	0.494
	0.00	1.1731	0.3223				
	0.75	0.9438	0.1938			fast	0.210
	0.50	1.4276	0.2700				
Step Width	0.56	0.0761	0.0218	0.000	0.026	normal	0.000
	0.13	0.0742	0.0250				
	0.53	0.0756	0.0229			slow	0.000
	0.89	0.0518	0.0140				
	0.48	0.0540	0.0189			fast	0.000
	0.96	0.0487	0.0139				
FFHF_front_80Prz	0.39	5.8516	4.2993	0.066	0.237	normal	-
	0.96	6.0451	4.3531				
	0.77	5.8153	4.3692			slow	-
	0.99	5.3931	4.4558				
	0.65	5.4207	4.4596			fast	-
	0.55	5.5240	4.3927				

FFHF_front_max	0.28	9.5720	4.2546	0.513	0.558	normal	-
	0.76	8.9814	4.4006				
	0.62	10.0699	4.5106			slow	-
	0.52	9.5386	4.3249				
	0.77	8.8210	4.1102			fast	-
	0.57	9.8171	4.5105				
FFHF_front_min	0.29	2.5346	4.3685	0.006	0.866	normal	0.020
	0.08	2.2216	4.3629				
	0.15	2.6205	4.3678			slow	0.005
	0.59	1.9396	4.2595				
	0.34	1.5436	4.2023			fast	0.014
	0.35	1.9360	4.2049				
FFHF_front_rom	0.17	7.0375	1.6614	0.000	0.732	normal	0.002
	0.34	6.7598	1.7865				
	0.32	7.4494	1.8167			slow	0.001
	0.50	7.5990	1.6255				
	0.31	7.2773	1.6181			fast	0.001
	0.54	7.8813	1.9415				
FFHF_sag_max	0.17	7.1049	4.1973	0.146	0.001	normal	-
	0.12	7.0837	4.3936				
	0.06	7.5371	4.3192			slow	-
	0.15	7.6548	4.7682				
	0.14	7.7689	4.5058			fast	-
	0.20	7.4484	4.9242				
FFHF_sag_min	0.93	-9.0519	4.6532	0.061	0.135	normal	-
	0.66	-7.7232	4.5125				
	0.62	-9.6383	4.8292			slow	-
	0.78	-8.2655	5.3192				
	0.90	-7.0866	5.1549			fast	-
	0.49	-9.3331	5.6958				

FFHF_sag_rom	0.55	16.1567	3.8428	0.376	0.056	normal	-
	0.19	14.8070	3.4230				
	0.43	17.1754	3.9242			slow	-
	0.22	15.9202	3.7019				
	0.71	14.8555	3.5555			fast	-
	0.68	16.7815	3.7801				
FFHF_trans_80Prz	2391	7.1616	6.4617	0.117	0.916	normal	-
	0.41	7.4737	6.4834				
	0.21	6.9959	6.7813			slow	-
	0.23	7.5400	6.8699				
	0.43	7.5898	6.7356			fast	-
	0.06	7.3067	7.0289				
FFHF_trans_max	0.97	12.2976	5.8159	0.671	0.356	normal	-
	0.50	12.1520	5.9713				
	0.23	12.4036	6.1808			slow	-
	0.12	12.5126	6.1492				
	0.08	12.3765	6.0929			fast	-
	0.05	12.5727	6.2545				
FFHF_trans_min	0.51	0.8192	5.8863	0.005	0.265	normal	0.002
	0.21	1.1418	6.0909				
	0.30	1.0120	6.1046			slow	0.013
	0.18	1.6342	6.1083				
	0.21	1.7903	6.0949			fast	0.013
	0.11	1.6550	6.0722				
FFHF_trans_rom	0.67	11.4784	2.1113	0.000	0.508	normal	0.000
	0.40	11.0102	2.0475				
	0.08	11.3916	2.2283			slow	0.003
	0.06	10.8784	2.0248				
	0.17	10.5862	1.9574			fast	0.004
	0.39	10.9177	2.0151				

FFTB_front_80Prz	0.07	7.5894	4.1053	0.000	0.006	normal	0.000
	0.00	7.9865	3.7672				
	0.02	7.1055	4.0902			slow	0.000
	0.45	5.8873	4.5197				
	0.02	6.4615	4.3319			fast	0.000
	0.34	6.0716	4.2602				
FFTB_front_max	0.00	13.8912	4.2828	0.000	0.886	normal	0.000
	0.01	13.7535	3.9718				
	0.00	13.2186	4.1654			slow	0.000
	0.21	12.3612	4.1497				
	0.40	12.3323	3.8752			fast	0.000
	0.10	11.7898	4.3989				
FFTB_front_min	0.56	0.0281	3.6327	0.000	0.006	normal	0.000
	0.41	-0.0426	3.1489				
	0.32	-0.4761	3.9142			slow	0.000
	0.60	-1.2818	3.6511				
	0.69	-1.2872	3.2780			fast	0.000
	0.68	-1.2375	3.6840				
FFTB_front_rom	0.44	13.8631	2.9317	0.036	0.098	normal	0.321
	0.16	13.7961	2.6912				
	0.41	13.6947	3.1854			slow	0.401
	0.50	13.6430	2.9895				
	0.42	13.6195	2.7095			fast	0.005
	0.46	13.0272	3.3440				
FFTB_sag_80Prz	0.51	4.6686	4.0204	0.000	0.957	normal	0.000
	0.80	5.4950	3.8100				
	0.60	5.3740	3.3655			slow	0.000
	0.16	3.1985	4.3584				
	0.57	3.9645	4.5291			fast	0.000
	0.54	3.9275	4.0670				

FFTB_sag_max	0.28	20.1541	3.3979	0.000	0.000	normal	0.000
	0.81	20.7344	3.3646				
	0.26	18.9814	4.3650			slow	0.000
	0.31	18.1916	4.5869				
	0.47	19.2212	4.4510			fast	0.000
	0.08	16.2930	5.4818				
FFTB_sag_min	0.04	-18.4861	8.9023	0.010	0.230	normal	0.074
	0.01	-13.9535	7.4984				
	0.52	-20.6159	8.5495			slow	0.026
	0.35	-19.6278	8.5652				
	0.02	-15.8007	9.4098			fast	0.004
	0.41	-22.7248	8.9049				
FFTB_sag_rom	0.11	38.6402	8.4659	0.511	0.084	normal	-
	0.56	34.6879	7.3437				
	0.01	39.5972	8.0569			slow	-
	0.13	37.8194	7.6403				
	0.12	35.0219	8.5404			fast	-
	0.12	39.0178	7.0981				
FFTB_trans_80Prz	0.14	15.2895	6.7304	0.000	0.106	normal	0.006
	0.18	15.6547	6.9004				
	0.40	14.3180	6.8937			slow	0.006
	0.50	15.9006	6.7678				
	0.47	16.2325	6.8024			fast	0.000
	0.54	15.2283	6.7035				
FFTB_trans_max	0.77	27.4269	7.2078	0.498	0.761	normal	-
	0.69	26.7560	7.1738				
	0.26	27.1508	1.3776			slow	-
	0.23	27.5821	6.9535				
	0.14	26.8147	6.7957			fast	-
	0.37	27.4373	6.9223				

FFTB_trans_min	0.35	7.0033	6.2775	0.056	0.987	normal	-
	0.64	8.0010	6.3684				
	0.65	6.3715	6.1017			slow	-
	0.57	7.2964	6.0839				
	0.48	8.2822	6.0274			fast	-
	0.56	6.6396	6.1909				
FFTB_trans_rom	0.02	20.4236	4.1718	0.638	0.755	normal	-
	0.02	18.7558	3.9678				
	0.91	20.7793	4.3871			slow	-
	0.42	20.2856	4.2878				
	0.13	18.5326	4.3860			fast	-
	0.62	20.7976	4.1282				
HFTB_front_80Prz	0.58	1.9377	4.0843	0.000	0.019	normal	0.000
	0.69	2.0583	4.0786				
	0.62	1.3870	4.3606			slow	0.000
	0.59	0.5971	4.5969				
	0.62	1.0675	4.4885			fast	0.004
	0.44	0.5703	4.6393				
HFTB_front_max	0.29	6.4386	4.3076	0.000	0.084	normal	0.000
	0.55	6.3554	4.2834				
	0.43	5.5748	4.5510			slow	0.001
	0.26	5.2913	4.6071				
	0.60	5.3754	4.6654			fast	0.014
	0.22	4.8880	4.8436				
HFTB_front_min	0.97	-4.4669	4.1267	0.055	0.038	normal	-
	0.76	-4.1851	3.8968				
	0.56	-4.9436	4.5025			slow	-
	0.79	-5.2043	4.6396				
	1.00	-4.5749	4.2919			fast	-
	0.67	-5.1901	4.7292				

HFTB_front_rom	0.04	10.9055	2.0891	0.001	0.485	normal	0.060
	0.049	10.5406	1.8692				
	0.66	10.5184	2.1982			slow	0.002
	0.17	10.4955	2.1905				
	0.11	9.9502	1.9572			fast	0.023
	0.11	10.0781	2.1832				
HFTB_sag__max	0.21	13.0266	3.0840	0.000	0.151	normal	0.000
	0.45	13.5505	3.2495				
	0.32	11.5189	3.4152			slow	0.000
	0.80	10.5727	3.3840				
	0.34	11.4334	3.6065			fast	0.000
	0.82	9.4109	3.4551				
HFTB_sag_min	0.20	-10.0259	5.2832	0.000	0.168	normal	0.000
	0.24	-7.7646	4.3423				
	0.39	-11.2435	4.8914			slow	0.000
	0.39	-11.7949	5.4714				
	0.24	-9.8474	5.9544			fast	0.000
	0.65	-13.7834	5.1918				
HFTB_sag_rom	0.02	23.0525	5.2518	0.854	0.031	normal	-
	0.16	21.3151	4.2933				
	0.01	22.7624	4.9130			slow	-
	0.26	22.3674	5.3248				
	0.12	21.2808	5.4076			fast	-
	0.54	23.1943	4.6907				
HFTB_trans_max	0.22	15.1831	6.2861	0.761	0.884	normal	-
	0.46	14.5844	6.2246				
	0.16	15.0053	6.4514			slow	-
	0.21	15.2506	6.3884				
	0.25	14.6212	6.2058			fast	-
	0.19	15.1442	6.3918				

HFTB_trans_min	0.51	1.8941	5.9492	0.626	0.964	normal	-
	0.43	2.5478	5.7002				
	0.56	1.2725	5.9508			slow	-
	0.36	1.7814	5.7937				
	0.29	2.4213	5.4093			fast	-
	0.34	1.1941	5.8615				
HFTB_trans_rom	0.63	13.2889	3.5942	0.408	0.972	normal	-
	0.21	12.0366	3.2878				
	0.02	13.7328	3.6356			slow	-
	0.07	13.4692	3.6735				
	0.28	12.1999	3.4670			fast	-
	0.17	13.9501	3.5040				
HXFF_sag_max	0.83	13.1872	9.9229	0.000	0.598	normal	0.000
	0.84	11.7681	9.7728				
	0.79	15.0529	11.3918			slow	0.001
	0.93	15.9553	11.2017				
	0.47	14.2468	11.1636			fast	0.004
	0.88	17.1456	11.5843				
HXFF_sag_min	0.03	-14.1360	6.3598	0.000	0.794	normal	0.000
	0.07	-14.2553	6.2635				
	0.27	-12.4722	7.5393			slow	0.000
	0.19	-14.4402	7.5236				
	0.23	-12.7298	7.2206			fast	0.001
	0.37	-11.4506	7.6181				
HXFF_sag_rom	0.95	27.3232	8.009	0.099	0.968	normal	-
	0.49	26.0234	7.1021				
	0.06	27.5251	7.9363			slow	-
	0.81	28.3955	9.4232				
	0.08	26.9766	9.4440			fast	-
	0.64	28.5962	9.2084				

Hip_sag_max	0.43	38.7650	4.5532	0.000	0.000	normal	0.000
	0.47	36.4555	4.6635				
	0.25	40.5556	5.3347			slow	0.000
	0.61	40.0716	4.8144				
	0.48	38.5644	4.6950			fast	0.000
	0.17	42.0447	5.4753				
Hip_sag_min	0.16	-5.4156	4.9559	0.374	0.001	normal	-
	0.20	-3.4943	4.8542				
	0.25	-8.1261	5.2153			slow	-
	0.21	-5.8717	5.2937				
	0.35	-3.3816	4.8465			fast	-
	0.14	-8.2200	5.3892				
Hip_sag_rom	0.41	44.1806	4.2910	0.000	0.286	normal	0.000
	0.30	39.9498	4.2257				
	0.97	48.6817	5.3248			slow	0.000
	0.68	45.9434	4.9130				
	0.30	51.9460	4.3131			fast	0.000
	0.38	50.2648	5.6981				
Knee_sag_max	0.87	68.6812	3.3481	0.000	0.000	normal	0.000
	0.52	66.3208	4.1079				
	0.12	68.4882	2.7565			slow	0.000
	0.49	70.7665	3.2274				
	0.63	69.4689	4.0990			fast	0.000
	0.04	70.6956	2.8935				
Knee_sag_min	0.84	6.0356	3.2027	0.831	0.136	normal	-
	0.99	6.2699	3.3254				
	0.72	5.3689	2.8171			slow	-
	0.97	5.8594	3.2243				
	0.93	6.3761	3.3776			fast	-
	0.90	5.5476	3.2603				

Knee_sag_rom	0.45	62.6456	4.8228	0.000	0.002	normal	0.000
	0.22	60.0509	5.6541				
	0.73	63.1193	3.6849			slow	0.000
	0.27	64.9070	4.3201				
	0.12	63.0928	5.1820			fast	0.000
	0.54	65.1480	3.8070				
ScoreG_Foot_GPS	0.15	6.0923	1.5138	0.008	0.051	normal	0.002
	0.13	6.4850	1.5636				
	0.03	6.1702	1.6460			slow	0.029
	0.04	6.4078	1.7694				
	0.16	6.6844	1.8388			fast	0.072
	0.04	6.3278	1.8431				

Table 14: Results of the two-way ANOVA with repeated measurements. The used data was collected while walking overground and while walking on the treadmill and clustered according to self-selected speed. The first column names the analysed parameter. The second, third and fourth columns give information about the normal distirbution, the mean value and the standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first three rows of each parameter for the these columns belong to the measurements conducted overground in the order normal - slow - fast walking speed. Rows 4 - 6 present the data of measurements conducted on the treadmill in the order normal - slow - fast walking speed. The fifth and sixth columns give information if the walking condition (Condition) does have a significant influence ($p < 0.05$) on the result and if there is an interaction with walking speed (Speed x Cond.). An interaction is indicated by a value smaller than 0.05. The last two columns show if the difference occur at normal, slow or fast walking speed. Results are significant if the value is smaller than 0.05.

Two-way ANOVA for unbalanced data

Parameter	Normal Distribution	Mean Value	Standard Deviation	Sig. Levene	Between-subject p-Value		Comparison p-Value	
					Condition	Speed x Cond.		
Cadence	0.50	110.4985	5.6180	0.066	0.047	0.443	normal	0.064
	0.89	94.3572	7.8827					
	0.73	123.7818	5.8612				slow	0.000
	0.88	111.4024	5.5261					
	0.53	99.2189	8.0967				fast	0.012
	0.94	125.7181	6.4502					
Walking Speed	0.75	1.2093	0.0897	0.554	0.007	0.685	normal	0.050
	0.98	0.8998	0.0880					
	0.99	1.5345	0.0970				slow	0.159
	0.00	1.0836	0.2916					
	0.53	0.8464	0.1514				fast	0.061
	0.03	1.4154	0.2237					
Step Width	0.50	0.0754	0.0224	0.698	0.000	0.606	normal	0.000
	0.22	0.0739	0.0274					
	0.56	0.0729	0.0241				slow	0.000
	0.52	0.0522	0.0140					
	0.49	0.0561	0.0203				fast	0.000
	0.45	0.0447	0.0119					
FFHF_front_80Prz	0.41	5.7597	4.2705	0.586	0.463	0.990	normal	-
	0.94	5.4104	4.7592					
	0.65	6.4532	3.8523				slow	-
	0.99	5.2036	4.3805					
	0.79	5.0081	436010				fast	-
	0.60	6.0865	4.3678					

FFHF_front_max	0.34	9.3744	4.1480	0.452	0.827	0.990	normal	-
	0.98	8.1539	4.7529					
	0.39	10.9007	3.6683				slow	-
	0.92	9.1705	4.1809					
	0.80	8.1457	4.2334				fast	-
	0.16	10.7327	4.0616					
FFHF_front_min	0.23	2.3533	4.3118	0.307	0.233	0.984	normal	-
	0.42	1.6057	4.6026					
	0.10	3.5693	3.6867				slow	-
	0.42	1.7303	4.1529					
	0.73	0.9866	4.3427				fast	-
	0.32	2.7292	3.9882					
FFHF_front_rom	0.12	7.0211	1.6501	0.306	0.020	0.890	normal	0.005
	0.18	6.5482	1.9781					
	0.83	7.3314	1.6594				slow	0.006
	0.84	7.4402	1.5651					
	0.40	7.1592	1.7703				fast	0.000
	0.40	8.0035	1.8919					
FFHF_sag_max	0.16	7.2334	4.2125	0.852	0.441	0.709	normal	-
	0.15	6.0658	3.8078					
	0.04	7.2879	4.5083				slow	-
	0.20	7.7847	4.6913					
	0.32	7.1455	4.3071				fast	-
	0.04	7.0724	4.6146					
FFHF_sag_min	0.90	-8.6729	4.5874	0.899	0.412	0.930	normal	-
	0.69	-7.9609	4.4067					
	0.95	-9.4599	4.7838				slow	-
	0.93	-7.9054	5.0330					
	0.91	-7.2323	5.2109				fast	-
	0.57	-9.2602	5.6150					

FFHF_sag_rom	0.62	15.9064	3.7116	0.716	0.856	0.840	normal	-
	0.64	14.0267	3.7313					
	0.43	16.7478	3.8221				slow	-
	0.21	15.6901	3.6167					
	0.61	14.3779	3.8557				fast	-
	0.21	16.3326	3.5527					
FFHF_trans_80Prz	0.93	7.2829	6.4505	0.070	0.662	0.991	normal	-
	0.39	9.0129	6.9311					
	0.82	4.9973	5.0255				slow	-
	0.27	7.7334	6.8238					
	0.40	9.2274	7.3280				fast	-
	0.67	5.4977	5.5037					
FFHF_trans_max	0.96	12.3071	5.8042	0.134	0.791	0.949	normal	-
	0.53	13.7036	6.2346					
	0.55	10.6702	4.5795				slow	-
	0.11	12.6242	6.0999					
	0.19	13.5398	6.4744				fast	-
	0.62	11.1494	4.8239					
FFHF_trans_min	0.47	0.8764	5.8455	0.070	0.397	0.948	normal	-
	0.34	2.8133	6.3881					
	0.93	-0.9322	4.5447				slow	-
	0.19	1.7349	6.0333					
	0.19	3.1015	6.5578				fast	-
	0.78	-0.0564	4.6970					
FFHF_trans_rom	0.75	11.4307	2.0862	0.719	0.118	0.977	normal	-
	0.62	10.8903	2.0715					
	0.46	11.6025	2.4392				slow	-
	0.10	10.8895	2.0168					
	0.25	10.4383	1.9676				fast	-
	0.82	11.2058	2.1368					

FFTB_front_80Prz	0.03	7.4966	4.0518	0.531	0.018	0.961	normal	0.000
	0.01	8.2526	4.3301					
	0.69	6.7074	3.6421				slow	0.000
	0.26	5.9634	4.3888					
	0.10	6.7401	5.0690				fast	0.000
	0.86	5.5340	4.1522					
FFTB_front_max	0.00	13.9015	4.2336	0.677	0.012	0.994	normal	0.000
	0.02	13.9075	4.5894					
	0.25	13.0635	3.9540				slow	0.000
	0.26	12.4728	4.1239					
	0.72	12.3221	4.4681				fast	0.000
	0.51	11.5906	4.3401					
FFTB_front_min	0.40	-0.1024	3.5859	0.633	0.022	0.970	normal	0.000
	0.38	-0.3508	3.7710					
	0.18	-0.4330	3.7308				slow	0.000
	0.69	-1.3286	3.6558					
	0.51	-1.6691	3.9262				fast	0.000
	0.31	-1.4394	3.5476					
FFTB_front_rom	0.35	14.0039	2.9352	0.888	0.441	0.959	normal	-
	0.10	14.2583	2.7245					
	0.73	13.4965	2.8872				slow	-
	0.71	13.8014	2.9261					
	0.50	13.9912	2.9522				fast	-
	0.62	13.0300	2.9908					
FFTB_sag_80Prz	0.51	4.6121	4.1438	0.033	-	-	normal	-
	0.74	6.1183	3.5802					
	0.12	4.7640	3.1218				slow	-
	0.09	3.1126	4.4184					
	0.57	4.4668	4.9190				fast	-
	0.31	3.3157	3.4611					

FFTB_sag_max	0.28	20.5120	3.2608	0.640	0.000	0.491	normal	0.000
	0.96	20.9591	3.4591					
	0.64	18.6634	3.8198				slow	0.018
	0.24	18.6506	4.4300					
	0.52	19.6768	4.7814				fast	0.000
	0.64	15.6978	4.4127					
FFTB_sag_min	0.04	-17.4075	8.5183	0.591	0.102	0.870	normal	-
	0.04	-11.9675	7.6932					
	0.57	-21.0820	8.0862				slow	-
	0.80	-18.9106	8.5183					
	0.11	-13.4331	9.8467				fast	-
	0.41	-23.8739	7.6960					
FFTB_sag_rom	0.04	37.9195	8.2794	0.405	0.921	0.982	normal	-
	0.07	32.9266	9.3236					
	0.07	39.7454	8.8629				slow	-
	0.07	37.5612	7.8419					
	0.01	33.1099	9.3701				fast	-
	0.58	39.5716	7.8815					
FFTB_trans_80Prz	0.15	15.3833	4.8182	0.086	0.433	0.995	normal	-
	0.07	16.5543	7.8036					
	0.27	12.2971	6.0466				slow	-
	0.61	16.0440	4.7860					
	0.18	17.2847	7.6837				fast	-
	0.35	13.1339	5.8534					
FFTB_trans_max	0.78	27.4291	7.1436	0.788	0.933	0.902	normal	-
	0.30	27.5177	7.7552					
	0.36	25.7219	7.4891				slow	-
	0.34	27.7541	6.8719					
	0.09	16.8218	7.3689				fast	-
	0.43	26.2471	7.2401					

FFTB_trans_min	0.31	7.2704	6.2494	0.237	0.819	0.992	normal	-
	0.19	9.0358	7.1052					
	0.24	4.6002	5.5539				slow	-
	0.32	7.5797	5.9793					
	0.07	9.0845	6.7474				fast	-
	0.15	4.8331	5.7008					
FFTB_trans_rom	0.03	20.1587	4.0765	0.158	0.851	0.826	normal	-
	0.02	18.3818	3.8528					
	0.31	21.1217	4.8279				slow	-
	0.62	20.1744	4.1491					
	0.08	17.7373	4.2147				fast	-
	0.30	21.4140	4.5565					
HFTB_front_80Prz	0.58	1.9281	4.0891	0.665	0.087	0.991	normal	-
	0.63	2.9826	4.2557					
	0.42	0.3872	4.0241				slow	-
	0.36	0.8460	4.6024					
	0.77	1.5858	4.6812				fast	-
	0.62	-0.5387	4.5571					
HFTB_front_max	0.32	6.4911	4.3154	0.629	0.122	0.956	normal	-
	0.98	7.1257	4.6001					
	0.15	4.8240	4.4783				slow	-
	0.28	5.5583	4.6777					
	0.78	5.8482	4.9696				fast	-
	0.10	4.0401	4.8593					
HFTB_front_min	0.94	-4.3528	4.0695	0.831	0.452	0.980	normal	-
	0.87	-3.5904	4.1899					
	0.44	-6.0624	4.2170				slow	-
	0.76	-4.9387	4.6119					
	0.99	-4.0802	4.5688				fast	-
	0.68	-6.3669	4.6761					

HFTB_front_rom	0.03	10.8439	1.9895	0.033	-	-	normal	-
	0.29	10.7160	1.6055					
	0.79	10.8864	4.1548				slow	-
	0.12	10.4971	2.1715					
	0.35	9.9284	1.5054				fast	-
	0.19	10.4070	2.1871					
HFTB_sag_max	0.14	13.2416	3.0274	0.751	0.000	0.989	normal	0.000
	0.14	14.7118	2.8880					
	0.07	11.5528	3.2894				slow	0.000
	0.73	10.8893	3.4427					
	0.71	12.4547	3.2285				fast	0.000
	0.88	9.1242	3.3922					
HFTB_sag_min	0.34	-9.5620	4.8465	0.060	0.002	0.723	normal	0.000
	0.26	-6.0014	3.6768					
	0.64	-11.4888	5.5095				slow	0.005
	0.35	-11.5316	5.4199					
	0.43	-7.7438	5.2071				fast	0.000
	0.91	-14.5598	5.4165					
HFTB_sag_rom	0.01	22.8036	5.0607	0.613	0.905	0.776	normal	-
	0.05	20.7132	4.1543					
	0.06	23.0416	5.6409				slow	-
	0.19	22.4209	5.4350					
	0.03	20.1985	5.2059				fast	-
	0.64	23.6840	5.1923					
HFTB_trans_max	0.23	15.1491	6.1403	0.444	0.961	0.991	normal	-
	0.36	13.6957	6.5777					
	0.59	15.3678	6.9789				slow	-
	0.27	15.2664	6.2983					
	0.27	15.5584	6.5516				fast	-
	0.12	15.5223	6.7144					

HFTB_trans_min	0.65	1.9872	5.9448	0.907	0.808	0.985	normal	-
	0.79	2.2600	5.6978					
	0.19	1.3999	5.7771				slow	-
	0.39	1.9061	5.7713					
	0.64	2.1439	5.4654				fast	-
	0.07	1.0169	5.5422					
HFTB_trans_rom	0.56	13.1619	3.4189	0.358	0.618	0.900	normal	-
	0.07	11.4357	2.8224					
	0.13	13.9679	3.8812				slow	-
	0.12	13.3604	3.5316					
	0.23	11.4145	3.2355				fast	-
	0.49	14.5055	3.4404					
HXFF_sag_max	0.92	12.6798	10.2238	0.006	-	-	normal	-
	0.79	11.2026	6.9649					
	0.76	14.3590	11.0008				slow	-
	0.96	15.6033	11.6497					
	0.56	14.3735	8.3317				fast	-
	0.96	16.5722	12.7676					
HXFF_sag_min	0.01	-14.1366	6.2618	0.600	0.068	0.991	normal	-
	0.23	-13.7660	5.2499					
	0.17	-12.5802	6.8185				slow	-
	0.27	-12.3903	7.0747					
	0.60	-12.1406	6.9412				fast	-
	0.09	-10.9303	7.6614					
HXFF_sag_rom	0.96	26.8164	8.0771	0.152	0.350	0.947	normal	-
	0.26	24.9686	6.1133					
	0.22	26.9392	7.5236				slow	-
	0.23	27.9935	10.0759					
	0.92	26.5141	8.3022				fast	-
	0.90	27.5025	8.9046					

Hip_sag_max	0.18	38.1200	3.9953	0.153	0.006	0.832	normal	0.000
	0.40	34.4154	4.0307					
	0.24	41.5023	5.0756				slow	0.000
	0.38	39.5227	4.3518					
	0.50	36.6709	4.1725				fast	0.000
	0.19	42.9547	4.8703					
Hip_sag_min	0.22	-4.8728	4.9583	0.545	0.968	0.957	normal	-
	0.24	-3.2378	4.6537					
	0.39	-8.3082	4.7645				slow	-
	0.37	-5.1649	5.3228					
	0.22	-3.0819	4.8876				fast	-
	0.31	-8.2552	4.5740					
Hip_sag_rom	0.79	42.9928	3.4096	0.134	0.001	0.873	normal	0.000
	0.54	37.6533	3.1608					
	0.68	49.8105	4.1056				slow	0.000
	0.62	44.6876	3.9656					
	0.34	39.7529	3.2707				fast	0.000
	0.57	51.2100	4.1387					
Knee_sag_max	0.92	68.3754	3.3393	0.166	0.000	0.526	normal	0.000
	0.68	64.5634	3.9326					
	0.36	69.0146	2.7983				slow	0.000
	0.75	70.6597	3.3014					
	0.45	67.9471	4.0985				fast	0.000
	0.20	71.0990	3.0682					
Knee_sag_min	0.99	6.1468	3.1562	0.739	0.973	0.956	normal	-
	0.93	7.1292	2.8905					
	0.92	5.1952	3.0662				slow	-
	0.96	5.9841	3.4103					
	0.89	7.1047	3.0336				fast	-
	0.99	5.3377	3.3489					

Knee_sag_rom	0.39	62.2286	4.7242	0.098	0.000	0.648	normal	0.000
	0.37	57.4342	4.9072					
	0.25	63.8194	3.8077				slow	0.000
	0.30	64.6756	4.5354					
	0.05	60.8424	4.6289				fast	0.000
	0.56	65.7613	3.6030					
ScoreG_Foot_GPS	0.15	6.1475	1.4962	0.100	0.311	0.980	normal	-
	0.31	6.8918	1.6412					
	0.27	5.9801	1.2874				slow	-
	0.12	6.4118	1.8075					
	0.25	7.1388	1.8673				fast	-
	0.72	6.1442	1.3940					

Table 15: Results of the two-way ANOVA for unbalanced data. The used data was collected while walking overground and while walking on the treadmill and clustered according to Schwartz et al. (2008). The first column names the analysed parameter. The second, third and fourth columns give information about the normal distirbution, the mean value and the standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first three rows of each parameter for the these columns belong to the measurements conducted overground in the order normal - slow - fast walking speed. Rows 4 - 6 present the data of measurements conducted on the treadmill in the order normal - slow - fast walking speed. The fifth and sixth columns give information if the walking condition (Condition) does have a significant influence ($p < 0.05$) on the result and if there is an interaction with walking speed (Speed x Cond.). An interaction is indicated by a value smaller than 0.05. The last two columns show if the difference occur at normal, slow or fast walking speed. Results are significant if the value is smaller than 0.05.

One-way ANOVA with repeated measurements - overground

Parameter	Normal Distribution	Mean Value	Standard Deviation	Sig.	Comparison p-Value (α/3)	
Cadence	0.58	114.0327	7.5388	0.000	1:2	0.000
	0.99	99.4908	9.7929		1:3	0.000
	0.51	122.4217	9.7135		2:3	0.000
Walking Speed	0.51	1.2851	0.1176	0.000	1:2	0.000
	0.55	0.9889	0.1377		1:3	0.000
	0.85	1.5277	0.1492		2:3	0.000
Step Width	0.56	0.0761	0.0218	0.612	1:2	-
	0.13	0.0742	0.0250		1:3	-
	0.53	0.0756	0.0229		2:3	-
FFHF_front_80Prz	0.39	5.8516	4.2993	0.297	1:2	-
	0.96	6.0451	4.3531		1:3	-
	0.77	5.8153	4.3692		2:3	-
FFHF_front_max	0.28	9.5720	4.2546	0.000	1:2	0.000
	0.76	8.9814	4.4006		1:3	0.003
	0.62	10.0699	4.5106		2:3	0.000
FFHF_front_min	0.29	2.5346	4.3685	0.049	1:2	0.016
	0.08	2.2216	4.3629		1:3	0.206
	0.15	2.6205	4.3678		2:3	0.010
FFHF_front_rom	0.17	7.0375	1.6614	0.001	1:2	0.017
	0.34	6.7598	1.7865		1:3	0.001
	0.32	7.4494	1.8167		2:3	0.000
FFHF_sag_max	0.17	7.1049	4.1973	0.055	1:2	-
	0.12	7.0837	4.3936		1:3	-
	0.06	7.5371	4.3192		2:3	-
FFHF_sag_min	0.93	-9.0519	4.6532	0.000	1:2	0.000
	0.66	-7.7232	4.5125		1:3	0.002
	0.62	-9.6383	4.8292		2:3	0.000
FFHF_sag_rom	0.55	16.1567	3.8428	0.000	1:2	0.000
	0.19	14.8070	3.4230		1:3	0.000
	0.43	17.1754	3.9242		2:3	0.000

FFHF_trans_80Prz	0.91	7.1616	6.4617	0.004	1:2	0.002
	0.41	7.4737	6.4834		1:3	0.098
	0.21	6.9959	6.7813		2:3	0.000
FFHF_trans_max	0.97	12.2976	5.8159	0.280	1:2	-
	0.50	12.1520	5.9713		1:3	-
	0.23	12.4036	6.1808		2:3	-
FFHF_trans_min	0.51	0.8192	5.883	0.011	1:2	0.000
	0.21	1.1418	6.0909		1:3	0.040
	0.30	1.0120	6.1046		2:3	0.071
FFHF_trans_rom	0.067	11.4784	2.1113	0.002	1:2	0.000
	0.40	11.0102	2.0475		1:3	0.167
	0.08	11.3916	2.2283		2:3	0.005
FFHF_front_80Prz	0.07	7.5894	4.1053	0.001	1:2	0.026
	0.00	7.9865	3.7672		1:3	0.001
	0.02	7.1055	4.0902		2:3	0.000
FFTB_front_max	0.00	13.8912	4.2828	0.003	1:2	0.200
	0.01	13.7535	3.9718		1:3	0.000
	0.00	13.2186	4.1654		2:3	0.005
FFTB_front_min	0.56	0.0281	3.6327	0.098	1:2	-
	0.41	-0.0426	3.1489		1:3	-
	0.32	-0.4761	3.9142		2:3	-
FFTB_front_rom	0.44	13.8613	2.9317	0.723	1:2	-
	0.16	13.7961	2.6912		1:3	-
	0.41	13.6947	3.1854		2:3	-
FFHF_sag_80Prz	0.51	4.6686	4.0204	0.008	1:2	0.001
	0.80	5.4950	3.8100		1:3	0.002
	0.60	5.3740	3.3655		2:3	0.235
FFTB_sag_max	0.28	20.1541	3.3979	0.000	1:2	0.001
	0.81	20.7344	3.3646		1:3	0.000
	0.26	18.9814	4.3650		2:3	0.000
FFTB_sag_min	0.04	-18.4861	8.9023	0.000	1:2	0.000
	0.01	-13.9535	7.4984		1:3	0.000
	0.52	-20.6159	8.5495		2:3	0.000

FFTB_sag_rom	0.11	38.6402	8.4659	0.000	1:2	0.000
	0.56	34.6879	7.3437		1:3	0.023
	0.01	39.5972	8.0569		2:3	0.000
FFHF_trans_80Prz	0.14	15.2895	6.7304	0.000	1:2	0.009
	0.18	15.6547	6.9004		1:3	0.000
	0.40	14.3180	6.8937		2:3	0.000
FFTB_trans_max	0.77	27.4269	7.2078	0.069	1:2	-
	0.69	26.7560	7.1738		1:3	-
	0.26	27.1508	7.3776		2:3	-
FFTB_trans_min	0.35	7.0033	6.2775	0.000	1:2	0.000
	0.64	8.0001	6.3684		1:3	0.000
	0.65	6.3715	6.1017		2:3	0.000
FFTB_trans_rom	0.02	20.4236	4.1718	0.000	1:2	0.000
	0.02	18.7558	3.9678		1:3	0.075
	0.31	20.7793	4.3871		2:3	0.000
HFTB_front_80Prz	0.58	1.9377	4.0843	0.001	1:2	0.158
	0.69	2.0583	4.0786		1:3	0.001
	0.62	1.3870	4.3606		2:3	0.000
HFTB_front_max	0.29	6.4386	4.3076	0.000	1:2	0.214
	0.55	6.3554	4.2834		1:3	0.000
	0.43	5.5748	4.5510		2:3	0.000
HFTB_front_min	0.97	-4.4669	4.1267	0.001	1:2	0.035
	0.76	-4.1851	3.8968		1:3	0.010
	0.56	-4.9436	4.5028		2:3	0.001
HFTB_front_rom	0.04	10.9055	2.0891	0.073	1:2	-
	0.09	10.5406	1.8692		1:3	-
	0.66	10.5184	2.1982		2:3	-
HFTB_sag_max	0.21	13.0266	3.0840	0.000	1:2	0.004
	0.45	13.5505	3.2495		1:3	0.000
	0.32	11.5189	3.4152		2:3	0.000
HFTB_sag_min	0.20	-10.0259	5.2832	0.000	1:2	0.000
	0.24	-7.7646	4.3426		1:3	0.002
	0.39	-11.2435	4.8914		2:3	0.000

HFTB_sag_rom	0.02	23.0525	5.2518	0.000	1:2	0.000
	0.16	21.3151	4.2933		1:3	0.117
	0.01	22.7624	4.9130		2:3	0.001
HFTB_sag_max	0.22	15.1831	6.2861	0.019	1:2	0.000
	0.46	14.5844	6.2246		1:3	0.134
	0.16	15.0053	6.4514		2:3	0.027
HFTB_sag_min	0.51	1.8941	5.9492	0.000	1:2	0.000
	0.43	2.5478	5.7002		1:3	0.000
	0.56	1.2725	5.9508		2:3	0.000
HFTB_sag_rom	0.63	13.2889	3.5941	0.000	1:2	0.000
	0.21	12.0366	3.2878		1:3	0.016
	0.02	13.7328	3.6356		2:3	0.000
HXFF_sag_max	0.83	13.1872	9.9229	0.000	1:2	0.000
	0.84	11.7681	9.7728		1:3	0.004
	0.79	15.0529	11.3918		2:3	0.000
HXFF_sag_min	0.03	-14.1360	6.3598	0.000	1:2	0.184
	0.07	-14.2553	6.2635		1:3	0.000
	0.27	-14.4722	7.5393		2:3	0.000
HXFF_sag_rom	0.95	27.3232	8.0009	0.009	1:2	0.001
	0.49	26.0234	7.1021		1:3	0.228
	0.06	27.5251	7.9363		2:3	0.004
GRF_x_pstand_max	0.15	21.5722	2.5866	0.000	1:2	0.000
	0.24	16.1256	2.9250		1:3	0.000
	0.00	25.3876	3.1798		2:3	0.000
GRF_x_pstand_min	0.22	-17.6175	2.7163	0.000	1:2	0.000
	0.09	-12.5571	2.1857		1:3	0.000
	0.20	-21.9286	3.9523		2:3	0.000
Hip_sag_max	0.43	38.7650	4.5532	0.000	1:2	0.000
	0.47	36.4555	4.6635		1:3	0.000
	0.25	40.5556	5.3347		2:3	0.000
Hip_sag_min	0.16	-5.4156	4.9559	0.000	1:2	0.000
	0.20	-3.4943	4.8542		1:3	0.000
	0.25	-8.1261	5.2153		2:3	0.000

Hip_sag_rom	0.41	44.1806	4.2910	0.000	1:2	0.000
	0.30	39.9498	4.2257		1:3	0.000
	0.97	48.6817	5.3248		2:3	0.000
Knee_sag_max	0.87	68.6812	3.3481	0.000	1:2	0.000
	0.52	66.3208	4.1079		1:3	0.160
	0.12	68.4882	2.7565		2:3	0.000
Knee_sag_min	0.84	6.0356	3.2027	0.000	1:2	0.052
	0.99	6.2699	3.3254		1:3	0.000
	0.72	5.3689	2.8171		2:3	0.000
Knee_sag_rom	0.45	62.6456	4.8228	0.000	1:2	0.000
	0.22	60.0509	5.6541		1:3	0.064
	0.73	63.1193	3.6849		2:3	0.000
ScoreG_Foot_GPS	0.15	6.0923	1.5138	0.000	1:2	0.000
	0.13	6.4850	1.5636		1:3	0.112
	0.03	6.1702	1.6460		2:3	0.000

Table 16: Results of the one-way ANOVA with repeated measurements. The used data was collected while walking overground and clustered according to self-selected speed. The second, third and fourth columns give information about the normal distirbution and the mean value and standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first row of each parameters for these columns belong to the measurements conducted at normal speed. The following two rows contain information about measurements conducted at slow and fast walking speed. The fourth column presents the outcome of the ANOVA. If Sig. is smaller than 0.05 the analysed data show somewhere a significant difference. The last two columns give the p-value of the post-hoc tests for the comparisons normal to slow (1:2), normal to fast (1:3) and slow to fast (2:3) walking speed. If the p-value is smaller than 0.017 a significant difference is detected.

One-way ANOVA with repeated measurements - treadmill

Parameter	Normal Distribution	Mean Value	Standard Deviation	Sig.	Comparison p-Value (α/3)	
Cadence	0.97	114.6616	7.4666	0.000	1:2	0.000
	0.72	102.9401	8.7758		1:3	0.000
	1.00	123.8600	9.6817		2:3	0.000
Walking Speed	0.00	1.1731	0.3223	0.000	1:2	0.000
	0.75	0.9438	0.1938		1:3	0.001
	0.50	1.4276	0.2700		2:3	0.000
Step Width	0.89	0.0518	0.0140	0.037	1:2	0.101
	0.48	0.0540	0.0189		1:3	0.031
	0.96	0.0487	0.0139		2:3	0.007
FFHF_front_80Prz	0.99	5.3931	4.4558	0.660	1:2	-
	0.65	5.4207	4.4596		1:3	-
	0.55	5.5240	4.3927		2:3	-
FFHF_front_max	0.52	9.5386	4.3249	0.000	1:2	0.000
	0.77	8.8210	4.1102		1:3	0.025
	0.57	9.8174	4.5105		2:3	0.000
FFHF_front_min	0.59	1.9396	4.2595	0.007	1:2	0.000
	0.34	1.5436	4.2023		1:3	0.328
	0.35	1.9360	4.2049		2:3	0.001
FFHF_front_rom	0.50	7.5990	1.6255	0.003	1:2	0.015
	0.31	7.2773	1.6181		1:3	0.028
	0.54	7.8813	1.9415		2:3	0.001
FFHF_sag_max	0.15	7.6548	4.7682	0.294	1:2	-
	0.14	7.7689	4.5058		1:3	-
	0.20	7.4484	4.9241		2:3	-
FFHF_sag_min	0.78	-8.2655	5.3192	0.000	1:2	0.000
	0.90	-7.0866	5.1549		1:3	0.000
	0.49	-9.331	5.6985		2:3	0.000
FFHF_sag_rom	0.22	15.9202	3.7019	0.000	1:2	0.000
	0.71	14.8555	3.5555		1:3	0.000
	0.68	16.7815	3.7801		2:3	0.000

FFHF_trans_80Prz	0.23	7.5400	6.8699	0.014	1:2	0.000
	0.43	7.8598	6.7356		1:3	0.083
	0.06	7.3067	7.0289		2:3	0.002
FFHF_trans_max	0.12	12.5126	6.1492	0.476	1:2	-
	0.08	12.3765	6.0929		1:3	-
	0.05	12.5727	6.2545		2:3	-
FFHF_trans_min	0.18	1.6342	6.1086	0.174	1:2	-
	0.21	1.7903	6.0949		1:3	-
	0.11	1.6550	6.0722		2:3	-
FFHF_trans_rom	0.06	10.8784	2.0248	0.077	1:2	-
	0.17	10.5862	1.9574		1:3	-
	0.38	10.9177	2.0151		2:3	-
FFHF_front_80Prz	0.45	5.8873	4.5197	0.018	1:2	0.003
	0.02	6.4615	4.3319		1:3	0.081
	0.34	6.0716	4.2602		2:3	0.032
FFTB_front_max	0.21	12.3612	4.1497	0.027	1:2	0.292
	0.40	12.3323	3.8752		1:3	0.002
	0.10	11.7897	4.3989		2:3	0.018
FFTB_front_min	0.60	-1.2818	3.6511	0.896	1:2	-
	0.69	-1.2872	3.2780		1:3	-
	0.68	-1.2375	3.6840		2:3	-
FFTB_front_rom	0.50	13.6430	2.9895	0.042	1:2	0.307
	0.42	13.6195	2.7095		1:3	0.002
	0.46	13.0272	3.3440		2:3	0.023
FFHF_sag_80Prz	0.16	3.1985	4.3584	0.049	1:2	0.006
	0.57	3.9645	4.5291		1:3	0.006
	0.54	3.9275	4.0670		2:3	0.309
FFTB_sag_max	0.31	18.1916	4.5869	0.000	1:2	0.000
	0.47	19.2212	4.4510		1:3	0.000
	0.08	16.2930	5.4818		2:3	0.000
FFTB_sag_min	0.35	-19.6278	8.5652	0.000	1:2	0.000
	0.02	-15.8007	9.4098		1:3	0.000
	0.41	-22.7248	8.9049		2:3	0.000

FFTB_sag_rom	0.13	37.8194	7.6403	0.000	1:2	0.000
	0.12	35.0219	8.5404		1:3	0.006
	0.12	39.0178	7.0981		2:3	0.000
FFHF_trans_80Prz	0.50	15.9006	6.7678	0.000	1:2	0.015
	0.47	16.2325	6.8024		1:3	0.000
	0.54	15.2283	6.7035		2:3	0.000
FFTB_trans_max	0.23	27.5821	6.9535	0.089	1:2	-
	0.14	26.8147	6.7957		1:3	-
	0.37	27.4373	6.9223		2:3	-
FFTB_trans_min	0.57	7.2964	6.0839	0.000	1:2	0.000
	0.48	8.2822	6.0274		1:3	0.000
	0.56	6.6396	6.1909		2:3	0.000
FFTB_trans_rom	0.42	20.2856	4.2878	0.000	1:2	0.000
	0.13	18.5326	4.3860		1:3	0.018
	0.62	20.7976	4.1282		2:3	0.000
HFTB_front_80Prz	0.59	0.5971	4.5969	0.002	1:2	0.001
	0.62	1.0675	4.4885		1:3	0.288
	0.44	0.5703	4.6393		2:3	0.001
HFTB_front_max	0.26	5.2913	4.6071	0.021	1:2	0.215
	0.60	5.3754	4.6654		1:3	0.002
	0.22	4.8880	4.8436		2:3	0.007
HFTB_front_min	0.79	-5.2043	4.6396	0.000	1:2	0.000
	1.00	-4.5749	4.2919		1:3	0.311
	0.67	-5.1901	4.7292		2:3	0.001
HFTB_front_rom	0.17	10.4955	2.1905	0.048	1:2	0.004
	0.11	9.9502	1.9572		1:3	0.006
	0.11	10.0781	2.1832		2:3	0.289
HFTB_sag_max	0.80	10.5727	3.3840	0.000	1:2	0.000
	0.34	11.4334	3.6065		1:3	0.000
	0.82	9.4109	3.4551		2:3	0.000
HFTB_sag_min	0.39	-11.7947	5.4714	0.000	1:2	0.000
	0.24	-9.8474	5.9544		1:3	0.000
	0.65	-13.7834	5.1918		2:3	0.000

HFTB_sag_rom	0.26	22.3674	5.3248	0.000	1:2	0.000
	0.12	21.2808	5.4076		1:3	0.018
	0.54	23.1943	4.6907		2:3	0.000
HFTB_sag_max	0.21	15.2506	6.3884	0.023	1:2	0.001
	0.25	14.6212	6.2058		1:3	0.197
	0.19	15.1442	6.3918		2:3	0.023
HFTB_sag_min	0.36	1.7814	5.7937	0.000	1:2	0.000
	0.29	2.4213	5.4093		1:3	0.000
	0.34	1.1941	5.8615		2:3	0.000
HFTB_sag_rom	0.07	13.4692	3.6735	0.000	1:2	0.000
	0.28	12.1999	3.4670		1:3	0.016
	0.17	13.9501	3.5040		2:3	0.000
HXFF_sag_max	0.93	15.9553	11.2017	0.001	1:2	0.000
	0.47	14.2468	11.1636		1:3	0.012
	0.88	17.1456	11.5843		2:3	0.001
HXFF_sag_min	0.19	-12.4402	7.4236	0.000	1:2	0.047
	0.23	-12.7298	7.2206		1:3	0.000
	0.37	-11.4506	7.6181		2:3	0.000
HXFF_sag_rom	0.81	28.3955	9.4232	0.050	1:2	0.002
	0.08	26.9766	9.4440		1:3	0.239
	0.64	28.5962	9.2084		2:3	0.022
Hip_sag_max	0.61	40.0716	4.8144	0.000	1:2	0.000
	0.48	38.5644	4.6950		1:3	0.000
	0.17	52.0447	5.4753		2:3	0.000
Hip_sag_min	0.21	-5.8718	5.2937	0.000	1:2	0.000
	0.35	-3.3816	4.8465		1:3	0.000
	0.14	-8.2200	5.3892		2:3	0.000
Hip_sag_rom	0.68	45.9434	4.9130	0.000	1:2	0.000
	0.30	41.9460	4.3131		1:3	0.000
	0.38	50.2648	5.6981		2:3	0.000
Knee_sag_max	0.49	70.7665	3.2274	0.001	1:2	0.000
	0.63	69.4689	4.0990		1:3	0.260
	0.04	70.6956	2.8935		2:3	0.002

Knee_sag_min	0.97	5.8594	3.2243	0.002	1:2	0.001
	0.93	6.3761	3.3776		1:3	0.041
	0.90	5.5476	3.2603		2:3	0.001
Knee_sag_rom	0.27	64.9070	4.3201	0.000	1:2	0.000
	0.12	63.0928	5.1820		1:3	0.166
	0.54	65.1480	3.8070		2:3	0.000
ScoreG_Foot_GPS	0.04	6.4078	1.7694	0.000	1:2	0.000
	0.16	6.6844	1.8388		1:3	0.053
	0.04	6.3278	1.8431		2:3	0.000

Table 17: Results of the one-way ANOVA with repeated measurements. The used data was collected while walking on the treadmill and clustered according to self-selected speed. The second, third and fourth columns give information about the normal distirbution and the mean value and standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first row of each parameters for these columns belong to the measurements conducted at normal speed. The following two rows contain information about measurements conducted at slow and fast walking speed. The fourth column presents the outcome of the ANOVA. If Sig. is smaller than 0.05 the analysed data show somewhere a significant difference. The last two columns give the p-value of the post-hoc tests for the comparisons normal to slow (1:2), normal to fast (1:3) and slow to fast (2:3) walking speed. If the p-value is smaller than 0.017 a significant difference is detected.

One-way ANOVA for unbalanced data - overground

Parameter	Normal Distribution	Mean Value	Standard Deviation	Levene	Sig.	Comparison	p-Value
Cadence	0.50	110.4985	5.6180	0.503	0.000	1:2	0.000
	0.89	94.3572	7.8827			1:3	0.000
	0.73	123.7818	5.8612			2:3	0.000
Walking Speed	0.75	1.2093	0.0897	0.875	0.000	1:2	0.000
	0.98	0.8998	0.0880			1:3	0.000
	0.99	1.5345	0.0970			2:3	0.000
Step Width	0.50	0.0754	0.0224	0.662	0.947	1:2	-
	0.22	0.0739	0.0274			1:3	-
	0.56	0.0729	0.0241			2:3	-
FFHF_front_80Prz	0.41	5.7597	4.2705	0.519	0.617	1:2	-
	0.94	5.4204	4.75+2			1:3	-
	0.65	6.4532	3.8523			2:3	-
FFHF_front_max	0.34	9.3744	4.1480	0.448	0.038	1:2	0.444
	0.98	8.1539	4.7529			1:3	0.243
	0.39	10.9007	3.6683			2:3	0.030
FFHF_front_min	0.23	2.3533	4.3118	0.289	0.178	1:2	-
	0.42	1.6057	4.6026			1:3	-
	0.10	3.5693	3.6867			2:3	-
FFHF_front_rom	0.12	7.0211	1.6501	0.419	0.215	1:2	-
	0.18	6.5482	1.9781			1:3	-
	0.83	7.3314	1.6594			2:3	-
FFHF_sag_max	0.16	7.2334	4.2125	0.867	0.438	1:2	-
	0.15	6.0658	3.8078			1:3	-
	0.04	7.2879	4.5083			2:3	-
FFHF_sag_min	0.90	-8.6729	4.5874	0.947	0.443	1:2	-
	0.69	-7.9609	4.4067			1:3	-
	0.95	-9.4599	4.7838			2:3	-
FFHF_sag_rom	0.62	15.9064	3.7116	0.984	0.018	1:2	0.097
	0.64	14.0267	3.7313			1:3	0.584
	0.43	16.7478	3.8221			2:3	0.015

FFHF_trans_80Prz	0.93	7.2829	6.4505	0.230	0.029	1:2	0.474
	0.39	9.0129	6.9311			1:3	0.235
	0.82	4.9973	5.0255			2:3	0.033
FFHF_trans_max	0.96	12.3071	5.8042	0.248	0.077	1:2	-
	0.53	13.7036	6.2346			1:3	-
	0.55	10.6702	4.5795			2:3	-
FFHF_trans_min	0.47	0.8764	5.8455	0.223	0.027	1:2	0.326
	0.34	2.8133	6.3881			1:3	0.333
	0.93	-0.9322	4.5447			2:3	0.028
FFHF_trans_rom	0.75	11.4307	2.0862	0.668	0.424	1:2	-
	0.62	10.8903	2.0715			1:3	-
	0.46	11.6025	2.4392			2:3	-
FFTB_front_80Prz	0.03	7.4966	4.0518	0.892	0.250	1:2	-
	0.01	8.2526	4.3301			1:3	-
	0.69	6.7074	3.6421			2:3	-
FFTB_front_max	0.00	13.9015	4.2336	0.808	0.506	1:2	-
	0.02	13.9075	4.5894			1:3	-
	0.25	13.0635	3.9540			2:3	-
FFTB_front_min	0.40	-0.1024	3.5859	0.914	0.732	1:2	-
	0.38	-0.3508	3.7710			1:3	-
	0.18	-0.4330	3.7308			2:3	-
FFTB_front_rom	0.35	14.0039	2.9352	0.895	0.559	1:2	-
	0.10	14.2583	2.7245			1:3	-
	0.73	13.4965	2.8872			2:3	-
FFHF_sag_80Prz	0.51	4.6121	4.1438	0.302	0.209	1:2	-
	0.74	6.1183	3.5802			1:3	-
	0.12	4.7640	3.1218			2:3	-
FFTB_sag_max	0.28	20.5120	3.2608	0.578	0.021	1:2	0.855
	0.96	20.9591	3.4591			1:3	0.055
	0.64	19.6634	3.8198			2:3	0.031
FFTB_sag_min	0.04	-17.4075	8.5183	0.731	0.000	1:2	0.018
	0.04	-11.9675	7.6932			1:3	0.121
	0.57	-21.0820	8.0862			2:3	0.000

FFTB_sag_rom	0.04	37.9195	8.2794	0.997	0.007	1:2	0.041
	0.07	32.9266	8.3236			1:3	0.609
	0.07	39.7454	8.8629			2:3	0.006
FFHF_trans_80Prz	0.15	15.3833	6.8182	0.338	0.039	1:2	0.757
	0.07	16.5543	7.8036			1:3	0.120
	0.27	12.2971	6.0466			2:3	0.044
FFTB_trans_max	0.75	27.4291	7.1436	0.902	0.543	1:2	-
	0.30	27.4177	7.7552			1:3	-
	0.36	25.7219	7.4891			2:3	-
FFTB_trans_min	0.31	7.2704	6.2494	0.308	0.022	1:2	0.472
	0.19	9.0358	7.1052			1:3	0.149
	0.24	4.6002	5.5539			2:3	0.018
FFTB_trans_rom	0.03	20.1589	4.0765	0.216	0.045	1:2	0.197
	0.02	18.3818	3.8528			1:3	0.581
	0.31	21.1217	4.8279			2:3	0.036
HFTB_front_80Prz	0.58	1.9281	4.0891	0.704	0.046	1:2	0.535
	0.63	2.9826	4.2557			1:3	0.227
	0.42	0.3872	4.0241			2:3	0.040
HFTB_front_max	0.32	6.4911	4.3154	0.774	0.103	1:2	-
	0.98	7.1257	4.6001			1:3	-
	0.15	4.8240	4.4783			2:3	-
HFTB_front_min	0.94	-4.3528	4.0695	0.826	0.054	1:2	-
	0.87	-3.5904	4.1899			1:3	-
	0.44	-6.0624	4.2170			2:3	-
HFTB_front_rom	0.03	10.8439	1.9895	0.252	0.940	1:2	-
	0.29	10.7160	1.6055			1:3	-
	0.79	10.8864	2.1548			2:3	-
HFTB_sag_max	0.14	13.2416	3.0274	0.834	0.001	1:2	0.119
	0.14	14.7118	2.8880			1:3	0.044
	0.07	11.5528	3.2894			2:3	0.000
HFTB_sag_min	0.34	-9.5620	4.8465	0.034	-	1:2	-
	0.26	-6.0014	3.6748			1:3	-
	0.64	-11.4888	5.5095			2:3	-

HFTB_sag_rom	0.01	22.8036	5.0607	0.226	0.143	1:2	-
	0.05	20.7132	4.1543			1:3	-
	0.06	23.0416	5.6409			2:3	-
HFTB_trans_max	0.23	15.1491	6.1403	0.638	0.554	1:2	-
	0.26	13.6957	6.5777			1:3	-
	0.59	15.3678	6.9789			2:3	-
HFTB_trans_min	0.65	1.9872	5.9448	0.940	0.833	1:2	-
	0.79	2.2600	5.6978			1:3	-
	0.19	1.3999	5.7771			2:3	-
HFTB_trans_rom	0.56	13.1619	3.4189	0.311	0.016	1:2	0.095
	0.07	11.4357	2.8224			1:3	0.555
	0.13	13.9679	3.8812			2:3	0.013
HXFF_sag_max	0.92	12.67	10.2238	0.053	0.447	1:2	-
	0.79	11.2026	6.9649			1:3	-
	0.76	14.3590	11.0008			2:3	-
HXFF_sag_min	0.01	-14.1366	6.2618	0.536	0.424	1:2	-
	0.23	-13.7660	5.2499			1:3	-
	0.17	-12.5802	6.8185			2:3	-
HXFF_sag_rom	0.96	26.8164	8.0771	0.270	0.505	1:2	-
	0.26	24.9686	6.1133			1:3	-
	0.22	26.9392	7.5236			2:3	-
GRF_x_pstand_max	0.07	20.1956	2.2765	0.041	-	1:2	-
	0.34	14.6172	2.4623			1:3	-
	0.00	25.7765	3.2507			2:3	-
GRF_x_pstand_min	0.05	-16.1232	2.4808	0.001	-	1:2	-
	0.02	-11.5386	1.8439			1:3	-
	0.03	-22.1654	3.8227			2:3	-
Hip_sag_max	0.18	38.1200	3.9953	0.183	0.000	1:2	0.002
	0.40	34.4154	4.0307			1:3	0.003
	0.24	41.5023	5.0756			2:3	0.000
Hip_sag_min	0.22	-4.8728	4.9583	0.833	0.000	1:2	0.337
	0.24	-3.2378	4.6537			1:3	0.006
	0.39	-8.3082	4.7645			2:3	0.000

Hip_sag_rom	0.79	42.9928	3.4096	0.282	0.000	1:2	0.000
	0.54	37.6533	3.1608			1:3	0.000
	0.68	49.8105	4.1056			2:3	0.000
Knee_sag_max	0.92	68.3754	3.3393	0.458	0.000	1:2	0.000
	0.68	64.5634	3.9326			1:3	0.677
	0.36	69.0146	2.7983			2:3	0.000
Knee_sag_min	0.99	6.1468	3.1562	0.860	0.051	1:2	-
	0.93	7.1292	2.8905			1:3	-
	0.92	5.1952	3.0662			2:3	-
Knee_sag_rom	0.39	62.2286	4.7242	0.159	0.000	1:2	0.000
	0.37	57.4342	4.9072			1:3	0.267
	0.25	63.8194	3.8077			2:3	0.000
ScoreG_Foot_GPS	0.15	6.1475	1.4962	0.402	0.041	1:2	0.093
	0.31	6.8918	1.6412			1:3	0.870
	0.27	5.9801	1.2874			2:3	0.045

Table 18: Results of the one-way ANOVA for unbalanced. The used data was collected while walking overgroundl and clustered according to Schwartz et al. (2008).. The second, third and fourth columns give information about the normal distirbution and the mean value and standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first row of each parameters for these columns belong to the measurements conducted at normal speed. The following two rows contain information about measurements conducted at slow and fast walking speed. The fourth column presents the outcome of the Levene's test (Levene). Only if the value in this column is greater than 0.05 an ANOVA can be conducted. The results of the ANOVA are shown in colum 6 called Sig.. If Sig. is smaller than 0.05 the analysed data differs somewhere a significantly. The last two columns give the p-value of the post-hoc tests for the comparisons normal to slow (1:2), normal to fast (1:3) and slow to fast (2:3) walking speed. If the p-value is smaller than 0.017 a significant difference is detected.

One-way ANOVA for unbalanced data - treadmill

Parameter	Normal Distribution	Mean Value	Standard Deviation	Levene	Sig.	Comparison	p-Value
Cadence	0.88	111.4024	5.8261	0.427	0.000	1:2	0.000
	0.53	99.21889	8.0967			1:3	0.000
	0.94	125.7181	6.4502			2:3	0.000
Walking Speed	0.00	1.0836	0.2916	0.459	0.000	1:2	0.015
	0.53	0.8464	0.1514			1:3	0.000
	0.03	1.4154	0.2237			2:3	0.000
Step Width	0.52	0.0522	0.0140	0.063	0.079	1:2	0.738
	0.49	0.0561	0.0203			1:3	0.288
	0.45	0.0447	0.0119			2:3	0.110
FFHF_front_80Prz	0.99	5.2036	4.3805	0.932	0.573	1:2	-
	0.79	5.0081	4.6010			1:3	-
	0.60	6.0865	4.3678			2:3	-
FFHF_front_max	0.92	9.1705	4.1809	0.868	0.050	1:2	0.561
	0.80	8.1457	4.2334			1:3	0.225
	0.16	10.1327	4.0616			2:3	0.043
FFHF_front_min	0.42	1.7303	4.1529	0.805	0.254	1:2	-
	0.73	0.9866	4.3427			1:3	-
	0.32	2.7292	3.9882			2:3	-
FFHF_front_rom	0.84	7.4402	1.5651	0.558	0.143	1:2	-
	0.40	7.1592	1.7703			1:3	-
	0.40	8.0035	7.8919			2:3	-
FFHF_sag_max	0.20	7.7847	4.6913	0.907	0.615	1:2	-
	0.32	7.1455	4.3071			1:3	-
	0.04	7.0724	4.6146			2:3	-
FFHF_sag_min	0.93	-7.9054	5.0330	0.857	0.297	1:2	-
	0.91	-7.2323	5.2109			1:3	-
	0.57	-9.2602	5.6150			2:3	-
FFHF_sag_rom	0.21	15.6901	3.6167	0.500	0.111	1:2	-
	0.61	14.3779	3.8557			1:3	-
	0.21	16.3326	3.5527			2:3	-

FFHF_trans_80Prz	0.27	7.7334	6.8238	0.291	0.064	1:2	-
	0.40	9.2274	7.3280			1:3	-
	0.67	5.4977	5.5037			2:3	-
FFHF_trans_max	0.11	12.6242	6.0999	0.481	0.201	1:2	-
	0.19	13.5398	6.4744			1:3	-
	0.62	11.1494	4.8239			2:3	-
FFHF_trans_min	0.19	1.7347	6.0333	0.293	0.073	1:2	-
	0.19	3.1015	6.5578			1:3	-
	0.78	-0.0564	4.6970			2:3	-
FFHF_trans_rom	0.10	10.8895	2.0168	0.891	0.341	1:2	-
	0.25	10.4383	1.9676			1:3	-
	0.82	11.2058	2.1368			2:3	-
FFTB_front_80Prz	0.26	5.9634	4.3888	0.596	0.443	1:2	-
	0.10	6.7401	5.0690			1:3	-
	0.86	5.5340	4.1522			2:3	-
FFTB_front_max	0.26	12.4728	4.1239	0.843	0.515	1:2	-
	0.72	12.3221	4.4681			1:3	-
	0.51	11.5906	4.3401			2:3	-
FFTB_front_min	0.69	-1.3286	3.6558	0.567	0.702	1:2	-
	0.51	-1.6691	3.9262			1:3	-
	0.31	-1.4394	3.5476			2:3	-
FFTB_front_rom	0.71	13.8014	2.9261	0.957	0.377	1:2	-
	0.50	13.9912	2.9522			1:3	-
	0.62	13.0300	2.9908			2:3	-
FFTB_sag_80Prz	0.09	3.1126	4.4184	0.055	0.398	1:2	-
	0.57	4.4668	4.9190			1:3	-
	0.31	3.3157	3.4611			2:3	-
FFTB_sag_max	0.24	18.6506	4.4300	0.940	0.002	1:2	0.612
	0.52	19.6768	4.7814			1:3	0.013
	0.64	15.6978	4.4127			2:3	0.002
FFTB_sag_min	0.80	-18.9106	8.5183	0.185	0.000	1:2	0.025
	0.11	-13.4331	9.8467			1:3	0.033
	0.41	-23.8739	7.6960			2:3	0.000

FFTB_sag_rom	0.07	37.5612	7.8419	0.170	0.010	1:2	0.069
	0.01	33.1099	9.3701			1:3	0.532
	0.58	39.5716	7.8815			2:3	0.008
FFTB_trans_80Prz	0.61	16.0440	6.7860	0.270	0.045	1:2	0.725
	0.18	17.2847	7.6837			1:3	0.143
	0.35	13.1339	5.8534			2:3	0.047
FFTB_trans_max	0.34	27.7541	6.8719	0.873	0.635	1:2	-
	0.09	26.8218	7.3689			1:3	-
	0.43	26.2471	7.2401			2:3	-
FFTB_trans_min	0.32	7.5797	5.9793	0.675	0.022	1:2	0.561
	0.07	9.0845	6.7474			1:3	0.120
	0.15	4.8331	5.7008			2:3	0.020
FFTB_trans_rom	0.62	20.1744	4.1491	0.635	0.003	1:2	0.051
	0.08	17.7373	4.2147			1:3	0.412
	0.30	21.4140	4.5565			2:3	0.003
HFTB_front_80Prz	0.36	0.8460	4.6024	0.948	0.124	1:2	-
	0.77	1.8585	4.6812			1:3	-
	0.62	-0.5387	4.5571			2:3	-
HFTB_front_max	0.28	5.5583	4.6777	0.902	0.260	1:2	-
	0.78	5.9492	4.9696			1:3	-
	0.10	4.0401	4.8593			2:3	-
HFTB_front_min	0.76	-4.9387	4.6119	0.954	0.144	1:2	-
	0.99	-4.0802	4.5688			1:3	-
	0.68	-6.3669	4.6762			2:3	-
HFTB_front_rom	0.12	10.4971	2.1715	0.062	0.485	1:2	-
	0.35	9.9284	1.5054			1:3	-
	0.19	10.4070	2.1871			2:3	-
HFTB_sag_max	0.73	10.8893	3.4427	0.906	0.001	1:2	0.134
	0.71	12.4547	3.2285			1:3	0.058
	0.88	9.1242	3.3922			2:3	0.001
HFTB_sag_min	0.35	-11.5316	5.4199	0.886	0.000	1:2	0.011
	0.43	-7.7438	5.2071			1:3	0.037
	0.91	-14.5598	5.4165			2:3	0.000

HFTB_sag_rom	0.19	22.4209	5.4350	0.941	0.038	1:2	0.192
	0.03	20.1985	5.2059			1:3	0.545
	0.64	23.6840	5.1923			2:3	0.030
HFTB_trans_max	0.27	15.2664	6.2983	0.700	0.441	1:2	-
	0.27	13.5584	6.5516			1:3	-
	0.12	15.5223	6.7144			2:3	-
HFTB_trans_min	0.39	1.9061	5.7713	0.959	0.692	1:2	-
	0.64	2.1439	5.4654			1:3	-
	0.07	1.0169	5.5422			2:3	-
HFTB_trans_rom	0.12	13.3604	3.5316	0.855	0.003	1:2	0.051
	0.23	11.4145	3.2355			1:3	0.306
	0.49	14.5055	3.4404			2:3	0.002
HXFF_sag_max	0.96	15.6033	11.6497	0.086	0.748	1:2	-
	0.56	14.3735	8.3317			1:3	-
	0.96	16.5722	12.7676			2:3	-
HXFF_sag_min	0.27	-12.3903	7.0747	0.854	0.608	1:2	-
	0.60	-12.1406	6.9412			1:3	-
	0.09	-10.9303	7.6614			2:3	-
HXFF_sag_rom	0.23	27.9935	10.0759	0.382	0.802	1:2	-
	0.92	26.5141	8.3022			1:3	-
	0.90	27.5025	8.9046			2:3	-
Hip_sag_max	0.38	39.5227	4.3518	0.521	0.000	1:2	0.025
	0.50	36.6709	4.1725			1:3	0.003
	0.19	42.9547	4.8703			2:3	0.000
Hip_sag_min	0.37	-5.1649	5.3228	0.604	0.000	1:2	0.194
	0.22	-3.0819	4.8876			1:3	0.020
	0.31	-8.2552	4.5740			2:3	0.000
Hip_sag_rom	0.62	44.6876	3.9656	0.278	0.000	1:2	0.000
	0.34	39.7529	3.2707			1:3	0.000
	0.57	51.2100	4.1387			2:3	0.000
Knee_sag_max	0.75	70.6597	3.3014	0.477	0.001	1:2	0.004
	0.45	67.9471	4.0985			1:3	0.841
	0.20	71.0990	3.0682			2:3	0.002

Knee_sag_min	0.96	5.9841	3.4203	0.863	0.113	1:2	-
	0.89	7.1047	3.0336			1:3	-
	0.99	5.3377	3.3489			2:3	-
Knee_sag_rom	0.30	64.6756	4.5354	0.329	0.000	1:2	0.001
	0.05	60.8424	4.6289			1:3	0.505
	0.56	65.7613	3.6030			2:3	0.000
ScoreG_Foot_GPS	0.12	6.4118	1.8075	0.224	0.068	1:2	-
	0.25	7.1388	1.8673			1:3	-
	0.72	6.1442	1.3940			2:3	-

Table 19: Results of the one-way ANOVA for unbalanced data. The used data was collected while walking on the treadmill and clustered according to Schwartz et al. (2008).. The second, third and fourth columns give information about the normal distirbution and the mean value and standard deviation of the dataset. If the value for normal distribution is smaller than 0.05 the data is not normally distributed. The first row of each parameters for these columns belong to the measurements conducted at normal speed. The following two rows contain information about measurements conducted at slow and fast walking speed. The fourth column presents the outcome of the Levene's test (Levene). Only if the value in this column is greater than 0.05 an ANOVA can be conducted. The results of the ANOVA are shown in colum 6 called Sig.. If Sig. is smaller than 0.05 the analysed data differs somewhere a significantly. The last two columns give the p-value of the post-hoc tests for the comparisons normal to slow (1:2), normal to fast (1:3) and slow to fast (2:3) walking speed. If the p-value is smaller than 0.017 a significant difference is detected.