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Dynamic Foot Morphology

Measurements of 3D static and dynamic foot morphology and recommendations for footwear

Doctoral Thesis

Submitted to the Faculty of Behavioral and Social Sciences of the Chemnitz University of Technology,

to fulfil the requirements for the degree of doctor rerum naturalium (Dr. rer. nat.)

February 2014

Vorsitzender des Promotionskolloquiums: JP Dr. Christian Maiwald

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For Marc
Abstract

Background: The foot has to fulfil important and complex functions which are, in most regions of the world, supported by shoes. The interface of feet and footwear has often been considered with respect to comfort and function but also to negative effects of shoes. One main contribution to the improvement of footwear fit is provided by matching the shape of the shoe to the shape of the foot. However, current approaches for implementation only include static information. There is still a lack of dynamic information about foot morphology and deformation. Recent advancements in scanner technology allow capturing the foot during natural walking. These advancements and the development of a dynamic foot scanner system (DynaScan4D) are preconditions for this thesis. The research question is: How does foot morphology differ between static and dynamic situations? This question is further specified toward three hypotheses by findings and deficits of the current state of research. The examination of the three hypotheses and their contribution to the research question are topic of this thesis. Furthermore, the findings are combined with comprehensive knowledge of the literature to formulate recommendations for last and footwear construction.

Methods: The three hypotheses (H₁, H₂, H₃) are evaluated within three research articles. The first research article aims to identify the differences in dynamic foot morphology according to age, gender, and body mass (H₁). The plantar dynamic foot morphology of 129 adults is recorded and analysed by two statistical methods: (1) comparison of matched groups and (2) multiple linear regression analysis. The second and third research article is dealing with differences between static and dynamic foot morphology in developing feet (H₂) and their inter-individual differences (H₃). For this reason, a large sample of 2554 children, aged between 6 and 16 years, is analysed. Foot measures, corresponding to last measures, are used to identify the differences between static and dynamic foot morphology (H₂) by Student’s t-test for paired samples. The influences of gender, age, and body mass (H₃) are analysed within the whole sample by multiple
linear regression analysis and within matched groups by Student’s t-test for independent samples.

**Results:** There are differences in dynamic foot morphology according to age, gender, and body mass in adults which confirm H$_1$. In general, the differences are rather small. Furthermore, the differences must be considered in a more differentiated way, as they are not consistent regarding all plantar foot measures. H$_2$ is confirmed as there are statistically significant differences between static and dynamic foot morphology in developing feet. Theses differences are found for all foot measures. However, the magnitude of these differences varies depending on each foot measure. Relevant differences, in particular the forefoot width and midfoot girth measures as well as the angles of the forefoot, must be considered for footwear construction. Influences of gender, age, and body mass are found for the dynamic foot morphology and the differences between static and dynamic foot morphology of developing feet. Thus, H$_3$ is verified. However, these findings are small, especially considering the high variance within each foot measure. The variables gender, age, and body mass cannot appropriately explain the variance of the differences between static and dynamic foot morphology. Thus, the customization of footwear to dynamic foot morphology can be conducted without individual adjustments to gender, age, or body mass.

**Conclusion:** This thesis presents different aspects to answer the question of differences between static and dynamic foot morphology. The findings of this thesis are critically discussed and recommendations for improvements of dynamic fit of footwear are formulated, taking into account the current state of research as well as practical aspects. The findings of the thesis contribute to the field of fundamental research, i.e. to broaden the knowledge about three-dimensional characteristics of dynamic foot morphology. Furthermore, this thesis can help to improve the fit of footwear and thus contributes to applied research in the field of footwear science.
Zusammenfassung


**Methoden:** Die drei Hypothesen (H₁, H₂, H₃) werden in drei wissenschaftlichen Veröffentlichungen untersucht. Die erste Veröffentlichung zielt darauf ab, die Unterschiede zwischen der dynamischen Fußgestalt in Abhängigkeit von Alter, Geschlecht und Körpermasse zu ermitteln (H₁). Die plantare dynamische Fußgestalt von 129 Erwachsenen wird hierzu erfasst und durch zwei statistische Verfahren analysiert: (1) Vergleich von gepaarten Probandengruppen und (2) multiple lineare Regressionsanalyse. Die zweite und dritte Hypothese befassen sich mit den Unterschieden der statischen und dynamischen Fußgestalt bei heranwachsenden Füßen (H₂) und deren inter-individuellen Unterschieden (H₃). Aus diesem Grund wird eine große Stichprobe mit 2554 Kindern im Alter zwischen 6 und 16 Jahren untersucht. Fußmaße, die den Maßen im Leistenbau entsprechen,
werden verwendet um die Unterschiede zwischen der statischen und der dynamischen Fußgestalt (H2) durch einen gepaarten Student’s t-Test zu identifizieren. Der Einfluss des Geschlechtes, des Alters und der Körpermasse (H3) werden in der gesamten Stichprobe durch eine multiple lineare Regressionsanalyse und innerhalb gepaarter Probandengruppen durch Student’s t-Test für unabhängige Stichproben untersucht.


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List of Abbreviations

ΔDyn  dynamic delta
AA     arch angle
AB-G   anatomical ball girth
AB-W   anatomical ball width
AH     arch height
AKA64  description of the standardization for children shoe lasts, since 1974 also known as WMS
ANOVA  analysis of variance
AW     arch width
B-H    ball height
BA, B-A ball angle
BMI    body mass index [kg/m2]
BMI-percentile normalized BMI to gender- and age-specific German reference data (Kromeyer-Hauschild et al., 2001)
BW     ball width
CCD    charge-coupled device
CI     confidence interval
CSI    Chippaux-Smirak-Index
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<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>DGOT</td>
<td>German association for orthopaedy and traumatology (Deutsche Gesellschaft für Orthopadie und Traumatologie)</td>
</tr>
<tr>
<td>DLP</td>
<td>digital light processor</td>
</tr>
<tr>
<td>DOG</td>
<td>German association for orthopaedy (Deutsche Orthopädische Gesellschaft)</td>
</tr>
<tr>
<td>FL, F-L</td>
<td>foot length</td>
</tr>
<tr>
<td>fps</td>
<td>frames per second</td>
</tr>
<tr>
<td>FWB</td>
<td>full weight-bearing</td>
</tr>
<tr>
<td>HW</td>
<td>heel width</td>
</tr>
<tr>
<td>HWB</td>
<td>half weight-bearing</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>I-H</td>
<td>instep height</td>
</tr>
<tr>
<td>ICC</td>
<td>intraclass correlation coefficient</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LB-G</td>
<td>last ball girth</td>
</tr>
<tr>
<td>LBL, LB-L</td>
<td>lateral ball length</td>
</tr>
<tr>
<td>LI-G</td>
<td>last instep girth</td>
</tr>
<tr>
<td>LW-G</td>
<td>last waist girth</td>
</tr>
<tr>
<td>MaxDyn</td>
<td>maximum value during dynamic situation</td>
</tr>
<tr>
<td>MBL, MB-L</td>
<td>medial ball length</td>
</tr>
<tr>
<td>MTH</td>
<td>metatarsal head</td>
</tr>
<tr>
<td>MW</td>
<td>midfoot width</td>
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<table>
<thead>
<tr>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>number of participants</td>
</tr>
<tr>
<td>NWB</td>
<td>non weight-bearing</td>
</tr>
<tr>
<td>OB-W</td>
<td>orthogonal ball width</td>
</tr>
<tr>
<td>OH-W</td>
<td>orthogonal heel width</td>
</tr>
<tr>
<td>RMSE</td>
<td>root mean square error</td>
</tr>
<tr>
<td>SD</td>
<td>standard deviation</td>
</tr>
<tr>
<td>SI</td>
<td>Staheli-Index</td>
</tr>
<tr>
<td>T1-A</td>
<td>toe 1 angle</td>
</tr>
<tr>
<td>T5-A</td>
<td>toe 5 angle</td>
</tr>
<tr>
<td>WMS</td>
<td>system for shoes with more width dimensions in Germany (&quot;weit&quot; = wide; &quot;mittel&quot; = medium; &quot;schmal&quot; = narrow)</td>
</tr>
</tbody>
</table>
1 Introduction

Footwear is as old as humanity and has always been important for human beings. Beside the protection of our feet, footwear fulfills further tasks. Taking for example the pointed shoes of the 14th century: The longer the shoe tip, the better the position of the wearer. Even more today, footwear is an expression of fashion and lifestyle.

Often enough, our feet are stressed by ill-fitting shoes and probably everybody can contribute own experiences. Therefore, it can be stated that the importance of our feet is often ignored. They carry us the whole life and enable the freedom of movement and mobility. Several studies have reported the effects of footwear on feet. Therefore, it is known that different problems are related to ill-fitting footwear (Menz and Morris, 2005; Klein et al., 2009). This is especially true for developing feet as they are in particular prone to external influences.

The often figurative sense of the English proverb “If the shoe fits, wear it” reflects the generally considered significance of well-fitting shoes. Similarly, several research studies are concerned with the topic “fit and comfort of footwear” at various levels (Goonetilleke et al., 2000; Piller, 2002; Kouchi et al., 2005). One conclusion is that footwear fit can be improved by matching the shape of the shoe to the shape of the foot (Luximon et al., 2001; Witana et al., 2004). In other words the model of a shoe should be the foot without a shoe (Staheli, 1991). Especially, the approach of Mauch et al. and Krauss et al. is promising regarding the coverage of the natural variability of feet (Mauch et al., 2009; Krauss et al., 2010). One lack of this approach, which is based on comprehensive foot measurements and subsequent categorisation of foot types, is that only static foot morphology is considered. However, the motion of feet and thus dynamic fit of footwear is also or even more important. With respect to children’s feet it is postulated that best development and maturation of the foot takes place barefoot (Staheli, 1991; Rao and Joseph, 1992).

In view of these considerations, the question arises: How does foot morphology differ between static and dynamic situations? This is the research question of this thesis. The
problem is reflected in the quote: “Boots that may be correct to stand in, may not be correct to walk in.” (Golding, 1902, p. 37). Although, this question arises much earlier, there is still a lack of information about dynamic foot morphology.

New and further developments of scanner systems allow capturing the foot three-dimensionally during walking. Even if there are dynamic foot scanner systems now available, significant results useful for the improvement of the dynamic fit of footwear are still missing. The aim of this thesis is to generate findings that are generally valid to provide practically applicable answers to the question of differences between static and dynamic foot morphology. In order to achieve this aim, this thesis comprehensively elaborates knowledge and research findings of the foot but also practically relevant fundamentals of footwear. For the claim to establish general recommendations for the dynamic fit of footwear, large samples must be incorporated. The findings obtained from the thesis can be situated in the range of fundamental research. The combination of the findings and the acquired basic knowledge contribute to applied research in the field of footwear science.

1.1 Structure of the thesis

This thesis aims to identify difference between static and dynamic foot morphology. The resultant objective is to give recommendations for the dynamic fit of footwear.

The theoretical Chapter 2 presents a review of the literature focussing on the topic foot. Within this chapter, anatomical structures of the foot, important for motion or potentially deformable, are reflected. In this context, the development of feet is considered with respect to the adaptation triggered by changing loading situations. Subsequently, the diversity of foot morphology is discussed by intra-individual and inter-individual differences.

Chapter 3 includes theoretical aspects of the interaction between foot and footwear. Some basics of last construction and shoe manufacturing are briefly described. This is followed by a review of the literature regarding the effects of footwear on feet and the knowledge about footwear fit. The generally accepted approach to improve footwear fit is to match shoe and foot shape. Thus, the foot must be measured. Several methods to measure the foot in static and dynamic situations are summarized.

In Chapter 4, the research question is formulated on the base of findings and deficits of the current state of research. Additionally, three hypotheses are derived. An overview
of the used methods to examine the three hypotheses is presented in Chapter 5. This chapter summarizes characteristics of the two samples, principles of measurement and data processing as well as statistical analysis. Furthermore, it refers to sections where more details are found. The three hypotheses are consecutively verified by the three research papers that are presented in Chapter 6, Chapter 7, and Chapter 8.

The subsequent discussion of Chapter 9 includes the consideration of the hypotheses with respect to the research question. Furthermore, the findings are critically discussed and recommendations for last construction and shoe manufacture are compiled. The thesis ends with a conclusion and highlights a possible future line of research and further development for practical applications.
2 Anatomical and functional basics of the foot

This chapter describes anatomical and functional basics of the foot. Section 2.1 responds to the general functions of standing and walking followed by the structural composition with their individual functionality (Section 2.2). Section 2.3 illustrates the structural development and maturation of the foot focusing on functional changes due to upright standing and walking. The last section (Section 2.4) addresses the variety of foot shapes demonstrated by the inter-individual influences closing with already known intra-individual differences between different static and dynamic situations.

2.1 General functions of the foot

The foot has to fulfil essential functions that are characteristic for the human being: First, it has to carry body weight. Second, it has to move body weight and is therefore important for locomotion (Brinckmann et al., 2012, p. 367; Götz, 2001; Rodgers, 1995). These tasks can be expanded in consideration of the general properties of the field of mechanics. Mechanics is the “branch of physical science that deals with energy and forces and their relation to the equilibrium, deformation, or motion” (Webster’s Third International Dictionary, p. 1401). Carrying body weight is synonymous to static situations, as this branch of mechanics is “dealing with relations of forces that produce equilibrium” (Webster’s Third International Dictionary, p. 2229). Moving body weight is synonymous to dynamic situations, as the “branch of mechanics that deals with forces and their relation primarily to the motion but sometimes also to the equilibrium of bodies of matters” (Webster’s Third International Dictionary, p. 711).

The foot has to be rigid for standing tasks. Whereas for walking, a balance between static and dynamic elements is required. Thus, the foot has to act as a spring to compensate influencing forces and as a lever to provide the locomotion of the body.
Simultaneously, the foot has to be flexible to adjust to the environment and transfer generated and acting forces (Götz, 2001; Rodgers, 1995). Vertical and horizontal forces constrain different structures of the foot to change their dimension or location. The forces differ in static compared to dynamic situations (Brinckmann et al., 2012, p. 51; Elftman, 1939). For instance, vertical static forces during standing comprise the magnitude of body weight, whereas they exceed body weight during walking (see Figure 2.1).

2.2 Structures and functionality of the foot

The foot consists of seven tarsal bones, five metatarsal bones, fourteen bones of the phalanges, and usually two sesamoid bones. These bones interact with each other in 33 articulated unions. To fulfill the static and dynamic tasks, 20 muscles and 107 ligaments and tensions, as well as thousands of blood vessels and nerve tracts are involved (Zimmermann, 2010, p. 10; Greisberg, 2007, p.1; Netter, 2001, p. 312; DeAsla and Deland, 2004, p. 1). For the functionality of the foot, skeletal structures and soft tissues are coequally important. Soft tissue is "a generic term for muscle, fat, fibrous tissue, blood vessels, or other supporting tissue matrix" (McGraw-Hill Dictionary).
2.2 Structures and functionality of the foot

2.2.1 Bones and joints

Starting with bony anatomy, the foot can be divided into three main parts: forefoot, midfoot, and hindfoot (see Figure 2.2). The hindfoot is composed of the talus and the calcaneus; the latter is the largest bone of the foot. The midfoot consists of the cuboid, navicular, and the three cuneiform (medial, central, and lateral) bones. The metatarsal and phalangeal bones form the forefoot (Patel and Horton, 2012; Netter, 2001, p. 316).

[Diagram of the foot showing bones and joints]

In kinematic analysis, the foot has been reduced, over a long period of time, to a rigid model and only the ankle have been regarded as the main contributor for foot motion. However, several studies point out considerable movement of the joints within the foot and thus state their important contribution to motion and reaction on acting forces. The articular connections of the hind- and midfoot are summarized to the transverse tarsal joint (a.k.a. Chopart’s joint). The comprehensive movements of the subtalar, talonavicular and calcaneocuboid joints have been clarified within the last decade by several studies. The results of in vitro and in vivo bone pin analysis or magnetic resonance...
imaging show that these joints are more mobile than formerly assumed (Nester et al., 2007; Arndt et al., 2004; Mattingly et al., 2006). Nester et al. have found, in 13 cadaveric feet, a broad range of motion in sagittal, frontal, and transverse plane (see Table 2.1). The authors have compared the in vitro bone pin data with in vivo data of three subjects and found similar kinematic patterns (Nester et al., 2007; Arndt et al., 2004). Thus, the assumption that the calcaneocuboid joint is less important for motion must be refused (Greisberg, 2007, p. 5). For inversion and eversion during walking, the subtalar and the talonavicular joints are important (Greisberg, 2007, p. 5; Mattingly et al., 2006).

The symbiosis of joints, connecting midfoot and forefoot, are summarized as the tarsometatarsal joint (a.k.a. Lisfranc's joint). These joints also feature sagittal, frontal, and transversal motion, even more pronounced within the lateral ray (Nester et al. 2007). Motion is also found between the three cuneiform and the five metatarsal bones (Nester et al., 2007).

Table 2.1: Range of motion of transversal and tarsometatarsal joints of the foot (according to Nester et al., 2007)

<table>
<thead>
<tr>
<th>Joints of the hind-, mid- and fore-foot</th>
<th>Sagittal Plane [*]</th>
<th>Frontal Plane [*]</th>
<th>Transverse Plane [*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcaneus - Talus</td>
<td>7.8 ± 3.8</td>
<td>9.7 ± 5.2</td>
<td>8.1 ± 4.7</td>
</tr>
<tr>
<td>Talus - Navicular</td>
<td>12.2 ± 7.1</td>
<td>12.4 ± 5.0</td>
<td>16.8 ± 9.2</td>
</tr>
<tr>
<td>Calcaneus - Cuboid</td>
<td>9.8 ± 4.0</td>
<td>7.6 ± 3.7</td>
<td>8.0 ± 3.2</td>
</tr>
<tr>
<td>Navicular - Medial Cuneiform</td>
<td>11.4 ± 5.1</td>
<td>8.3 ± 2.3</td>
<td>4.5 ± 2.2</td>
</tr>
<tr>
<td>Navicular - Central Cuneiform</td>
<td>9.8 ± 3.6</td>
<td>8.1 ± 2.2</td>
<td>5.4 ± 2.7</td>
</tr>
<tr>
<td>Navicular - Lateral Cuneiform</td>
<td>14.3 ± 4.7</td>
<td>7.4 ± 1.6</td>
<td>11.2 ± 4.0</td>
</tr>
<tr>
<td>Navicular - Cuboid</td>
<td>9.4 ± 4.5</td>
<td>8.3 ± 3.3</td>
<td>7.9 ± 2.8</td>
</tr>
<tr>
<td>Metatarsal 1 - Medial Cuneiform</td>
<td>5.6 ± 2.4</td>
<td>6.9 ± 2.4</td>
<td>5.1 ± 2.1</td>
</tr>
<tr>
<td>Metatarsal 2 - Central Cuneiform</td>
<td>5.3 ± 1.6</td>
<td>5.1 ± 2.1</td>
<td>4.6 ± 2.0</td>
</tr>
<tr>
<td>Metatarsal 3 - Lateral Cuneiform</td>
<td>7.3 ± 3.1</td>
<td>7.7 ± 2.2</td>
<td>4.9 ± 1.6</td>
</tr>
<tr>
<td>Metatarsal 4 - Cuboid</td>
<td>10.4 ± 3.0</td>
<td>10.4 ± 2.8</td>
<td>5.3 ± 1.8</td>
</tr>
<tr>
<td>Metatarsal 5 - Cuboid</td>
<td>12.5 ± 3.2</td>
<td>12.9 ± 4.4</td>
<td>5.1 ± 1.7</td>
</tr>
</tbody>
</table>

The metatarsophalangeal joints, with their wide range of motion, are essential for the functionality of the foot during locomotion (Greisberg, 2007, p. 1). Whereas, the interphalangeal joints are more important for grasping which signs to the preliminary tasks of the foot (Greisberg, 2007, p. 6).
2.2 Structures and functionality of the foot

The operating forces during standing are distributed through the talus to the fore- and hindfoot. This distribution is realised by the constitution of the arches of the foot. The arches of the foot are contradictorily described, especially regarding their function and significance (Logan, 1995, p. 9). Consensus exists on the occurrence of a longitudinal and a transverse arch. The longitudinal arch can be divided into a medial and a lateral part. The medial longitudinal arch is formed by the calcaneus, the talus, the navicular, the three cuneiforms, and the three medial metatarsals. The lateral longitudinal arch is composed by the calcaneus, the cuboid and the lateral the two metatarsal bones (Logan, 1995, p. 9). The curved array of the MTHs is responsible for the formation of the transverse arch (Logan, 1995, p. 9). Both arches are passively tensed up by ligaments and actively by muscles. The dynamic behaviour depends on the individual constitution especially of the individual muscular and ligamentous tension (Appell, 2008, p. 79).

2.2.2 Soft tissues of the foot

The soft tissue is actively and passively important for foot function. The muscles, as active portions of soft tissue, are important for both static and dynamic functions and also for the transfer of forces on bones and soft tissues due to their activation (Lloyd et al., 2008). The muscles of the foot can be divided into intrinsic and extrinsic muscles. The muscle bulges of the intrinsic muscles are within the foot. Whereas, the muscle bulges of the extrinsic muscles are in the lower leg and only their tendons insert and function within the foot (DeAsla and Deland, 2004, p. 9; Soysa et al., 2012).

Most of the intrinsic muscles can be found on the plantar side of the foot. On the dorsum of the foot, the extensor hallucis longus and extensor digitorum brevis is located. The plantar intrinsic muscles are divided into four layers (Table 2.4). It is generally accepted that intrinsic muscles fulfil several important tasks during walking, which can be summarized by supporting the arch. Nevertheless, not much is known about their activation patterns as well as their concentric or eccentric functions and their overall strength, due to challenges in examining these muscles (Soysa et al., 2012).

The extrinsic muscles can be divided into anterior, lateral, and posterior compartments. The anterior compartment consists of tibialis anterior, extensor hallucis longus, extensor digitorum longus, and peroneus tertius. Their tendons pass through the superior extensor retinaculum and are mainly responsible for dorsiflexion and inversion of the ankle, dorsiflexion of the hallux, and dorsiflexion of the other four toes (DeAsla and Deland,
Table 2.2: The four muscle layers of the plantar foot

<table>
<thead>
<tr>
<th>Muscle Layers</th>
<th>Intrinsic Muscles</th>
<th>Extrinsic Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>first (superficial) layer</td>
<td>adductor hallucis, flexor digitorum brevis, adductor digiti</td>
<td>tendons of flexor hallucis longus and flexor digitorum longus</td>
</tr>
<tr>
<td>second layer</td>
<td>quadrates plantae, four lubricals</td>
<td></td>
</tr>
<tr>
<td>third layer</td>
<td>flexor hallucis brevis, flexor digiti minimi brevis, adductor hallucis</td>
<td>tendons of tibialis posterior, tibialis anterior and peroneus longus</td>
</tr>
<tr>
<td>forth (deep) layer</td>
<td>seven interosseous</td>
<td></td>
</tr>
</tbody>
</table>

2004, p. 10). Peroneus longus and brevis form the lateral compartment. Their tendons, going through the superior peroneal retinaculum, evert the foot and plantar flex the ankle as well as the first metatarsal (DeAsla and Deland, 2004, p. 10). Furthermore, the tension of the peronaeus longus is important for the function of the longitudinal arch. The deep posterior compartment comprises the flexor digitorum longus, tibialis posterior, and flexor hallucis longus that pass through the flexor retinaculum. They are involved in inversion of the foot and plantar flexion of foot and ankle. The superficial posterior compartment consists of the gastrocnemius and soleus that confluence into the Achilles tendon (DeAsla and Deland, 2004, p. 10).

Manifold ligaments are involved to stabilize the foot and to support force transmission during locomotion. Short links run plantar and dorsal between the bones next to each other (Putz and Müller-Gerbl, 1991). On the dorsum of the foot, these ligaments form a heterogeneous fibre slap that is entangled to the articular capsules. In this respect, the ligament birfurcatum is most important for the limitation of pronation in the transvers tarsal joint. Around the tarsometatarsal joint, the same kind of fibre slap is found, although only the medial part can be seen as an amphiarthrosis (Putz and Müller-Gerbl, 1991).
2.2 Structures and functionality of the foot

Figure 2.3: Example of force-deformation relations for a selection of excised human tissues reported by Kenedi et al. (Kenedi et al., 1975)

On the plantar side of the foot, main task of the ligaments is to support the longitudinal arch. A deeper layer is mainly formed by the ligament plantare longum which is also connected to the smaller ligaments. The plantar aponeurosis is most functionally important as it spans over the whole arch (Netter, 2001, p. 320; Greisberg, 2007, p. 6). During the stance phase of walking, the plantar aponeurosis elongates from 9 to 12%. This has been found by Gefen who has tested the in vivo elastic properties by a radiographic fluoroscopy system on a pressure-sensitive optical gait platform. The conclusion of this study is that these findings are in line with results of cadaveric analysis (Gefen, 2003). The plantar aponeurosis significantly contributes to the locomotion. The reason can be found by their longitudinal fibres, that continue to the base of the proximal phalanges and are therefore responsible for the windlass mechanism. This windlass mechanism, primarily described by Hicks, is the increased tension of the plantar aponeurosis when the toes are in dorsiflexion. The increased tension of the plantar aponeurosis provides the foot stability and contributes to its function as a lever during the push-off, when the heel is lifted off the ground (Hicks, 1954; Bojsen-Moller and Flagstad, 1976).

The skin on the dorsum of the foot is relatively mobile due to its thin composition and low connection to the underlying fascia as well as minor subcutaneous fat (DeAsla and Deland, 2004, p. 1). In contrast, the skin on the plantar side in combination with the
plantar fat pads have to absorb high forces and shocks. Therefore, they have a special composition. The skin is tightly bonded by the strong vertical fibrous elements located on the heel, medial and lateral borders, and the ball of the feet (DeAsla and Deland, 2004, p. 1). The fibrous lamellae of the plantar subcutaneous layers are adipose-filled chambers, which provide the absorption of the peak forces and the damping of vibrations (Bojsen-Moller and Flagstad, 1976; Wang et al., 1999).

Between 1947 and 1965, several historic developments have been done that are important for the interpretation of soft tissue deformation. These studies analysed the mechanical properties of biological tissues and found that most of them feature non-linear viscoelastic behaviour (see Figure 2.3). The mixture-composition, considering the cellular level, as well as high proportions of elastin and water explain the viscoelasticity of the biological tissues and non-linear deformation (Larrabee, 1986; Kenedi et al., 1975).

The structures under the heel and MTHs have been most frequently studied (Prichasuk et al., 1994; De Clercq et al., 1994; Aerts et al., 1995; Cavanagh et al., 1999; Wearing et al., 2009; Wang et al., 1999) and their non-linear properties have been verified (Pioletti and Rakotomanana, 2000; Gefen et al., 2001; Wearing and Smeathers, 2011; Aerts et al., 1995). The highest thickness of the tissue is under the heel, followed by the MTHs. The thickness progressively decreases from MTH1 to MTH5 (Hsu et al., 1979; Wang et al., 1999). Ledoux and Belvins have found different compressive properties beneath the heel. They have found an increased relaxation time and energy loss compared to other plantar soft tissue areas (Ledoux and Belvins, 2007). Table 2.3 presents the main findings of soft tissue compression between static non-weight-bearing (NWB) and weight-bearing (WB).
2.2 Structures and functionality of the foot

Table 2.3: Main results for plantar soft tissue deformation

<table>
<thead>
<tr>
<th>References</th>
<th>Sole beneath the heel</th>
<th>Methods</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prichasuk et al., 1994</td>
<td>· 400 subjects</td>
<td>· Radiographic test</td>
<td>· Static NWB: 18.70 ± 2.5 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Static WB: 10.0 ± 2.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Compression Index (WB/NWB): 0.53</td>
</tr>
<tr>
<td>De Clercq et al., 1994</td>
<td>· 2 subjects (a,b)</td>
<td>· Cineradiography</td>
<td>· Static NWB: 15.3 mm (a), 14.5 mm (b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Compression during walking: 9 mm (a,b)</td>
</tr>
<tr>
<td>Cavanagh et al., 1999</td>
<td>· 5 adults</td>
<td>· Ultrasonography</td>
<td>· Static thickness: 15.2 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Quasi-dynamic deformation of 5.8-8.8 mm</td>
</tr>
<tr>
<td>Gefen et al., 2001</td>
<td>· 2 subjects (a,b)</td>
<td>· radiographic fluoroscopy system, in vivo</td>
<td>· Static NWB: 11.2 mm (a), 13.1 mm (b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Compression during walking: 3.8 mm (a), 4.8 mm (b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Measurement error: ± 0.5 mm</td>
</tr>
<tr>
<td>Wearing et al., 2009</td>
<td>· Control sample</td>
<td>· In vitro</td>
<td>· Static NWB: 19.1 ± 1.9 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Static WB: 8.8 ± 1.5 mm</td>
</tr>
<tr>
<td>Sole beneath the MTHs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al., 1999</td>
<td>· 20 subjects</td>
<td>· Ultrasonography</td>
<td>· Static NWB: MTH1 15.0 mm, MTH2 13.6 mm, MTH3 12.5 mm, MTH4 11.4 mm, MTH5 10.4 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· Compressibility Index decrease from MTH1 to MTH5</td>
</tr>
</tbody>
</table>
2.3 Development of the foot

At the time of birth, the child’s foot already resembles an adult’s foot in appearance. However, the foot has to pass through different developing processes until it reaches the functional characteristics of an adult’s foot. These processes can be regarded from an external point of view as foot growth (Section 2.3.1) but also from an internal point of view as functional development (Section 2.3.2).

2.3.1 Foot growth

The changes of foot anthropometry have been analysed in different studies (Anderson et al., 1956; Cheng et al., 1997; Mauch, 2007; Volpon, 1994). Newborn’s foot length comprises one third of its final length and already three years later about two thirds are reached (Maier and Killmann, 2003; Volpon, 1994). From birth to the age of three years, feet grow on average 24 mm a year, to the age of five years approximately 12 mm a year, and to the age of twelve years 8-10 mm (Anderson et al., 1956; Cheng et al., 1997; Mauch, 2007; Volpon, 1994). Girls reach the final foot length at the age of twelve to 13 years and boys approximately two years later (see Figure 2.4). Between the ages of five to twelve years, boy’s feet are on average 2 mm longer than girl’s feet. The gender-specific differences of foot length are extended as the feet of boys grow further to the age of about 15 years (Anderson et al., 1956; Cheng et al., 1997; Gould et al., 1990; Maier and Killmann, 2003; Walther et al., 2005).

The pronounced growth of the first toe, accompanied by diminishing growing tendencies from the second to the fifth toe, changes the shape of the forefoot by the age. The pointier forefoot of an adult and therefore more acute-angled ball angle obviously differs from the round-shaped forefoot of a child (Maier and Killmann, 2003; Stracker, 1966).

Other dimensions like foot width and foot girth change due to the growing process, too. Relative ball width and girth as well as relative heel width decrease up to the age of eleven years followed by a small increase (Kouchi, 1998; Mauch, 2007). Several studies, that studied the feet of children and adolescents, have summarized that smaller feet are usually more voluminous than larger feet (Debrunner, 1965; Gould et al., 1990; Kristen, 1968; Mauch, 2007).
2.3 Development of the foot

Figure 2.4: Overview of foot growth (data from Anderson et al., 1956, Cheng et al., 1997, and Mauch, 2007)
2.3.2 Functional development

The visible growth of the flexible children's feet is accompanied by other developing processes. The numerous developing processes even continue after the foot has reached its final length and proportion. Main processes, important to achieve full function of the foot, comprise ossification of bones and reduction of the flexibility of tendons, ligaments, and joint capsules due to increased inclusion of proteoglycans and crosslinks of collagens (Anderson et al., 1965; Cheng et al., 1997; Gould et al., 1990; Maier and Killmann, 2003; Mauch, 2007; Stavlas, 2005). Complete stiffness and resistance of all soft tissues and full ossification are not achieved until late adolescence (Drenckhahn, 2003; Drennan, 1992; Maier and Killmann, 2003; Walther et al., 2005).

Most essential developing processes take place by the time of upright standing and walking (Maier et al., 1980). Related to this developmental stage, different functional adaptations occur. Wilhelm Roux described fittingly that morphogenesis is the adaptation to functional performance (Sander, 1991). The changed and enlarged forces cause an increase of the strength of muscles and ligaments and the tightening of connecting tissues within the foot (Maier and Killmann, 2003). Furthermore, skeletal changes take place, with their onset in the hip joint. Asymmetric growth, which is caused by compressive load on the lateral side of the leg, and the sequential internal rotation of the hip are responsible for the conversion of the primary genu varum to an intermediate state of genu valgum. Further compressive load accounts for the increased growth of the lateral epiphyseal cartilage and yields in a straight position of the leg (Hefti, 2000; Hefti and Brunner, 1999; Jani, 1986; Maier and Killmann, 2003). Additional contribution to the neutral leg centreline is supplied by the outward rotation of malleoli of ankle. The neutral position of the ankle is reached at the age of about three years (Nakai et al., 2000). Whereas, a neutral leg centreline is usually achieved at the age of six years (Maier, 1999).

The changes, regarding foot function, are associated with the described changes of the leg centreline. Within the foot, most important changes concern the hindfoot and the longitudinal arch. The hindfoot starts to reorganize with the beginning of upright standing and walking. The calcaneus rotates in a longitudinal and pronated pattern and gradually undercut the talus which is more pronated and medially positioned, in the foot of an infant (Jani, 1986; Koebke, 1993). Asymmetric growth is again responsible for the erection of the hindfoot (Maier and Killmann, 2003; Walther et al., 2005). A genu valgum of the hindfoot of 15-20° is still visible at the age of four years (Jani, 1986).
2.4 Influences on foot morphology

The erection of the hindfoot is decisive for the maturation of the medial longitudinal arch. The bones of the midfoot move from a formerly supinated into a pronated location (Koebke, 1993; Nigg and Segesser, 1992; Rabl and Nyga, 1994). On the contrary, some authors stated that the bony constitution of the medial longitudinal arch exists already prenatally (Bähler, 1986; Jani, 1986; Von Lanz, 1972, p. 383-386). Indeed, the maturation of the medial longitudinal arch may depend more on the dimension of the subjacent fat pad and on weaker ligaments and muscles (Dowling et al., 2001; Ker et al., 1987). The fat pad has to protect the growing enchondral cartilage by distributing the acting forces (Dowling et al., 2001; Ker et al., 1987). Until the age of approximately five years, this fat pad is responsible for an enlarged contact area, which is similar to pathological flat feet, when only footprints are examined (Anetzberger and von Liebe, 2000; Hefti and Brunner, 1999; Schilling, 1985). The decline of this fat pad is evidence of a developmental process. The time of this decline differs between the genders and is earlier attained in girls (Hefti and Brunner, 1999; Hennig and Rosenbaum, 1991; Hennig et al., 1994; Mickel et al., 2008; Pfeiffer et al., 2006).

The incidence of flat feet is considered as a developmental stage which is manifested in footprints of 97% of infants aged between twelve to 18 months (Forriol and Pascual, 1990; Morely, 1957; Staheli, 1999). Responsible factors for development of a normal-arched foot are the combined factors of skeletal changes within the hindfoot, strengthening of ligaments and muscles and reduction of the fat pad.

2.4 Influences on foot morphology

The variability of the feet has been reported in many studies (Cheskin, 1987; Krauss et al., 2008; Mauch, 2007). The reason for the high variability of foot morphology can be explained by the statement: form follows function (Sullivan, 1947). Roux has also stated that morphogenesis is the outcome of functional adaptation that occurs through performing the functions (Sander, 1991). Thus, the combination of individual behaviour and aging as well as body mass in combination with the genetic program causes the inter-individual influences of foot morphology (see Figure 2.5).
2.4.1 Inter-individual influences on foot morphology

In the past 20 years, a plenty of studies have investigated the variability of human feet, based on several anthropometric variables like gender, age, and body mass. Table 2.4 provides an overview of current studies and findings related to inter-individual influences on feet, ordered on the base of the starting age of their sample. This table allows drawing the following conclusions for the anthropometric variables age, gender, and body mass:

Age-related influences

- The age-related differences reported in childhood and adolescence result from developmental processes (see Section 2.3). In general the younger feet are more often flat and voluminous.

- Differences according to age are reported for the characteristics of the soft tissue which changes with the age of about 60 years.

- Older people feature an increased thickness of the heel pad, a reduced elasticity of the whole plantar soft tissue as well as decreased values of plantar force and pressure under the heel.
2.4 Influences on foot morphology

Gender-related influences

- At the age of three to five years, there are gender-related differences relating the arch. These differences refer to the retarded foot development of boys.

- The prevalence of flat feet is still increased in boys at the age of twelve to 15 years. No difference is found at the age of 16 to 17 years.

- Differences according to gender are reported in full-grown feet. The feet of males participants are usually longer, higher, and broader. However, the findings are controversial when the foot measures are normalized to foot length.

- Higher plantar pressure under the midfoot and less stiffness of the arch of the feet of female participants point to differences of the characteristics of soft tissue.

Influences related to overweight or obesity

- Differences according to overweight are already reported in childhood. Feet of overweight children are more often flat and voluminous.

- The prevalence of flat feet is increased in younger overweight children.

- In general, the magnitude of measured force is higher under the feet of overweight participants. However, similar plantar pressures of normal and overweight participants, due to increased contact area, are found.

- The thickness of the soft tissue under the heel and the ball is higher in overweight adults.

These inter-individual differences are especially important for the construction of footwear. However, not much is known about the intra-individual influences of foot morphology.
Table 2.4: State-of-the-art of science concerned with inter-individual influences on feet

<table>
<thead>
<tr>
<th>Age</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-80</td>
<td>441</td>
<td><strong>Age</strong>: Flat feet usual in infants, common in children and normal range in adults feet</td>
<td>Staheli et al., 1987</td>
</tr>
<tr>
<td>2</td>
<td>2-14</td>
<td>2887</td>
<td><strong>Age</strong>: More slender and long foot types, less flat, robust and short foot types with increasing age&lt;br&gt;<strong>Body mass</strong>: More flat and robust foot types in overweight, more slender and long foot types in underweight children</td>
<td>Mauch et al., 2008</td>
</tr>
<tr>
<td>3</td>
<td>3-5</td>
<td>88</td>
<td><strong>Gender</strong>: Flatter feet and thicker midfoot fat pad in boys</td>
<td>Mickle et al., 2008</td>
</tr>
<tr>
<td>4</td>
<td>3-5</td>
<td>38</td>
<td><strong>Body mass</strong>: Lower plantar arch height in overweight children; No differences in thickness of midfoot fat pad due to body weight</td>
<td>Mickle et al., 2006a</td>
</tr>
<tr>
<td>5</td>
<td>3-5</td>
<td>34</td>
<td><strong>Body mass</strong>: Larger force, larger contact area, higher peak pressure under the midfoot of overweight children</td>
<td>Mickle et al., 2006b</td>
</tr>
<tr>
<td>6</td>
<td>3-6</td>
<td>835</td>
<td><strong>Age, body mass, and gender</strong> has influences on the prevalence of flat foot</td>
<td>Pfeiffer et al., 2006</td>
</tr>
<tr>
<td>Age</td>
<td>Sample Size</td>
<td>Methods</td>
<td>Results</td>
<td>Reference</td>
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<td>-----------</td>
</tr>
<tr>
<td>9</td>
<td>4-13</td>
<td>1181</td>
<td><strong>Methods:</strong> Plantar foot print</td>
<td><strong>Body weight:</strong> Increased prevalence of flat feet in 4-5 year-old, overweight children</td>
</tr>
</tbody>
</table>
| 10  | 6-12        | 1032    | **Methods:** External foot morphology; 3D digitizer, static | **Age:** No differences  
**Body mass:** Differences in width, ball height, and arch height; differences in whole foot measures in overweight and obese children; most differences disappeared with normalization to foot length | Jiménez-Ormeno et al., 2013 |
| 11  | 6-10; adult$^1$ | 125; 111 | **Methods:** Dynamic plantar pressure distribution | **Age:** Lower peak pressure and larger relative contact area in children; medial load shift with age to forefoot  
**Body mass:** Higher plantar pressure distribution in overweight subjects  
**Gender:** No differences | Hennig et al., 1994 |
<p>| 12  | 7-9         | 26      | <strong>Methods:</strong> Static foot print and plantar pressure distribution | <strong>Body mass:</strong> Lower footprint angle, higher mean peak dynamic forefoot pressures in obese children | Dowling et al., 2001 |
| 13  | 7-10        | 140     | <strong>Methods:</strong> Identification of flat feet; Foot Posture Index, Static | <strong>Body mass:</strong> Less flat feet in overweight children | Evans, 2011 |</p>
<table>
<thead>
<tr>
<th>Age</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>8-11</td>
<td>20</td>
<td>Static and dynamic plantar pressure distribution</td>
<td><strong>Body mass:</strong> Larger contact area during standing and walking in obese children, biggest differences in the midfoot area</td>
</tr>
<tr>
<td>15</td>
<td>9-12</td>
<td>900</td>
<td>External foot morphology; Foot board, static</td>
<td><strong>Body mass:</strong> Foot length and width increase with body mass, navicular height drops</td>
</tr>
<tr>
<td>16</td>
<td>10-12</td>
<td>60</td>
<td>External foot morphology; Measuring tape</td>
<td><strong>Age, body mass, and gender:</strong> No differences in normalized foot measures</td>
</tr>
</tbody>
</table>
| 17  | 12-17       | 1180    | Static plantar footprint | **Age and gender:** More flatfoot in boys at the age 12-15 years; no differences at the age 16-17 years  
**Body mass:** No influence on prevalence of flatfoot with obesity | Daneshmandi et al., 2009 |
<p>| 18  | 14-60       | 847     | External foot morphology; 3D static scan, cluster analysis | <strong>Gender:</strong> Wider and higher feet in men compared to same foot length in women; no gender-specific differences in averaged measures | Krauss et al., 2008 |
| 19  | 17-25       | 305     | Static external foot morphology | <strong>Gender:</strong> Greater foot girth and width in men compared to women within the same foot length | Anil et al., 1997 |
| 20  | 17-44       | 20      | Ultrasonography | <strong>Age and body mass:</strong> Positive relationship to unloaded thickness of soft tissue under the ball | Wang et al., 1999 |</p>
<table>
<thead>
<tr>
<th>Age</th>
<th>Sample Size</th>
<th>Age</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>18-26</td>
<td>19</td>
<td>Static internal foot morphology; radiography</td>
<td>Gender: Greater medial and lateral arch angles in female in weight bearing condition</td>
<td>Fukano and Fukubayashi, 2012</td>
<td></td>
</tr>
</tbody>
</table>
| 22  | 18-65       | 145 | External foot morphology; arch height and stiffness | Age: No differences in arch height index and stiffness  
Gender: No differences in arch height index; less stiffness of arch in women | Zifchock et al., 2006                        |
| 23  | 18-78       | 33  | Ultrasonography | Age: Loss of elasticity of the heel pad in older people | Hsu et al., 1998                             |
| 24  | 18-24; 74-86| 100 | Plantar force and pressure distribution | Age: Decreased magnitude of force and pressure under the heel in older people | Scott et al., 2007                           |
| 26  | 18-24; 71-90| 70  | Plantar pressure distribution | Age: Greater contact area and less contact time in the forefoot; no differences in force or peak pressures in older people | Kernozek and LaMott, 1995                   |
| 27  | 19-29       | 72  | Static plantar imprint and ground reaction force | Body mass: Larger plantar contact area and pressure in overweight subjects  
Gender: No differences | Gravanate et al., 2003                       |
<p>| 28  | 19-35; 42-72| 19  | In vivo tissue tester | Age: Effects of aging on plantar soft tissue properties under metatarsal heads in older people | Hsu et al., 2005                             |</p>
<table>
<thead>
<tr>
<th>Age</th>
<th>Sample Size</th>
<th>Methods</th>
<th>Results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>20-25</td>
<td>300</td>
<td>Foot volume (water displacement)</td>
<td>Gender: In all foot dimensions</td>
</tr>
<tr>
<td>30</td>
<td>20-59</td>
<td>90</td>
<td>Static external foot morphology</td>
<td>Gender: Longer feet in men, relatively narrower but higher feet in women</td>
</tr>
<tr>
<td>31</td>
<td>20-60</td>
<td>400</td>
<td>Radiography of heel pad</td>
<td>Age and body mass: Increase of heel pad thickness with age and body weight Gender: Thicker unloaded heel pad in men</td>
</tr>
<tr>
<td>32</td>
<td>20-30; 60-70</td>
<td>20</td>
<td>In vivo tissue tester</td>
<td>Age: Higher tissue stiffness under MTH2 and heel in older people</td>
</tr>
<tr>
<td>33</td>
<td>21-37</td>
<td>45</td>
<td>Static and dynamic external foot morphology; cross sections</td>
<td>Gender: No differences</td>
</tr>
<tr>
<td>34</td>
<td>30-53</td>
<td>70</td>
<td>Static and dynamic plantar pressure distribution</td>
<td>Body mass: Higher plantar pressure, broader ball width in overweight subjects Gender: Higher plantar pressure under the mid-foot in women</td>
</tr>
<tr>
<td>35</td>
<td>37-74</td>
<td>50</td>
<td>Ultrasonography</td>
<td>Body mass: Positive correlations with unloaded heel pad thickness Gender: Compressibility index is related to gender</td>
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### 2.4 Influences on Foot Morphology

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<th>Methods</th>
<th>Results</th>
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<td>41-83</td>
<td>Tissue ultrasound palpation system</td>
<td><strong>Age</strong>: Stiffness of plantar soft tissue at big toe, MTH 1, 3, 4 and heel increase with age; trend that soft tissue thickness increase with age</td>
<td>Kwan et al., 2010</td>
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<td>37</td>
<td>adult 1</td>
<td>784 Static external foot morphology</td>
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<td>50 Plantar pressure distribution</td>
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<td>39</td>
<td>adult 1</td>
<td>28 Plantar pressure distribution</td>
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<td>312 Static external foot morphology; 3D scan</td>
<td><strong>Age</strong>: Different foot anthropometries in older people with foot problems; <strong>Gender</strong>: Significant differences</td>
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</tbody>
</table>

1. Adult sample, no specified age
2.4.2 Intra-individual differences

Intra-individual differences imply all changes within a subject's foot. These influences are important for each individual but also for footwear design. This subchapter focuses on differences caused by static or dynamic situations; other influences based on thermal, hormonal or daytime factors are not considered.

Several studies have compared different loading situations with regard to changes of foot dimension. In 1968, Carlsöö and Wetzstein compared in vitro skeletal changes in NWB, half weight-bearing (HWB), and full weight-bearing (FWB). They examined the feet of 19 students by x-ray examination. Their conclusion was that not the skeletal changes but soft tissue deformation are responsible for changes of foot dimension. However, they found no significant differences of foot length, width, or height (Carlsöö and Wetzstein, 1968).

Current findings conclude that there are differences of foot dimensions due to different loading situations. Plantar foot deformation of 126 Nigerian subjects has been analysed for NWB, HWB and FWB situations. The foot length of men increases by 2.5% in HWB and 3.0% in FWB compared to NWB situation. For women, the corresponding values are smaller with 1.6% and 2.3%, respectively. Foot width of men increases by 3.7% in HWB and 5.4% in FWB situation, foot width of women by 5.0% and 6.4%. The measurements have been taken using a sliding caliper. No information about reproducibility is provided (Oladipo et al., 2009). Tsung et al. have measured the 3D plantar foot shape of 16 normal feet in NWB, HWB, and FWB situation by an optical digitizing system. The contact area, foot length, width and rearfoot width increase while average height, arch height, and arch angle decrease. From NWB to HWB and FWB foot length increase about $2.7 \pm 1.2\%$ and $3.4 \pm 1.3\%$, foot width about $2.9 \pm 2.4\%$ and $6.0 \pm 2.1\%$, and rearfoot width $5.9 \pm 4.8\%$ and $8.7 \pm 4.9\%$. The presented Root Mean Square Error is $> 1$ mm for foot length and width measures (Tsung et al., 2003). For the feet of 40 men, captured by an optical digitizer, Houston et al. have found an increase in foot length from NWB to HWB of about $1.7\%$ and from NWB to FWB of about $2.2\%$. Ball width increases by $3.8\%$ in HWB and $4.3\%$ in FWB (Houston et al., 2006). Xiong et al. have analysed nine foot dimensions of the whole foot of 30 Chinese adults using a laser scanner. They have also compared NWB, HWB, and FWB of the 3D foot and concluded similar to the plantar comparisons that the foot becomes significantly longer, wider, and is reduced in height with weight-bearing. Main changes have been found for the midfoot.
2.4 Influences on foot morphology

Another study has compared the foot length and width in NWB and FWB situation of 2829 Chinese children, aged between 3 and 18. The values for the reproducibility of the foot measures obtained by an electronic caliper are about ± 0.1 cm for foot length and ± 0.2 cm for foot width. The increases are independent of age and gender and comprise 3.1% for foot length and 4.8% for foot width (Cheng et al., 1997).

The dynamic foot morphology is in particular important with respect to the fit of footwear. To adequately capture the dynamic foot morphology, analysis systems like kinematic set-ups, goniometers, or pressure platform do not provide sufficient information about the deformation of the foot. Advances in scanner technology allow capturing the foot during walking. Different scanner technologies are described in detail in Section 3.3.2. The focus on this section is on the findings regarding dynamic foot morphology compared to static foot morphology.

Several research groups are engaged in the development of dynamic foot scanner systems. Regarding the literature of the last years, some different feasibility studies of dynamic foot scanner systems can be found (Jezershek and Mozina 2009; Kimura et al., 2005; Wang et al., 2006). Jezershek and Mozina have calculated the foot girth at 55% of foot length and found a change of 16 mm (about 5.6%). However, these changes are not captured during natural walking but during plantarflexion of a static situation (Jezershek and Mozina, 2009). During the stance phase of walking, i.e. the phase from the position when the MTHs hit the ground to the position when the whole foot is on the ground before the heel lift up, Coudert et al. have analysed one foot by example. They have found an increase in foot width of about 5 mm for this subject, the width of the forefoot deforms about 5%. However, the authors have not precisely defined the used foot measures and have reported some technical problems regarding the synchronisation and measurement frequency (Coudert et al., 2006). Kouchi et al. have examined different foot girth measures of the feet of 45 Japanese. They have directly drawn four lines on the foot of each subject and compared these cross-sections at two different times of the stance phase. They have compared the two dynamic situations, determined by vertical ground reaction forces (first peak and midstance valley), with a static situation. Especially, the width of the heel and instep cross-section is wider at the first peak compared to standing. The width of the forefoot cross-section is wider, whereas the width of the heel cross-section narrower at the midstance valley compared to the standing situation.
Anatomical and functional basics of the foot

(Kouchi et al., 2009). Kimura et al. have provided one example of the measured 40 subjects. For this example the maximum of ball girth during walking is about 4 mm larger compared to the standing situation. However, they have stated that the analysis of the foot shape deformation will be future work (Kimura et al., 2011). Another study has showed that the foot length of 27 subjects increases on average of 9 mm during dynamic situation compared to static situation (Thabet et al., 2011). The repeatability of the static and dynamic foot length on the plantar system comprises 2.44 mm and 2.81 mm, respectively. Schmeltzpfenning et al. have achieved on a plantar scanner system a Root Mean Square Error (RMSE) for foot length and width measures, ranging from 0.43 mm to 1.72 mm (Schmeltzpfenning et al., 2009a). In 144 subjects, an increase of heel width, medial ball length, and width as well as ball angle in several phases during the stance phase compared to static situations has been reported (Schmeltzpfenning et al., 2010).

The different studies, focusing on dynamic foot morphology are promising. However, there is still a lack of information about the entire foot deformation compared to the respective static values. Furthermore, no study aimed to give concrete recommendations for the improvement of the dynamic fit of footwear. These recommendations can be beneficial for foot development and health, the subsequent Chapter 3 presents fundamentals of footwear construction as well as the interface of foot and footwear to derive these recommendations.
3 Fundamentals of footwear

This chapter presents fundamentals of footwear. Section 3.1 describes principles of last and shoe construction with respect to sizing and grading. The interfaces of feet and shoes are presented by the current state of research, in Section 3.2. Main focus is on effects of footwear on feet and thus, the fit of footwear. The last subchapter (Section 3.3) explains basic methods to record static foot morphology followed by current approaches to capture the foot during walking.

3.1 Footwear construction

Footwear construction is a complex process with several working steps. The primal footwear has been manufactured solely by handcraft. Until now, knowledge and experiences of footwear construction have been kept and passed on from generation to generation. Today, most of the workflow is automated, however, the first steps of designing shoes is still handcrafted. Likewise, main steps of the construction as well as the general architecture of shoes are the same as a hundred years ago.

3.1.1 How a shoe arises

Basically, the shoe is formed by the upper and the sole. The sole can be divided into different parts (outsole, midsole, insole). All parts fulfil, at a variable extent, the main function of shock absorption and thus contribute to the comfort of shoes. The design of the upper part is determined by the type of the shoe and decisive for its fit (Cheskin, 1987; Miller, 1989; Rossi and Tennant, 2011; Satra, 1993). The first working step to receive a shoe, and even the most important, is designing a shoe last (Mitchell et al., 1995).

A shoe last is the model or internal support to create a shoe. The very first lasts have been made of stone, followed by wooden lasts that have been used for centuries. In the
course of industrialisation, metal lasts were introduced in 1818. In 1961, commercial plastic lasts came into the market. However, wooden handmade lasts are still the initial models for shoes (Cavanagh, 1980; Luximon and Luximon, 2013, p. 194; Mitchell et al., 1995; Rossi, 1980).

Nowadays, shoe manufacturing usually starts by a copy of a proven hind part of a shoe last. The fore part of this shoe last is mainly modified following the current fashion trends or key measurements or sometimes also an example of another shoe. To achieve a promising shoe, the “heart of a shoe”, as Rossi entitled the last, has to be thoroughly finished, following years of experience (Rossi, 1980, p. 1). According the six measures, presented in Figure 3.1, last designers inspect their lasts of the respective size. Usually, last designers work on one master piece in the size EU 38 or US 6 for women and EU 42 or US 9 for men (Cavanagh, 1980; Cheskin, 1987; Luximon and Luximon, 2013; Mitchell et al., 1995; Rossi, 1980).

Figure 3.1: Important last measures (adjusted to Mitchell et al., 1995)
3.1 Footwear construction

3.1.2 Sizing and grading

The required variety of shoe sizes is attained by grading the master piece last. Grading means that the master piece is enlarged or reduced. Usually, a combination of length and girth measures is used and one of three types of grading. The first type, most frequently used, is called arithmetic grading. This type implies that the increments of the measures are constant. The second type is called geometric grading where the increments are specified as percentages of the dimensions. The third type, called proportional grading, uses constant increments for all dimensions within all sizes (Miller, 1989).

<table>
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<tr>
<th>UK</th>
<th>Inches</th>
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Figure 3.2: Illustration of several sizing systems (in accordance with Luximon and Luximon, 2013, p.206; Rossi, 2011, p. 88)

Even if sizing of shoes dates back several thousand years, it has become more important within mass production of shoes. A differentiated and advanced system for sizing and
grading was introduced by Edwin B. Simpson, in 1880. This system followed the English system, based on one third inch for a whole shoe size with additional half sizes and also different widths for each size. This system includes a proportional grading and was adopted by the US footwear industry, in 1888 (Rossi and Tennant 2011, p. 81).

Nowadays, there are several coexistent sizing systems all over the world, for instance the English (UK), the American (US), the French (EU, a.k.a. Continental system or Paris Point), the Chinese, and the Mondopoint system. The sizing, based on foot or shoe length, of commonly used systems is presented in Figure 3.2. Their increments vary depending on the system and comprise for the UK and US systems, from one shoe size to the other, 8.46 mm (1/3 inch), for the EU system 6.67 mm and for the Mondopoint 5 mm.

The different shoe widths are based on girth measure on lasts or feet, respectively. The US system uses up to twelve different widths for each shoe size (AAAAA to EEEEE). The increments for the US and the UK system comprise 1/4 inch (6.35 mm) from one width to the other. Within the EU system, seven widths, with an increment of 5 mm, are common (F, G, H, J, K, L, M). The same increments, from one width to the other within a shoe size, are used for grading the width from one shoe size to the other. Economically reasons are responsible that not all shoe manufacturers offer this range of shoe widths. This might be the reason why another classification of shoe widths can be found. A simpler and reduced shoe width system is often characterized by the letters N (narrow), M (medium), and W (wide). However, there are no standards behind these terms (Luximon and Luximon, 2013, p. 206-207; Rossi and Tennant, 2011, p. 82-83). The Mondopoint system (see Section 3.1.3) also describes different shoe widths for each size that refer to the measured foot width (ISO 9407).

Another approach to account for the diversity of feet is based on the consideration of the entire foot, rather than only one width or girth measure. A cluster analysis has been used to define several types of feet based on foot length, width and height measures. Three main types of feet could be categorized by data of static foot scans (Krauss et al., 2010; Mauch, 2007; Mauch et al., 2009). According to these analysed foot types, three types of lasts as well as shoes have been produced for each shoe size. Up to now, this promising procedure is only insularly adopted in German footwear industry.
3.1.3 Standards for footwear construction

In most cases, the various sizing systems depend on guidelines of individual shoe manufacturers and only a few national guidelines are available. However, there have been several efforts to standardize shoe and sizing systems. The international ISO technical committee of footwear sizing system (ISO 9407) has aimed to introduce one sizing system with standardized unit and increments. Furthermore, their objective has been to standardize systems for calibrating lasts or equivalent equipment, as well as terminology. In 1991, they presented the Mondopoint system, which is a standardized sizing system where the distinction of the sizes is based on foot length and width measures. This system is used for military shoes as well as, in parts, security shoes and skiing boots. However, it has still not been expanded to other fields (Blattner, 2007).

The handcraft of last construction mostly follows exclusively collected guidelines of last designers or shoe manufacturers. Only few guidelines, depending on national or collaborative activities of manufacturers, do exist. Two guidelines for shoe last construction are accessible to the public: First, the German AKA64-WMS and second, the Chinese System (Luximon and Luximon, 2009). The AKA64-WMS is a result of research activities in Germany. They have started to identify deficits of shoes regarding the physiological support of children's feet. Thus, the consortium of shoe manufacturers, last designers and researchers, called "Arbeitskreis Kinderschuh" has been formed. In 1964, they primarily presented guidelines that included threshold values for the construction of children's and adolescents' shoes which were drawn on two-dimensional lasting boards. The main benefit of this reform is a better standardization of existing widths systems. This is realized by a reduction of the prior recommended eleven shoe widths to four or five widths. These recommendations has better be accepted by shoe manufacturers. Furthermore, the recommendations include instructions for the design of the toe box and the characteristics of the sole (Maier and Killmann, 2003). The expansion of the system, adopted in 1974, is still known as WMS system. Subsequently, it has been conformed to adults' and has also been introduced in other countries, for example America (Adrian, 1991).

In China, standards for footwear construction were also defined and published, in 1984. These standards refer to extensive foot studies. According to Luximon and Luximon, however, these standards have not been implemented in common software for last construction. Therefore, Luximon and Luximon have presented a new bottom design template on the base of the American (adopted WMS) and Chinese standards, applicable for last
construction (Luximon and Luximon, 2009).

Regarding the international available standards, it can be concluded that it is the responsibility of each shoe manufacturer to rely on one of these rarely available standardizations. However, in reality, form, fashion, and economy are more often the decision making criteria for footwear.

### 3.2 Foot and shoe interface

Archaeological findings have shown that footwear is as old as humanity. Footwear has always been important to protect against abrasion and injury due to different ground surfaces. Furthermore, the developed footwear has always reflected the climate in which it has been used. Thus, its characteristics depend on the protection either against heat or cold (Blattner, 2007, p. 1; Cheskin, 1987, p. 3). These positive reasons to wear shoes are accompanied by several side effects resulting from the interactions of shoe and foot.

#### 3.2.1 Effects of footwear

The positive effect of shoes is the protection of the foot against environmental influences. This is important for daily demands and even more in particular settings, for example working or sports environments. Eventually, footwear is an expression of fashion and lifestyle. In several cases, physiological requirements of feet are ignored, at best for a certain time. In most countries worldwide, any kind of footwear is worn all day long. Consequently, foot development takes place “within” shoes. On the one hand the protection is important for the foot, however on the other hand different kinds of problems due to wearing footwear are reported. This problems can be summarized in dermatological problems, deformities, and functional impairments.

Dermatological problems are primarily caused by dynamic friction between shoes and skin. This friction generates high temperatures on which the natural response is callused skin. Callused skin reduces the conductivity of temperature with its Beilby-layer and thus reduces the impairment of deeper layers. Another protective mechanism is perspiration which enables a ten times higher heat absorption due to evaporation. Natural adaptation is that more respiratory glands can be found in areas where high dynamic

\[^2\text{Beilby-layer: hard layer with a greater density and reduced thermal conductivity; caused by bonding of horn cells of the skin due to friction heat (Gr"unewald, 2002, p. 175)}\]
3.2 Foot and shoe interface

friction appears (Beilby, 1921; Günewald, 2002, p. 174-176). If the friction exceeds a certain threshold regarding time or magnitude it may result in painful dermatological problems. These problems are often reported and range from calluses, corns, plantar warts, blisters etc. (Rossi and Tennant, 2011).

Deformities of the foot, which are continuously developed over time, occur frequently. The relationship between foot deformities and ill-fitting footwear was already reported in the middle of the 19th century. Hermann von Meyer reasoned that lateral and frontal pressure pushes the toes aside and in some cases one upon the other (von Meyer, 1888). Until then, shoes have been straight-shaped without obvious differences between right and left shoe. The results of several studies of von Meyer can be seen as the origin of curved lasts and shoes. However, current studies still indicate that shoe shape but also incorrectly fitted footwear is responsible for foot deformities. Frey et al. described the connection between shoe trends and foot deformities and pain in women. The majority of the 356 women wore smaller shoes than their feet would need and reported foot pain (Frey et al., 2000). Menz and Morris similarly concluded that forefoot diseases and foot pain relate to incorrectly fitted footwear, on the base of their study of 176 older adults (Menz and Morris, 2005). In 858 pre-school children, Klein et al. have found a relationship between shoe length and the amount of the hallux valgus angle. Thus, ill-fitted footwear is particularly harmful for the feet of children, that are prone to external influences (Klein et al., 2009). Rao and Joseph, who have analysed 2300 static footprints, found that the prevalence of flat feet is higher in children who have worn shoes, especially closed-toe shoes, at an early age (Rao and Joseph, 1992). Already in 1939, Emslie reported that 80% of children, aged between two and four years, who have worn shoes had deformities (Emslie, 1939). Jerosch and Mamsch have found mild to significant deformities in ten to thirteen years old children. They have found 19.1% with flat feet and 17.1% with a hallux valgus (Jerosch and Mamsch, 1998). Differences in foot morphology between shoed and un-shoed populations have been found in barefoot and shoed walkers. General findings are that the feet of barefoot walkers are wider especially in the forefoot (D’Aout et al., 2009).

Different walking patterns that may lead to functional impairments have been demonstrated in several studies using kinetic, kinematic, and temporal-spatial analysis methods. The centre of pressure during walking has been investigated by Grundy et al. in 1975. Sixteen subjects, have shown different patterns when walking with shoes compared to
barefoot walking. The conclusion is that the function of the forefoot is progressively reduced by increasing rigidity of the shoe sole (Grundy et al., 1975). In a kinematic analysis of Wolf et al., most obvious differences have been found for the motion of the tibio-talar joint, the medial arch, and the foot torsion (along the long foot axis) for 18 children (mean age 8 years). The authors have shown that walking patterns with more flexible footwear are approximated to the barefoot walking pattern (Wolf et al., 2008). González et al. have found, for toddlers who have worn shoes, increased relative step length and gait velocity as well as decreased relative step width and duration. The authors have concluded that with appropriate footwear the gait patterns are more mature (González et al., 2005). It is not clear whether this is a desirable goal. Future research and especially longitudinal study designs can provide clarity on this issue.

### 3.2.2 Fit of footwear

The fit of footwear can be defined as "... the preference for a shoe to accommodate an individual’s foot." (Goonetilleke et al., 2000, p. 1). Footwear fit is hard to define but generally accepted as important for foot health. It is one of the main criterions for buying a shoe (Chong and Chan, 1992; Piller, 2002). However, every person with its individual preconditions perceives fit in a different way.

The perceived fit results in the individual assessment if the shoe is comfortable or uncomfortable. The relationship between perception and measured pressure has been evaluated for 15 subjects who tested three pairs of commercially available shoes. The negative relationship has been found for measured plantar and dorsal pressure distribution and perceived comfort, rated by a questionnaire (Jordan et al., 1997). Several studies have assessed the relationship between pressure and comfort of running shoes. The conclusion is that increased pressure, no matter whether it comes from different insoles or the whole shoe, results in reduced comfort (Chen et al., 1994; Miller et al., 2000; Mündermann et al., 2002; 2003). The same relationship between perceived comfort and variables resulting from kinematic or EMG analysis has been demonstrated for insoles (Mündermann et al. 2003).

A shoe is perceived as uncomfortable if high pressures or forces occur. Interestingly, the same perception is provoked by shoes that are too loose. The reason can be found in slipping forward within the shoe. Thus, several researchers have stated that the quality of footwear fit is in accordance with the match between foot and footwear or last,
3.3 Measuring foot morphology

respectively (Bataller et al., 2001; Cheskin, 1987, p. 126; Gould et al., 1991; Hawes et al., 1994; Janisse, 1992; Kouchi, 1995; Rossi, 1980).

An indicator for the quality of fit has been presented by Goonetilleke et al. in 2000. They have compared the 2D outline of the foot with the outline of the shoe and calculated the dimensional differences (Goonetilleke et al., 2000). This procedure has been expanded to a 3D comparison of lasts and feet by Luximon et al. (Luximon et al., 2001). Witana et al. have found a high correlation between the perceived fit of a shoe and the match of a last and the foot shape (Witana et al., 2004). Kouchi et al. have evaluated the favoured fit of running shoes, compared to the exact match of last an foot by 3D scans. Their results show that athletes with broad feet tend to wear narrow shoes whereas athletes with slender feet prefer wide shoes (Kouchi et al., 2005).

The best fit of a shoe also implies to find the correct shoe. Following Rossi that the fit of footwear is the „ability of the shoe to conform to the size, width, shape and proportions of the foot“ (Rossi, 2000, p. 63), it might be hard fitting the correct shoe solely on the base of length and width measures. Several studies aimed to use additional foot measures, beside foot length and foot width, to improve the 3D fit of footwear. This is already common in individual shoe customization. However, the procedure of Mauch et al. and Krauss et al. have shown a way to improve the fit as well as the fitting of footwear for a larger population (Krauss et al., 2010; Mauch, 2007; Mauch et al., 2009). The remaining lack is the information about dynamic changes of foot morphology.

3.3 Measuring foot morphology

The generally accepted assumption that footwear should follow foot shape makes it necessary to measure the foot. For fitting the correct shoe it is recommended to measure foot length and width in standing (half weight-bearing) situation (ISO 7250, Rossi and Tennant, 2011, Telfer and Woodburn, 2010). Several methods to capture foot morphology are available ranging from basic tools up to scanning technologies.

3.3.1 Static measurements

The basic tools and techniques to capture static foot morphology are calliper rulers or tapes (Golding, 1902, p. 53-57). These basic tools allow capturing foot height, width, length, and girth measures. Several foot measuring devices like the Brannock Foot-
Fundamentals of footwear

Measuring Device® Ritz stick, and Scholl focus on foot length and maximum forefoot width (Goonetilleke et al., 2000; Krauss and Mauch, 2013).

Further common methods are imprints produced by foam impressions and castings. A positive shape of the imprint is reproduces and used to manufacture a foot orthotic on the base of the model. Today, scanner systems are commonly used for this procedure and several software packages allow time effectively processing and designing of orthotics (Telfer and Woodburn, 2010).

Several scanner systems allow capturing and digitizing foot morphology from a plantar view but also in its entirety. Basic information is obtained by 2D scanner systems with the same mode of operation like flatbed scanners (Telfer and Woodburn, 2010). The information is reduced to the outline of the plantar foot shape. 3D information of the static foot morphology is mainly obtained by laser scanners (e.g. Yeti, scanGogh II) or projected white light (e.g. FootScan3D, Artec M-Series, FootScaper FTS-4) (Saunders and Chang, 2012). Both methods are based on the principle of active triangulation which requires a projecting and a recording unit. Laser light (usually in lines) or structured white light is projected onto the foot. Light sensors or cameras simultaneously record the scene at a known angle (D'Apuzzo, 2007; Saunders and Chang, 2013). All methods allow recalculating the 3D models of the foot and the calculation of different foot measures. Several methods for the calculation of the foot measures are available. First, foot measures based on anatomical landmarks are calculated with information about markers. These markers are attached on several anatomical landmarks prior to the scanning process. Second, the foot measures based on anatomical landmarks are calculated after the 3D model. Thus, the anatomical landmarks have to be defined on the 3D image by editing digital points. Third, the foot measures do not rely on anatomical landmarks but on defined percentages of foot length (Krauss and Mauch, 2013, p. 21; Mauch et al., 2009).

In general, most of the scanner systems and especially those that are based on laser technology need several seconds to record a static scene. Necessarily, participants have to stand still for several seconds which is difficult to realize especially with children (D'Apuzzo, 2007; Saunders and Chang, 2013).

3.3.2 Dynamic foot scanning

Several authors, concerned with footwear fit, have claimed information about foot morphology during natural walking (D'Aout et al., 2009; Kimura et al., 2009; Krauss et al.,
3.3 Measuring foot morphology

Current enhancements in scanner technology provide approaches for the challenge of scanning 3D objects during motion. In the entertainment industry some systems, like Microsoft Kinect, are already well-known and furthermore affordable for everybody. However, a dynamic foot scanner presents major challenges. Regarding the grading and sizing system but also the sensitivity of perceived comfort, it can be stated that only few millimetres make a big difference. Thus, the accuracy has to be very high.

There are only a few studies available that have presented dynamic foot scanner systems. The contemplated systems can be divided by their used methods: First, stereo matching method and second, structured light method. The stereo matching method is an optical method based on the principle of passive triangulation. Dynamic foot scanners, on the base of stereo matching, have been introduced in several publications. The advantage of this method is that the measurements can be conducted with high resolution (Coudert et al., 2006; Kouchi et al., 2009; Wang et al., 2006). However, the main disadvantage is that correspondence problems exacerbate the 3D reconstruction of the foot. Main reason for these correspondence problems is the uniform texture of the surface of the foot. These problems have been differently solved in the studies and are therefore regarded for each system.

Wang et al. have presented a set-up of eight CCD cameras based on the principle of passive triangulation. They have captured the dorsum of the foot and the reconstruction of the foot is based on the principal component analysis. Thus, the dynamic 3D model has been approximated on the base of 397 feet. The solution for the correspondence problems is that participants wear socks. The measurement frequency comprises 7.5 frames per second (fps) with a resolution of 640 x 480 pixels. The accuracy is specified ranging from 2 to 4 mm (Wang et al., 2005; 2006).

Coudert et al. have reconstructed the surface of the whole foot. They have used six cameras (three pairs) to generate a 3D model of the foot. The authors have offered two options to solve the correspondence problem. First, the foot can be covered with a sock and second the foot can be sprayed with paint. The measurement frequency comprises 25 fps with a resolution of 1280 x 960 pixels. Another limitation of this system is that the synchronisation of the camera pairs is time shifted which may bias the results. Furthermore, no information about the accuracy of the system is available (Coudert et al., 2006).
Kouchi et al. have used twelve cameras to capture the foot. They solve the correspondence problems by drawing lines on the foot. Thus, only these lines can be evaluated. The measurement frequency comprises 14 fps at a full resolution of 1026 x 768 pixels. The accuracy is given at 0.5 mm (Kouchi et al., 2009).

During running, Blenkinsopp et al. have measured the dynamic dorsal foot surface (Blenkinsopp et al., 2012). They have used six cameras (three pairs) and calculated the foot morphology by digital image correlation. Contrasting random patterns on the surface of the foot have been used to increase corresponding problems. These patterns have been generated by water based face paints. A single subject has been studied with the speed of about 4 ms\(^{-1}\). The measurement frequency is not reduced due to the post-processing and is provided by the cameras (250 fps). The resolution comprises 1024 x 1024 pixels. The accuracy of the system and reliability of the foot measures is not presented (Blenkinsopp et al., 2012).

Basically, two methods to solve the corresponding problems are presented in the studies: First, using socks, and second, drawing lines or painting the whole foot. The first one possibly influences the natural deformation of soft tissue. The second might affect the reproducibility of the foot measures. Thus, both methods are not appropriate to capture a higher number of persons. Other research groups chose approaches to capture the dynamic foot morphology based on the principle of active triangulation. The advantage is that the correspondence problems do not appear.

One system has been presented by the company Lionssystems. This system, called Dynamic FootMorphology, is based on the principle of time of flight. There are no scientific notes available about details of this system. The measurement frequency is stated as 42 fps (Dynamic FootMorphology, Lionssystems).

Jezersek and Mozina have presented a foot scanner system based on laser multiple-line triangulation technique with four scanner units. The measurement frequency is 25 fps. The accuracy of the system is given with 0.3 mm. The maximum error for the foot length, width, height, and girth varies from 0.24 to 0.82 mm. However, the foot has not been scanned during natural walking but only when rising on its toes. (Jezersek and Mozina, 2009).

Thabet et al. have presented a plantar scanner system consisting of a single scanner unit. Structured light is projected by a 3-LCD projector. The measurement frequency is not presented. The resolution comprises 1080i HD resolution. The accuracy of the
Measuring foot morphology

A system comprises 0.34 mm with a maximum of 0.5 mm. The reproducibility of empirical feet is presented with an average of 2.44 mm in static situation and 2.81 mm in dynamic situation (Thabet et al., 2011).

Schmeltzpfenning et al. have presented a plantar system using three scanner units. Structured light is projected onto the foot and coded by pulse-width-modulation. The timely synchronized high speed cameras capture the light patterns and the elevation profile of the object is recalculated by equations of Frankowski et al. (Frankowski et al., 2000). The measurement system comprises 41 fps with a resolution of 320 x 240 pixels. For detailed calculation of the repeatability of each foot measure it is referred to Schmeltzpfenning et al., (2009) and Schmeltzpfenning (2011).

It can be summarized that capturing the dynamic foot morphology is possible. The challenge is much more the analysis of the data and the interpretation in terms of practical relevance and applicability of the results.
4 Formulation of research question and hypotheses

The research question and hypotheses of this thesis are derived from findings and deficits of the current state of research. In Section 4.1 the deficits of the theoretical background (Chapter 2 and Chapter 3) are summarized. These deficits raise three main hypotheses that are presented in Section 4.2.

4.1 Findings and deficits of the current state of research

The main findings and deficits of anatomical and functional basics of the foot can be summarized as follows:

1. The foot has a very complex composition and is more mobile than formerly assumed.

2. Movement of the foot is more or less known for single structures like bones and joints as well as soft tissues like muscles or fat pad. Not much is known about the entirety of foot deformation regarding the external foot morphology.

3. The development of the foot is important for the whole body and not finished until late adulthood. A major part of the development takes place within shoes considering the shoed populations.

4. Influences of gender, age, and body mass are verified for static foot morphology and functionality regarding pressure and force distribution as well as soft tissue characteristics. However, these influences have not been considered for dynamic deformation of the foot.
5. Intra-individual differences of foot morphology have not been considered as differences between static and dynamic foot morphology. These differences are most important for developing feet.

6. Up to now, anthropometric influences on the differences between static and dynamic foot morphology have not been analysed.

With respect to fundamentals of footwear as well as foot and shoe interface following deficits can be summarized:

1. The last, which has to represent the shape of the shoe, is mainly designed on the base of experiences. The design of the last is still a handcraft and follows the traditions as a hundred years ago.

2. Customization to dynamic changes of the foot is less considered in last construction. Mainly foot length is regarded and usually implemented by adding a specified toe allowance which is the space in front of the toes.

3. Sizing and grading procedures are discrete even if the feet are continuous. Using the words of Cheskin "Girth and size intervals – regular on lasts, irregular on the feet" (Cheskin, 1987, p. 127).

4. Friction is one of the reasons for foot problems. Thus, footwear should account for dynamic friction.

5. Footwear can change the walking patterns which might be a reason for further problems. Thus, footwear should allow natural walking.

6. It is generally accepted that information about static foot morphology improves the fit of footwear. Dynamic foot morphology, which has not been considered, can further improve footwear fit.

7. Several systems allow generating static foot measures. Only, advancements in scanner technology allow capturing dynamic foot morphology and calculating dynamic foot measures.

8. Previous studies focus on the feasibility of the dynamic scanner systems. Thus, there is a lack of comprehensive samples to formulate recommendations for the dynamic fit of footwear.
9. There is no study that has considered dynamic foot morphology of developing feet.

The summarized findings and deficits are twice as important: First, they are reason for the raise of the research question and hypotheses. Second, they highlight the importance of the responses and benefit for footwear. The latter will be discussed in Section 9.2.

4.2 Research question and hypotheses

This thesis aims to evaluate dynamic foot morphology. Furthermore, the aim is to generate results that help improve footwear fit and formulate recommendations for the construction of footwear.

Research question 1:

How does foot morphology differ between static and dynamic situations?

(RQ\textsubscript{1})

This research question in addition with the state of the research is conducted to formulate the three hypotheses.

Hypothesis 1 is established on previous findings that dynamic foot morphology in adults differs from static foot morphology. The disparity in static and dynamic foot morphology regarding anthropometric influences has not been evaluated. The detected influences of gender, age, and body mass on static foot morphology raise the question if these influences can also be detected in dynamic situation.

Hypothesis 1:

There are differences in dynamic foot morphology of adults according to age, gender, and body mass.

(H\textsubscript{1})

Hypothesis 2 also relies on the research question. However, this question has not been answered for developing feet. The physiological development of the feet is very important for the whole body. Static foot morphology has already been used to improve footwear fit of children's shoes. However, the differences between static and dynamic foot morphology is very important in terms of the fact that footwear is worn in most countries worldwide and footwear can negatively affect the foot morphology.

Hypothesis 2:

Dynamic foot morphology of developing feet differs from static foot morphology.

(H\textsubscript{2})
Hypothesis 3 further examines these differences by detecting the influence of gender, age, and body mass. The inter-individual differences regarding static foot morphology has also been detected in developing feet. Thus, it can be assumed that these variables also affect the differences between static and dynamic foot morphology.

Hypothesis 3:
Gender, age, and body mass affect the dynamic foot morphology and the differences between static and dynamic foot morphology of developing feet.

\( (H_3) \)

The three hypotheses are examined within three research articles, which are presented in Chapter 6, Chapter 7, and Chapter 8. A brief overview of the used methods to examine the three hypotheses is presented in the following Chapter 5.
5 Methods

The aim of this chapter is to provide an overview of the used methods within this thesis. The methods to examine the hypotheses are elaborated within each research article. This chapter does not introduce the methods in detail, but references to chapters that provide these details. Section 5.1 presents information about characteristics of the two analysed samples and collections of foot data. The measurement system and analysis procedure is briefly described in Section 5.2, followed by the statistical analysis in Section 5.3.

5.1 Samples

The first sample comprises adult participants that were recruited from the area around Tübingen. Criteria for exclusion were injuries or diseases of lower extremities affecting normal gait, other limitations of free walking, vertigo, age less than 18 years, and body weight of more than 125 kg. Precondition for the participation was that the participants had read and understood the information about aims and contents of the study and had signed the informed consent. 129 adults were included in the study. One randomly defined foot of each adult was recorded during walking, with predefined walking speed of 4.5 km/h ±5%. More details on this sample can be found in Section 6.2.2.

The second sample includes 2554 children and adolescents from the southern part of Germany. They were recruited within 15 schools. Measurements took place in these schools. Children with written consent of one parent were included. Exclusion criteria comprised injuries or diseases of the lower extremities that influence normal gait. One randomly defined foot of each child was recorded during standing and walking (see Section 7.2.1). Walking speed was predefined and adjusted to body height and is presented in Table 7.2.

Both studies were approved by the ethics committee of the medical clinic of Tübingen. The characteristics of the first and second sample are summarized in Table 5.1.
Table 5.1: Characteristics of the two samples. Mean values with standard deviation in brackets.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age [years]</th>
<th>N</th>
<th>Gender</th>
<th>Body Height [m]</th>
<th>Body Weight [kg]</th>
<th>BMI/BMI Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>38 (14)</td>
<td>129</td>
<td>F: 77</td>
<td>1.71 (0.08)</td>
<td>72.7 (12.6)</td>
<td>25.0 (4.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M: 52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sample 2</td>
<td>11 (3)</td>
<td>2554</td>
<td>F: 1285</td>
<td>1.45 (0.16)</td>
<td>38.9 (13.9)</td>
<td>52.2 (29.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M: 1269</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F = female; M = male

5.2 Measurement system and analysis procedure

The used measurement system, called DynaScan4D, is based on the principle of active triangulation. This system has been developed at the University of Tübingen (Schmelzpfenning et al. 2009). The scanner units, zSnapper®, have been developed by ViALUX (ViALUX GmbH, Chemnitz, Germany). The primarily used system, within the first research article, is based on three scanner units to capture the plantar side of the foot (see Chapter 6, Section 6.2.1).

This plantar system has been extended by two additional scanner units to enable the recording of the whole foot. Further improvements result in a measuring frequency of 46 Hz with a resolution of 640 x 480. This improved system was used to record the second sample of 2554 developing feet, presented in Chapter 7 and Chapter 8. Details about this system are presented in Section 7.2.2 and Section 8.2.2. Details about the accuracy of the DynaScan4D with the five scanner units can be found in the Appendix A.3.

The analysis of the captured point clouds and thus calculation of foot measures of the adults sample was done by the software program Geomagic Qualify8® (Geomagic Inc., USA). Within this software program the foot measures were manually defined (see Section 6.2.3). The analysis of the second sample was improved and realized within the DynaScan4D software. A semi-automatical procedure was developed to provide a higher reliability of the foot measures. However, two anatomical landmarks were still manually detected and characteristic instants to define the measurement phase (see Section 7.2.2).

The calculated foot measures for the first sample are presented in Table 6.1 and for the second sample in Table 7.3 and Table 8.2.
5.3 Statistical analysis

Hypothesis 1 and hypothesis 3 assume that dynamic foot morphology of adults (see Chapter 6) and children (see Chapter 8) is affected by the variables gender, age, and body mass. Thus, the used statistical procedures to examine these influences are similar. Section 6.2.4 and Section 8.2.5 describe two methods in detail:

- First, an analysis of matched pairs with the identification of differences by Student’s t-test for independent samples.
- Second, a multiple regression analysis was conducted.

Hypothesis 2 states that there are differences between static and dynamic foot morphology in developing feet. The differences between HWB, FWB and MaxDyn are tested by one-way ANOVA with paired Student’s t-test (see Section 7.2.3). Furthermore, within this research article the repeatability of calculated foot measures was calculated by intraclass correlation coefficient (ICC) as well as root mean squared error (RMSE) (Perini et al. 2005; Shrout and Fleiss 1979).

The statistical analysis was performed using the software JMP 9.0.2 (version 9.0.2, SAS, Cary, USA) and SPSS (version 20, SPSS Inc. Chicago, IL, USA).
Research Paper

Influences on plantar dynamic foot morphology in adults

Summary: The foot changes its shape in dynamic situations. This has been discussed and proven with several studies (Coudert et al., 2006; Leardini et al., 2007; Kouchi et al., 2009). Furthermore, it has been verified that anthropometric variables like gender, age, and BMI affect static foot morphology (Krauss et al., 2010; Xiong et al., 2009; Zifchock et al., 2006). The aim of the present study is to identify the influence of gender, age, and BMI on dynamic foot morphology and therefore prove hypothesis 1.

Published in: Footwear Science, 2013, Vol. 5, No. 2, 121–129

DOI: 10.1080/19424280.2013.789559
6 Anthropometric influences on dynamic foot shape: Measurements of plantar three-dimensional foot deformation

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(Received November 6, 2012; accepted March 21, 2013)

Abstract

Purpose: Advances in scanner technology enable the capture of feet during walking. Knowledge of dynamic deformation is essential for fundamental research and application-oriented improvements in terms of comfortable and functional footwear. The core hypothesis of our study is that there is a relationship between dynamic foot measures and the anthropometric dimensions age, gender and body mass index.

Methods: We measured the dynamic foot shape of 129 subjects (77 female, 52 male) with a plantar dynamic scanner system. During stance phase we captured maximum values (MaxDyn) and changes (ΔDyn) of length, width, and height measures as well as angles and indices of feet. We identified relationships between foot measures and anthropometric dimensions by two statistical methods: analysis of variance (ANOVA) between matched groups and multiple regression analysis within whole sample size.

Results: MaxDyn values of foot width measures are higher in overweight subjects. Most important predictors of MaxDyn are static measures and gender, regarding values
that characterise the longitudinal arch as well as lateral ball length. More dynamic deformation was found in ball and arch angle as well as medial ball length and ball width of overweight subjects and in width measures of women. Multiple regression analysis detects body weight as an important predictor for changes in foot width measures as well as arch height and angle.

**Conclusion:** The ability to collect foot measures during natural walking is the basis for the following findings. First, our study confirms that static foot measures can be used as basic design criteria for footwear. Second, our study points out the influence of factors like gender and body weight on dynamic foot morphology. Consideration of these additional factors can essentially improve design methods and particularly the fit of footwear.

Keywords: dynamic scanning; dynamic foot deformation; footwear design; anthropometry; comfort; customisation

### 6.1 Introduction

Capture of the foot shape during walking is an essential and therefore frequently desired procedure (Tsung et al., 2003; D’Aout et al., 2009; Kimura et al., 2009; Morio et al., 2009; Krauss et al., 2010). The knowledge of dynamic deformation of the foot is a benefit for fundamental research as well as application-oriented improvements in terms of comfortable and functional footwear. The fit of a shoe is a mostly long-kept secret of last designers and based on long-standing manual craft experience. Advances in scanner technology render it possible to capture feet in dynamic situations (Coudert et al., 2006; Kouchi et al., 2009; Kimura et al., 2011). Moreover, this new input can help to objectify the universal topic of well-fitting shoes.

Foot morphology is highly variable and therefore measures such as length, width, girth and height, as well as flexibility of feet, are individually pronounced. Different factors influence characteristics of static foot shape, for example ethnicity, age, sex and body mass index (BMI) (Hawes and Sovak, 1994; Kouchi, 1998; Wunderlich and Cavanagh, 2001; Mauch et al., 2008; Krauss et al., 2010). Several studies identified the influence of BMI on static foot width. Especially children’s foot shape and functionality of longitudinal arch are influenced by BMI (Hills et al., 2002; Mauch et al., 2008; Xiong et al., 2009). The anthropometric dimension age causes controversial debates. In fact, biological structures
change with increasing age, for example flexibility of soft tissues (Hsu et al., 1998). However, some authors found no significant changes in foot shape between different ages (Menz and Morris, 2006; Zifchock et al., 2006). The influences of gender have been intensively studied during recent years. The main findings are that within the same shoe size female feet are more slender and foot girth is smaller than in male feet (Krauss et al., 2010). Recommendations to last designers are obvious: females need different lasts to males and it is not sufficient to graduate a men’s last to a smaller size (Wunderlich and Cavanagh, 2001; Krauss et al., 2010).

All identified influences are important to improve comfort and fit of footwear and therefore approximate the last’s shape to the anatomical foot shape. Certainly, more attention needs to be paid to anatomical conditions, because there is still a lack of well-fitting shoe lasts (Kouchi, 1998; Witana et al., 2004; Richter and Schaefer, 2009). Possibly, insufficient considerations of dynamic situations can explain this lack. Comfort and functionality of footwear is certainly more than assisting someone’s buying decision (Michel et al., 2009). Literature shows associations between insufficient fit of shoes and the development of foot deformities like hallux valgus, hammer or claw toes (Rossi and Tennant, 1984; Janisse, 1992; Frey, 2000). Recent findings postulate that footwear has long-term negative effects on foot morphology, function, and biomechanical qualities (Wunderlich and Cavanagh, 2001; Zipfel and Berger, 2007; D’Aout et al., 2009).

Without controversy, feet change their shape in dynamic situations (Coudert et al., 2006; Leadini et al., 2007; Kouchi et al., 2009). Based on assumptions and experiences, designers of lasts and insoles try to include dynamic changes. However, there are only a few studies that provide data for them. To the best of our knowledge, there is no investigation that systematically examines influencing factors of dynamic changes. Until now technology has not allowed the capture of three-dimensional foot shape during natural walking. Methods based on markers or goniometers and also efforts to interpret dynamic plantar pressure analysis provide dissatisfying results. Furthermore, the results may also be error-prone due to relative moments of markers or coarse resolutions of pressure platforms (Leadini et al., 2005; Wolf et al., 2008). In recent years, several research groups have presented different measurement systems for dynamic three-dimensional foot scanning (Coudert et al., 2006; Wang et al., 2006; Kimura et al., 2009; Kouchi et al., 2009; Schmeltzpfenning et al., 2009; Schmeltzpfenning et al., 2010). Most publications address feasibility and show potentials and limitations of their systems (Wang et al., 2006;
Kimura et al., 2009; Kimura et al., 2011). Beside technical deficiencies (e.g. low sample rate), the core limitation of these studies is the small sample size (Coudert et al., 2006; Kouchi et al., 2009). However, their scientific findings are auspicious and also seminal for objectification of dynamic customisation in footwear. Coudert et al. identified increasing ball width (5%) and heel width (about 5 mm) during walking. However, they did not capture plantar foot morphology (Coudert et al., 2006). Kouchi et al. compared static and dynamic situations and found statistically significant differences in heel width, instep height, width of forefoot, and medial ball length. Their sample rate was only 14 Hz and they only analysed cross sections of the foot instead of the whole three-dimensional shape (Kouchi et al., 2009).

Previous studies of foot deformation due to different loading situations specify changes especially in foot length, width of rear and forefoot and decreasing height of arch and instep (Rossi and Tennant, 1984; Frey, 2000; Tsung et al., 2004; Xiong et al., 2009). These changes or maybe more pronounced changes can also be expected during natural walking. However, if you take into account the attitudes of several elastic and active soft tissues it is impossible to predict the magnitude of deformation. A radiographical examination of length, height and width of feet showed no changes in skeletal dimensions (Carlsoo and Wetzenstein, 1968). In contrast, another group of researchers recently analysed the kinematics of foot bones during walking and slow running by bone pins. They concluded that in all studied joints movement was found and these movements in some joints were higher than expected (Nester et al., 2007; Lundgren et al., 2008). Therefore, deformation of soft tissues can be supposed. Elaborating on these thoughts, anthropometric factors like age, gender, and BMI can be important and expanding in analysing dynamic foot characteristics. The core hypothesis of this study is: there is a relationship between dynamic foot deformation and the anthropometric dimensions age, gender, and BMI.

6.2 Methods

6.2.1 Measurement system

To measure foot morphology during natural walking a special system based on active triangulation was designed (Schmeltzpenning et al., 2010). This dynamic scanner (DynaScan4D) operates with three scanner systems (z-Snapper, Vialux, Chemnitz, Ger-
6.2 Methods

Figure 6.1: Dynamic plantar foot scan during walking - five frames of stance phase.

many), in which each system consists of a high-speed camera and a projector. The used cameras (Pike F-032 B/W, Allied Vision, Stadtroda, Germany) record 205 frames per second with a resolution of 640x480. The Digital Light Processing projectors project different structured light patterns by laminar technique on the foot. The light patterns are coded by pulse-width-modulation and the shifting time of applied digital micro mirror device technology (DMD™ by Texas Instruments, USA) generates luminous intensity (Schmeltzpfenning et al., 2010). Timely synchronised cameras capture these light patterns. With information about phase positions an elevation profile of the object can be calculated by the equations of Frankowski et al. (Frankowski et al., 2000).

The scanner systems are installed on a 4.6 m long and 0.8 m high walkway. One scanner system captures plantar foot morphology from beneath the walkway through a glass platform. The other two scanner systems are installed above on the left and right side of the walkway. Subjects walk over the walkway on which strain gauges additionally trigger the detection of the roll-over process. In addition, we use light barriers to control subjects' walking speed. We captured feet with a measurement frequency of 41 Hz and a shutter time of less than 2 ms. The resolution was reduced to a 2x2 binning mode to guarantee the high record rate (Figure 6.1).

6.2.2 Study design and study population

We recruited subjects from the medical clinic of the university to identify influences of BMI, gender, and age. The study was approved by the local Ethics Committee of the university. Altogether 187 subjects replied to announcements by email and flyers. We informed all subjects about the aims and contents of the study as well as exclusion criteria. Exclusion criteria comprised injuries or diseases of lower extremities affecting normal gait, other limitations of free walking, vertigo, age younger than 18 years, and body weight of more than 125 kg. Before starting measurements, exclusion criteria where observed and subjects had to give written consent to participate.
We collected potential influencing variables like age, gender, body weight, and body height. Body mass index (BMI) was calculated according to body weight (kg) divided by squared body height (m). Additionally, we asked for the usually worn shoe size of each subject. We defined the captured foot randomly and subsequently conducted dynamic measurements. All subjects achieved a period of adaptation to assess that they walk naturally with a specified walking speed of 4.5 km/h ±5%. We captured three valid naturally conducted trials per subject. Additionally, we captured all foot measures in a static situation. Subjects were instructed to position their feet parallel and distribute weight equally on both feet. Therefore, in the static situation, half body weight was on the measured foot. The whole measurement procedure took about 25 minutes per participant.

The final and representative sample is composed of 77 women and 52 men with a mean age of 38 ±14 years. Body weight (72.7 ±12.6 kg), body height (1.71 ±0.08 m) and BMI (25 ±4.2 kg/m2) are normally distributed. Shoe size for each gender is also normally distributed with a peak around shoe size 39 (Paris Point) for women and around 42 for men. We found a skewed distribution for the variable age that can be explained because of increased voluntary participation of students.

6.2.3 Foot measures
Captured point clouds of the foot were processed with the software program Geomagic Qualify8® (Geomagic Inc., USA). The orientation of the foot was standardised on an axis through the most medial point of the heel and first metatarsal head (MTH1). We identify the plane of the glass platform within foot flat and transferred it to the other frames of the roll-over process. Because of the marker-less technology, anatomical landmarks MTH1 and MTH5 and also further foot measures were manually detected on the point clouds. All foot measures are specified in Table 6.1.
<table>
<thead>
<tr>
<th>Foot Length Measures</th>
<th>Foot Width Measures</th>
<th>Foot Angles and Height M.</th>
<th>Arch I.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foot Length (FL)</strong></td>
<td><strong>Heel Width (HW)</strong></td>
<td><strong>Ball Angle (BA)</strong></td>
<td><strong>Chipaux-Smirak-Index (CSI) Ratio of AW and BW.</strong></td>
</tr>
<tr>
<td>Distance between most posterior point of the heel and most anterior point of the longest toe. This measure is only defined in static situations.</td>
<td>Distance between most lateral and medial point of the heel at right angles to the medial axis.</td>
<td>Angle of the connecting line (MTH1 and MTH5) and the x-axis.</td>
<td></td>
</tr>
<tr>
<td><strong>Medial Ball Length (MBL)</strong></td>
<td><strong>Midfoot Width (MW)</strong></td>
<td><strong>Arch Angle (AA)</strong></td>
<td><strong>Staheli-Index (SI) Ratio of AW and HW.</strong></td>
</tr>
<tr>
<td>Distance between most posterior point of the heel and most medial point of MTH1.</td>
<td>Distance between most lateral and medial point of the midfoot at right angle to the medial axis.</td>
<td>Angle of the connecting line (MTH1 and the angular point of the arch) and the y-axis.</td>
<td></td>
</tr>
<tr>
<td><strong>Lateral Ball Length (LBL)</strong></td>
<td><strong>Arch Width (AW)</strong></td>
<td><strong>Arch Height (AH)</strong></td>
<td></td>
</tr>
<tr>
<td>Distance between most posterior point of the heel and most lateral point of MTH5.</td>
<td>Narrowest distance of the exit field.</td>
<td>Distance between the ground (xy-plane) and the highest point of the arch.</td>
<td></td>
</tr>
<tr>
<td><strong>Ball Width (BW)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance between most medial point of MTH1 and most lateral point of MTH5.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Four phases of the roll-over process were defined according to Blanc et al. (1999). The first phase (P1) starts with the initial heel contact when the heel hits the glass platform and ends with the first metatarsal contact. We standardised the beginning of this phase with the second frame of heel contact. The second phase (P2) begins with the first metatarsal contact and ends when the toes hit the ground. We defined the beginning of the phase as the frame on which first and fifth metatarsals have complete contact with the ground. Mean stance phase (P3) is the phase when the toes have contact with the ground until the heel takes off. We standardised the end of this phase by choosing the second frame when the heel moves upwards and is no longer completely loaded but also not off the ground. The terminal stance phase (P4) is specified from heel take off to the frame before MTH1 leaves the ground. Within these phases we calculated the different foot measures.

To analyse influences of anthropometric variables, we determined two response values for each dynamic foot measure: (1) maximum value (MaxDyn) measured during dynamic loading; (2) magnitude of changes during dynamic loading calculated as difference between minimum and maximum (ΔDyn). In which phases these data were captured depends on the load situation during stance phase and differs for each foot measure. Therefore, the three foot length measures foot length (FL), medial ball length (MBL), and lateral ball length (LBL) were analysed within P2, and P3. During the same phases ball angle (BA), arch angle (AA), arch height (AH), arch width (AW), and midfoot width (MW) as well as the arch indices Chipaux-Smirak-Index (CSI), and Staheli-Index (SI) were calculated. We additionally observed heel width (HW) within P1 and ball width (BW) within P4.

6.2.4 Statistical analysis

We chose two different methods to identify influences of age, gender, and BMI on dynamic foot morphology. First, we normalised foot width, length, and height measures to static foot length to eliminate or minimise influences of foot length on the dimension of dynamic changes. In the first statistical approach we generated matched groups of subjects by individually assigning subjects. Therefore, two groups for each variable were formed with the aim to minimise the effect of confounding variables (see Table 6.2). Furthermore, mean values between groups were compared by one-way analysis of variance (ANOVA) and tested by independent t-test. With the second statistical method we calculated
multiple regression analysis within the whole sample to identify influencing variables. This method provides additional advantages in terms of estimating the magnitude of effects as well as relationships between different variables (Aiken et al., 1991). We calculated a multiple linear regressions model on the basis of adding the variables stepwise forward into the model. Critical p-value for inclusion of variables was ascertained at $p \leq 0.25$. The model was calculated according to Equation (1). $Y$ is the target variable, which represents the dynamic foot measures. $X_i (i = 1, n)$ are the influencing variables that describe dynamic foot measures.

$$E\left(\frac{Y}{X}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

All analyses were performed by using JMP Version 9.0.2 (SAS, Cary, USA). The level of significance was set to $p < 0.05$. If we state 'difference', this refers to a statistically significant difference at this alpha level, throughout the paper.

### 6.3 Results

#### 6.3.1 Differences between matched groups

Table 6.2 describes the matched groups formed according to the influencing variables gender, BMI, and age. Main criteria of individual assignment were that groups were as similar as possible within remaining anthropometric variables.
## Table 6.2: Characteristics of matched groups

<table>
<thead>
<tr>
<th>Influencing Variables</th>
<th>Level</th>
<th>N</th>
<th>Age [years]</th>
<th>Body Height [m]</th>
<th>Body Weight [kg]</th>
<th>BMI [kg/m²]</th>
<th>Shoe Size</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>21</td>
<td>35.0 ± 13.0</td>
<td>1.74 ± 0.1</td>
<td>77.6 ± 11.7</td>
<td>25.3 ± 3.9</td>
<td>43 ± 1.0</td>
<td>♂ 21</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>21</td>
<td>35.0 ± 14.0</td>
<td>1.68 ± 0.1</td>
<td>71.8 ± 8.7</td>
<td>25.3 ± 3.8</td>
<td>40 ± 1.4</td>
<td>♀ 21</td>
</tr>
<tr>
<td></td>
<td>BMI Overweight</td>
<td>37</td>
<td>40.7 ± 14.8</td>
<td>1.69 ± 5.6</td>
<td>84.1 ± 10.7</td>
<td>29.4 ± 5.6</td>
<td>41 ± 2.1</td>
<td>♂ 19; ♂ 18</td>
</tr>
<tr>
<td></td>
<td>Normal Weight</td>
<td>37</td>
<td>39.6 ± 14.3</td>
<td>1.70 ± 7.1</td>
<td>68.0 ± 8.0</td>
<td>22.5 ± 1.9</td>
<td>41 ± 2.1</td>
<td>♀ 19; ♀ 18</td>
</tr>
<tr>
<td></td>
<td>Age Older</td>
<td>26</td>
<td>57.6 ± 5.6</td>
<td>1.70 ± 5.6</td>
<td>74.3 ± 11.6</td>
<td>25.9 ± 3.8</td>
<td>41 ± 1.8</td>
<td>♀ 13; ♂ 13</td>
</tr>
<tr>
<td></td>
<td>Younger</td>
<td>26</td>
<td>24.6 ± 2.3</td>
<td>1.72 ± 7.1</td>
<td>74.5 ± 8.7</td>
<td>25.1 ± 3.1</td>
<td>41 ± 2.2</td>
<td>♀ 13; ♂ 13</td>
</tr>
</tbody>
</table>
Table 6.3, 6.4 and 6.4 show the results of comparing each pair by ANOVA. We tested the differences between the matched groups for MaxDyn and $\Delta$Dyn of all foot measures.

No gender-specific differences exist for MaxDyn of all foot measures. However, there are differences between women and men for $\Delta$Dyn of AW and BW. With both measures women have higher values for $\Delta$Dyn.

Between the matched groups overweight and normal weight we found differences for $\Delta$Dyn of MBL, BW, BA, and AA. Furthermore, all maximum values of foot width measures differ between overweight and normal weight subjects. All values are higher in the group with overweight subjects.

The differences in $\Delta$Dyn between the two age groups were statistically significant only in BA. Older subjects have higher differences in BA during dynamic loading. The maximum value of HW is also higher in older subjects.
### Table 6.3: Differences in dynamic foot measures between matched groups

<table>
<thead>
<tr>
<th>Subgroups</th>
<th>Length Measures</th>
<th>Width Measures</th>
<th>Angles and Heights</th>
<th>Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBL [%FL]</td>
<td>LBL [%FL]</td>
<td>HW [%FL]</td>
<td>MW [%FL]</td>
</tr>
<tr>
<td>Gender</td>
<td>MaxDyn</td>
<td>Dyn</td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
</tr>
<tr>
<td>MaxDyn</td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
</tr>
<tr>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
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<td><img src="image" alt="image" /></td>
</tr>
<tr>
<td><img src="image" alt="image" /></td>
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<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
<td><img src="image" alt="image" /></td>
</tr>
</tbody>
</table>

**Notes:**
- ΔDyn = 0.03
- Significant differences are indicated by *p* < 0.05.
Table 6.4: Differences in dynamic foot measures between matched groups – BMI

<table>
<thead>
<tr>
<th>Subgroups</th>
<th>Length Measures</th>
<th>Width Measures</th>
<th>Angles and Heights</th>
<th>Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overweight</td>
<td>1.02 ± 0.54</td>
<td>2.15 ± 1.04</td>
<td>2.01 ± 0.40</td>
<td>1.05 ± 0.55</td>
</tr>
<tr>
<td>Normal Weigh</td>
<td>0.80 ± 0.37</td>
<td>1.83 ± 0.74</td>
<td>2.03 ± 0.47</td>
<td>0.96 ± 0.57</td>
</tr>
<tr>
<td>p-value</td>
<td>0.038</td>
<td>0.140</td>
<td>0.790</td>
<td>0.477</td>
</tr>
<tr>
<td>MaxDyn</td>
<td>72.70 ± 1.46</td>
<td>59.81 ± 1.11</td>
<td>25.79 ± 1.46</td>
<td>32.97 ± 1.76</td>
</tr>
<tr>
<td>Overweight</td>
<td>73.21 ± 1.11</td>
<td>60.52 ± 1.64</td>
<td>24.89 ± 1.51</td>
<td>31.33 ± 2.16</td>
</tr>
<tr>
<td>Normal Weigh</td>
<td>73.21 ± 1.11</td>
<td>60.52 ± 1.64</td>
<td>24.89 ± 1.51</td>
<td>31.33 ± 2.16</td>
</tr>
<tr>
<td>p-value</td>
<td>0.100</td>
<td>0.089</td>
<td><strong>0.013</strong>&lt;0.001&gt;</td>
<td>0.020</td>
</tr>
</tbody>
</table>
### Table 6.5: Differences in dynamic foot measure between matched groups – Age

<table>
<thead>
<tr>
<th>Subgroups</th>
<th>Length Measures</th>
<th>Width Measures</th>
<th>Angles and Heights</th>
<th>Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Older</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔDyn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Younger</td>
<td>0.93 ± 0.48</td>
<td>2.15 ± 0.78</td>
<td>1.93 ± 0.41</td>
<td>1.10 ± 0.56</td>
</tr>
<tr>
<td>p-value</td>
<td>0.282</td>
<td>0.108</td>
<td>0.596 ± 0.36</td>
<td>0.810 ± 0.52</td>
</tr>
<tr>
<td>ΔDyn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Younger</td>
<td>72.88 ± 1.08</td>
<td>60.24 ± 1.49</td>
<td>26.09 ± 1.32</td>
<td>32.64 ± 1.61</td>
</tr>
<tr>
<td>p-value</td>
<td>0.002</td>
<td>0.412</td>
<td>0.001 ± 0.12</td>
<td>0.161 ± 0.18</td>
</tr>
</tbody>
</table>

6 Anthropometric influences on dynamic foot shape
6.3 Results

6.3.2 Predictors of dynamic foot shape and deformation

With creating regression models we could identify predicting variables of the responses \(\Delta{\text{Dyn}}\) and MaxDyn for all foot measures. The explained variances in all regression models calculated for \(\Delta{\text{Dyn}}\) are very low. The highest value of variance \(R^2\) comprises 0.50 for AA. This model includes the variables body weight and static values and shows statistically significant influences. For the other foot measures minor explainable variances from \(R^2\) of 0.15 to 0.05 are found. Body weight and static values have predicting influence in multiple regression analysis for \(\Delta{\text{Dyn}}\) of most foot measures and explain changes in HW. Body weight explains changes in MW. Furthermore, body weight in combination with body height explains changes in AH. The static values are also statistically significant predictors for \(\Delta{\text{Dyn}}\) of MBL and, in combination with gender, of BW. In LBL body height statistically significantly predicts dynamic changes. \(\Delta{\text{Dyn}}\) of AW and BA cannot be predicted by chosen variables.

Explained variance in models calculated for the response MaxDyn are much higher and range from \(R^2\) of 0.48 to 0.96. In all foot measures static values are statistically significant predictors of MaxDyn. Furthermore, in MBL, HW, BW, BA, and AA the static values are the only predictor. Gender does additionally predict MaxDyn of AH and LBL. In addition, the combination of static values, gender and body height can explain the variance of MaxDyn of MW (\(R^2 = 0.85\)) and AW (\(R^2 = 0.90\)).
Table 6.6: Results of multiple regression analysis within whole sample

<table>
<thead>
<tr>
<th>Dynamic Foot Measure</th>
<th>Length Measures</th>
<th>Width Measures</th>
<th>Angles and Heights</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔDyn Intercept [β]</td>
<td>5.456*</td>
<td>5.846*</td>
<td>1.297*</td>
</tr>
<tr>
<td>Static [β]</td>
<td>-0.066*</td>
<td>0.051*</td>
<td>-0.243*</td>
</tr>
<tr>
<td>Gender [β]</td>
<td></td>
<td>-2.710*</td>
<td>1.543</td>
</tr>
<tr>
<td>Body Weight [β]</td>
<td></td>
<td>-0.008*</td>
<td>0.029*</td>
</tr>
<tr>
<td>Age [β]</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of Determination ($R^2$)</td>
<td>0.07</td>
<td>0.11</td>
<td>0.07</td>
</tr>
</tbody>
</table>

| MaxDyn Intercept [β] | 11.046*         | 13.580*        | 0.559             | 9.253*   | 19.185*  | 0.094   | 4.567   | 2.887   | -6.594  |
| Static [β]           | 0.854*          | 0.847*         | 0.995*            | 0.828*   | 0.703*   | 1.012*  | 0.608*  | 0.760*  | 0.869*  |
| Gender [β]           | -2.438*         |                |                   | 0.160*   | 1.055*   |         | 0.796*  | 1.964   |         |
| Body Height [β]      |                 | -2.358*        | -7.743*           |          |          |         | 0.624   |         | 6.894   |
| Body Weight [β]      |                 |                |                   |          |          |         |          |         |         |
| Age [β]              | -0.008          |                |                   |          |          |         |          |         |         |
| Coefficient of Determination ($R^2$) | 0.77 | 0.80 | 0.96 | 0.85 | 0.90 | 0.96 | 0.48 | 0.63 | 0.83 |

* = $p < 0.05$; critical p-value for inclusion of variables = $p \leq 0.025$; Static = static value of foot measure
6.4 Discussion

6.4.1 Influence of gender on dynamic foot shape

In the present study we identified almost no gender-specific influences on dynamic foot shape. For MaxDyn of all foot measures gender-specific influences are rather marginal. This is confirmed by the method of matched pairs and by multiple regression models in the whole sample size. Foot measures were normalised to foot length, this can be one reason for small differences. Regarding matched groups, women have a mean shoe size of 40 and men 43. We can say that dynamic foot measures normalised to foot length show no differences in dynamic foot measures between men and women. This is in line with reports for static foot shape. In contrast, there are differences comparing feet of the same foot length with regard to gender-specific influences. Women's and men's feet of the same size have different proportions of static foot shape (Krauss et al., 2008; Krauss et al., 2010). If this holds for dynamic foot shape, additionally comparisons of the same sizes as well as the same proportions are required. The results of multiple regression models confirm influences of gender. In the whole sample, gender can predict MaxDyn of the foot measures LBL, MW, AW, and AH. We can state that measures characterising longitudinal arch are affected by gender in dynamic situations.

There are gender-specific differences between $\Delta$Dyn of AW and BW, compared in matched groups. Therefore, women show higher dynamic deformation in width measures. Also multiple regression models approve the influence of gender on $\Delta$Dyn of BW. Overall, the influences due to gender are marginal. We expected more pronounced gender-specific differences in $\Delta$Dyn, because literature shows higher laxity of ligaments and lower stiffness of longitudinal arch for women (Hennig and Milani, 1993; Krauss, 2006; Zifchock et al., 2006). In summary, the variable gender has low influences on dynamic foot shape. Predominantly, gender affects the dynamic characteristics of longitudinal arch which is in agreement with previous assumptions.

6.4.2 Influence of BMI on dynamic foot shape

A few studies pursued the identification of influences on dynamic characteristics of gait for overweight subjects. Until now only studies on ground reaction force, plantar pressure or kinematic measures have been available (Hills et al., 2002; Wearing et al., 2006). Related work points out relationships between obesity and the prevalence of flat foot deformities.
There are differences in MaxDyn between normal weight and overweight subjects. These findings show that maximum values of all foot width measures are exceeded in overweight compared to normal weight subjects. Broader dynamic foot measures for overweight subjects have not been reported before. For children static foot shape has been examined before with regard to changes with increasing BMI, but more often body weight was used as the predictor (Dowling et al., 2004; Mickle et al., 2004; Mickle et al., 2006a; Mauch et al., 2008; Riddiford-Harland et al., 2011). We calculated regression models of each foot measure for the whole sample size and found no statistically significant input of body weight for the explanation of variance. In contrast, body height is a statistically significant predictor of MaxDyn in MW and AW. Whereas, each static foot measure is a statistically significant predictor for MaxDyn of all foot measures.

The magnitude of dynamic deformation is also increased for overweight subjects. Differences are found in \( \Delta \)Dyn of MBL, BW, BA, and AA comparing groups of overweight and normal weight subjects. The longitudinal arch of overweight subjects flattens more and their BW broadens more during stance phase.

The relationship between ground reaction force and body weight is obvious, but plantar pressure and body weight is linked marginally (Cavanagh et al., 1987; Hennig and Milani, 1993). The reason is the increased loading area for overweight subjects. Our results confirm the results of reported studies (Gravante et al., 2003; Hennig and Milani, 1993).

Examination of the whole sample by multiple regression analysis determined body weight as a predictor for \( \Delta \)Dyn of HW, MW, AH, and AA. Within the longitudinal arch, dynamic changes are more pronounced whereas values of AH and HW decrease with increasing weight. The smaller differences during stance phase can be explained by non-linear deformation of the fat pad. More compression does not mean that the fat pad deforms at a same level (Nass et al., 1999).

We can say that body weight and also BMI influence dynamic foot measures. It is not visible if differences in \( \Delta \)Dyn of foot measures between overweight and normal weight subjects relate to reported differences in static foot morphology. These static differences are obvious for children: feet of overweight children are more voluminous, more flat and robust (Mickle et al., 2006b; Mauch et al., 2008). We also found more pronounced changes of MBL and BW during stance phase in subjects with higher BMI levels. With increasing body weight the changes in MW do also increase. One reason for this is the
thicker fat pads in overweight subjects as Nass et al. detected (Nass et al., 1999).

6.4.3 Influence of age on dynamic foot shape

Differences of dynamic foot morphology in older subjects have not been analysed before. We found that MaxDyn of HW is higher in older subjects. In literature, findings regarding age-related influences are controversial (Menz and Morris, 2006; Mickle et al., 2010). Menz and Morris find only marginal influences of age. Their conclusion was that body weight is a more important influencing factor (Menz and Morris, 2006). We confirm their results. Our analysis of the whole sample size shows that age has no predicting contribution on the variance for MaxDyn of any foot measure.

Other studies assume that feet in elderly persons show less changes in dynamic situations because of their more pronounced stiffness (Hsu et al., 1998; Wearing et al., 2006). Our results do not confirm this conclusion. We found no influence of age on the magnitude of changes within the whole sample size. The only difference could be found for \( \Delta \text{Dyn} \) of BA, where older subjects showed higher values. The reason for these marginal differences between the two age groups may be the comparatively low mean age of 57.6 ±5.6 years in the group of older subjects. Age-related differences of foot morphology are already reported at the age of 30 years and it is assumed that it is a progressive development (Staheli et al., 1987). Therefore, the differences in dynamic foot morphology should be more obvious with increasing age. However, this must be assessed in future studies with subjects at older ages.

6.4.4 Conclusions

We found statistically significant influences in dynamic situations within different foot measures. These differences are most obvious for the variable BMI as well as body weight and in parts for the variable gender. The chosen statistics help to identify these influences. Furthermore, these findings can help last designers and shoe manufacturers. The maximum values during loaded situations of the roll-over process can be best predicted by static values. Therefore, customisation of footwear is still important and for this reason static values can be consulted. In addition, adjustments to dynamic situations must be carried out. The improvements for better-fitting shoes in dynamic situations can be achieved by consideration of changes during stance phase (\( \Delta \text{Dyn} \)). These changes depend on each foot measure and the main predictors for these changes are body weight.
and body height as well as gender for BW. How these improvements can be realised is the subject of future work, which has to consider the differences between static and dynamic foot morphology.

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Schmeltzpfenning, T., et al., 2009. Dynamic foot scanning: A new approach for mea-
6.4 Discussion


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Research Paper II

Differences between static and dynamic foot morphology in developing feet

**Summary:** The differences between static and dynamic foot morphology in developing feet have not been evaluated before. The literature overview points out that relevant difference can be expected. Furthermore, these differences are important to improve the dynamic fit of footwear, which contributes to a physiological development of feet. The following original article examines hypothesis 2, and beyond that, it focusses on the relevance of these differences for footwear construction.

**Published in:** Ergonomics (in press)
7 Foot deformation during walking: Differences between static and dynamic 3D foot morphology in developing feet

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(Received April 6, 2013; accepted February 15, 2014)

\textbf{Abstract}

The complex functions of feet require a specific composition which is progressively achieved by developmental processes. This development should take place without being affected by footwear. The aim of this study is to evaluate differences between static and dynamic foot morphology in developing feet. Feet of 2554 participants (6-16 years) were recorded using a new scanner system (DynaScan4D). Each foot was recorded in static half and full weight-bearing and during walking. Several foot measures corresponding to those used in last construction were calculated. The differences were identified by one-way ANOVA and paired Student’s t-test. Static and dynamic values of each foot measure must be considered to improve the fit of footwear. In particular footwear must account for the increase of forefoot width and the decrease of midfoot girth. Furthermore, the toe box should have a more rounded shape. The findings are important for the construction of footwear for developing feet.
Practitioner Summary

Until now, foot deformation has not been analysed in developing feet. The presented differences between standing and walking of 2554 children were obtained using a new dynamic 3D scanner system. The results show that especially differences between foot width and girth measures and angles must be considered in footwear construction.

Keywords: children, anthropometry, healthcare ergonomics, industrial ergonomics, biomechanics

7.1 Introduction

The foot is a complex organ that has to fulfil three essential functions: First, it has to carry body weight with appropriate stability. Thus it must be rigid. Second, the foot must interact with all ground conditions. Therefore, it must be flexible. Third, the foot has to support the balance between static and dynamic tasks during movement. This means that it has to act as a spring to compensate influencing forces and as a lever to support the movement of the body (Rodgers 1995). These complex functions require a specific composition of the foot, which is progressively achieved by different developmental processes. These processes start prenatally and continue until late adolescence (Maier and Killmann 2003; Walther et al. 2005). Therefore, it is wrong to treat children’s and adults’ feet equally. There are numerous differences comprising foot shape, proportion, and size, as well as structural and functional characteristics (Maier and Killmann 2003). The development of a foot includes ossification of bones as well as a reduction of the flexibility of tendons, ligaments, and joint capsules by increased inclusion of proteoglycans and crosslinks of collagens (Maier and Killmann 2003; Walther et al. 2005). Foot development continues after the foot has reached its final length at the age of 12-13 years in girls and 13-15 years in boys (Cheng et al. 1997; Mauch 2007; Stavlas et al. 2005).

The well-regulated and coordinated developmental processes of the foot are open programs that are prone to be affected by negative external influences (DiMeglio 2001; Maier and Killmann 2003). Shoes are one external influence which should not be negative. Various effects of shoes have been reported, ranging from differences during the roll-over process between barefoot walking and walking with shoes and reduced flexibility of the
7.1 Introduction

Foot up to serious deformities like hallux valgus, hammer toes, or flat feet (González et al. 2005; Klein et al. 2009; Rao and Joseph 1992; Staheli 1991; Wolf et al. 2008b).

Staheli (1991) has concluded that the best guideline for children's shoes is the foot without a shoe. Following this recommendation, several studies used anatomical foot measures to improve last design (Krauss et al. 2008; Mauch et al. 2009). For example, Mauch et al. (2009) developed a method to categorize children's feet to embrace their natural variability. A comprehensive study by Cheng et al. (1997) compared the static foot morphology of 2829 Chinese children in loaded and unloaded static situation. The differences between unloaded and loaded foot length and width were 2.5-3.4 mm and 2.1-4.4 mm, respectively. However, there is still a lack of information about dynamic changes during walking. These changes are essential for the construction of well-fitting shoes and thus the physiological development of the foot.

Guidelines for footwear construction should also consider dynamic information about the foot (Kouchi, Kimura and Mochimaru 2009; Mauch et al. 2009). In parts, this information has been obtained by methods based on markers, goniometers, plantar pressure analysis or interpretation of imprints (Alvarez et al. 2008; Bosch, Gress and Rosenbaum 2007; Hennig and Rosenbaum 1991; Maier and Killmann 2003). These methods bear limitations in terms of the partial view on the foot morphology and therefore have limited applicability.

Children's three-dimensional (3D) foot deformation during natural walking has not been evaluated before due to previous deficits in scanner technology. Advancements in 3D scanner systems allow recording the foot during walking (Coudert et al. 2006; Kimura, Mochimaru and Kanade 2009; Schmeltzpfenning et al. 2009; Wang et al. 2006). Existing work only focusses on the feasibility of these systems as well as their potentials and limitations. In order to evaluate the systems, small sample sizes have been used (Kimura, Mochimaru and Kanade 2009; Wang et al. 2006). This is sufficient to evaluate the system but not to obtain significant results on foot changes. Furthermore, no study has examined dynamic 3D foot deformation in children and adolescents.

The aim of the present study is to identify differences between loaded static and dynamic 3D foot morphology for the developing feet of children aged between 6 and 16 years. To achieve this aim, the feet of more than 2000 children and adolescents were recorded and the results were evaluated with respect to their relevance for last construction. The relevance of the results was assessed by putting the increments of shoe grading
in contrast to the obtained foot measures. The error of the system was determined by calculating the Root Mean Square Error (RMSE). These findings are important for last construction and can help improve footwear fit for developing feet. Well-fitting shoes for children and adolescents are important to ensure normal and physiological development of feet, which is significant for the whole body.

7.2 Methods

7.2.1 Participants

This study was approved by the ethics committee of the medical clinic of Tübingen. Data acquisition took place in the southern part of Germany, between April 2010 and December 2011, with collaboration of 15 different schools. Parents and children received written information about the aim and content of the study prior to data acquisition. All children and adolescents in this experiment voluntarily participated and had written consent of one parent. Exclusion criteria comprised injuries or diseases of the lower extremities that influence normal gait. The foot measures of 1285 female and 1269 male children and adolescents (51% female; 49% male), aged between 6 and 16 years with an average age of 10.6 ± 2.5 years, were analysed. The data from both genders were merged as there is no influence of gender on the foot deformation of developing feet (Barisch-Fritz et al., 2013). This is in contrast to the influence of gender on the plantar pressure distribution (Chung and Wang, 2012) and the static foot shape (Hong et al., 2013). The secondary measurements, body weight and body height, were carried out without shoes in lightweight clothing. Body mass index was calculated (weight [kg]/height [m²]) and normalized to German reference data (Kromeyer-Hauschild et al. 2001) to attain gender and age-specific BMI percentiles. The mean percentile of the entire sample was 52.2 ± 29.0 (see Table 7.1).

One foot per participant was captured and analysed using DynaScan4D. In previous studies, no statistically significant or practically relevant differences between the data of right and left feet have been found. Thus, the foot to be measured was randomly determined as recommended by Menz (2004). Foot morphology was captured in static and dynamic situations. Each participant conducted one static trial with full weight-bearing (FBW) and one with half weight-bearing (HWB). For FWB, participants had to stand on the defined foot and had to look straight ahead. To ensure static stance,
7.2 Methods

Table 7.1: Characteristics of the participants. Mean and standard deviation of anthropometric variables for the whole sample as well as different age groups.

<table>
<thead>
<tr>
<th>Age [years]</th>
<th>N</th>
<th>Gender</th>
<th>Body Height [m]</th>
<th>Body Weight [kg]</th>
<th>BMI-Percentile</th>
<th>Shoe Size [French Scale]</th>
<th>Foot Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 - 7</td>
<td>343</td>
<td>F: 156</td>
<td>1.23 ± 0.06</td>
<td>24.4 ± 4.7</td>
<td>52.0 ± 27.3</td>
<td>32 ± 2</td>
<td>197.7 ± 11.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 187</td>
<td>±4.7</td>
<td>±27.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 - 10</td>
<td>920</td>
<td>F: 468</td>
<td>1.36 ± 0.08</td>
<td>31.9 ± 7.1</td>
<td>52.5 ± 28.6</td>
<td>35 ± 2</td>
<td>217.1 ± 17.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 452</td>
<td>±7.1</td>
<td>±28.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 - 13</td>
<td>943</td>
<td>F: 480</td>
<td>1.53 ± 0.09</td>
<td>44.2 ± 11.3</td>
<td>51.8 ± 30.1</td>
<td>39 ± 2</td>
<td>240.9 ± 17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 463</td>
<td>±11.3</td>
<td>±30.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 - 16</td>
<td>348</td>
<td>F: 181</td>
<td>1.66 ± 0.09</td>
<td>57.3 ± 12.5</td>
<td>53.0 ± 28.7</td>
<td>41 ± 3</td>
<td>254.9 ± 16.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 167</td>
<td>±12.5</td>
<td>±28.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 - 16</td>
<td>2554</td>
<td>F: 1285</td>
<td>1.45 ± 0.16</td>
<td>38.9 ± 13.9</td>
<td>52.2 ± 29.0</td>
<td>37 ± 4</td>
<td>228.3 ± 24.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 1269</td>
<td>±13.9</td>
<td>±29.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F = female; M = male

Subjects were allowed to grip the handrails of the scanner walkway without shoring up while lifting the other foot backwards. The HWB condition was achieved by asking the participants to stand on both feet. The children and adolescents had to flex and subsequently extend their knees to ensure equally distributed weight on both feet.

Dynamic foot morphology was recorded during natural barefoot walking. The participants were asked to walk over a 4.6 m long walkway with the mounted scanner system. They had time to get used to the scanner setup and to the walking task by completing several training walks. During the training walks, the starting point was varied until the children were able to tread centrally on the measuring field. Walking speed was predefined and monitored. The reason for predefining walking speed is to consider the effects of factors such as body height and age as well as contact time and functionality (Sutherland 1997; Wheelwright et al. 1993). Furthermore, it could minimize the step-to-step variability. In reference to the indicated comfortable walking speed of adults normalised to body height (Bohannon 1997), we developed a scale for children. The foundation of the presented ranges of the walking speed (see Table 7.2) was the index of 0.78 (comfortable walking speed normalised to body height) according to Bohannon (1997). Three valid trials were recorded per participant.
Differences between static and dynamic 3D foot morphology in developing feet

Table 7.2: Walking speed adjusted to body height

<table>
<thead>
<tr>
<th>Body Height [cm]</th>
<th>Walking Speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 110.0</td>
<td>0.78 – 0.86</td>
</tr>
<tr>
<td>110.0 – 119.9</td>
<td>0.83 – 0.94</td>
</tr>
<tr>
<td>120.0 – 129.9</td>
<td>0.92 – 1.03</td>
</tr>
<tr>
<td>130.0 – 139.9</td>
<td>1.00 – 1.11</td>
</tr>
<tr>
<td>140.0 – 149.9</td>
<td>1.06 – 1.17</td>
</tr>
<tr>
<td>150.0 – 159.9</td>
<td>1.14 – 1.25</td>
</tr>
<tr>
<td>160.0 – 169.9</td>
<td>1.22 – 1.33</td>
</tr>
<tr>
<td>170.0 – 179.9</td>
<td>1.28 – 1.42</td>
</tr>
<tr>
<td>≥ 180.0</td>
<td>1.36 – 1.50</td>
</tr>
</tbody>
</table>

The final sample sizes ranged from 2017 to 2047 participants, depending on each foot measure. Reasons for excluding participants were insufficient quality of scan data due to challenges in the alignment of the shutter time as well as technical problems during saving processes and trigger functions. Other problems were caused by the high sensitivity of the scanner system to ambient light or deficits in adjusting to darker or unsteady coloured skin types. The HWB and FWB scans of each participant were matched to the mean of the three dynamic trials. Missing trials were the reason for further dropouts.

7.2.2 Measurement system and data processing

The scanner system, DynaScan4D, was used within this study to capture images of the foot during standing and natural walking. This scanner system has been developed at the University of Tübingen (Schmeltzpfenning et al. 2009). It is based on the principle of full-field triangulation by structured light projection with five scanner units (zSnapper®, ViALUX GmbH, Germany). The DynaScan4D has a measurement frequency of 46 Hz and a resolution of 640 x 480. Reducing resolution to a 4x4 binning mode allows the high frequency. The measurement volume is about 55 cm length, 35 cm width, and 25 cm height. The five scanner units are calibrated to each other to guarantee that the captured images of each unit can be merged in a single coordinate system. The accuracy of the system comprises 0.23 mm in static full resolution and 0.89 mm in dynamic 4x4 binning mode with a velocity of 0.8 m/s. This has been evaluated by recording a bowling
ball (circumference 32.25 mm) in static and dynamic situations. For more details on the hardware of the scanner system, it is referred to Schmeltzpfenning et al. (2009; 2010).

A strain gauge was used to trigger the recording of the roll-over process and light detectors to measure the walking speed of the participants. The room with the scanner system was darkened and synthetic light was used to produce constant illumination conditions.

The DynaScan4D is operated using a self-developed software program which automates the scanning process and the post-processing of the recorded data. The latter includes the alignment of the foot scans to the x-axis, which is the connecting line between the most medial point of the heel and of the first metatarsal head (MTH 1). In collaboration with last designers, typical measures that are used in last construction were identified (Mitchell et al. 1995). The identified girth measures in this study comply with those taken on lasts. The location of each girth measure depends on the shoe size and was defined according to a last marking device (Behrens, Alfeld, Germany). This device provides the distance relative to the heel where the girth has to be measured for each shoe size. With these measures, the transfer from research to implementation could be simplified. The foot measures are defined in Figure 7.1 and Table 7.3. All foot measures were calculated for each static scan as well as for each frame of dynamic scans.
Differences between static and dynamic 3D foot morphology in developing feet

Figure 7.1: Illustration of analysed foot measures (see Table 7.3 for the descriptions of the foot measures)
<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>Description</th>
<th>Measurement Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-H</td>
<td>Instep Height</td>
<td>Highest point of the foot at 50 % of foot length.</td>
</tr>
<tr>
<td>B-H</td>
<td>Ball Height</td>
<td>Highest point of the foot at 61.8 % (a.k.a. golden ratio) of foot length.</td>
</tr>
<tr>
<td>Foot Length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F-L</td>
<td>Foot Length</td>
<td>Distance between most posterior point of the heel and foremost point of the longest toe parallel to the x-axis.</td>
</tr>
<tr>
<td>M-BL</td>
<td>Medial Ball Length</td>
<td>Distance between most posterior point of the heel and most medial point of MTH1 parallel to the x-axis.</td>
</tr>
<tr>
<td>LB-L</td>
<td>Lateral Ball Length</td>
<td>Distance between most posterior point of the heel and most lateral point of MTH5 parallel to the x-axis.</td>
</tr>
<tr>
<td>Foot Width</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB-W</td>
<td>Anatomical Ball Width</td>
<td>Distance between most medial point of MTH1 and most lateral point of MTH5.</td>
</tr>
<tr>
<td>OB-W</td>
<td>Orthogonal Ball Width</td>
<td>Distance between most lateral and medial point of the forefoot measured orthogonally to the x-axis.</td>
</tr>
<tr>
<td>OH-W</td>
<td>Orthogonal Heel Width</td>
<td>Distance between most lateral and medial point of the heel measured orthogonally to the x-axis between 14-20 % of foot length.</td>
</tr>
<tr>
<td>Foot Girth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB-G</td>
<td>Anatomical Ball Girth</td>
<td>Girth around the anatomical landmarks MTH 1 and MTH5 (vertical to the standing surface).</td>
</tr>
<tr>
<td>LB-G</td>
<td>Last Ball Girth</td>
<td>Girth around the first point detected on the last at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
</tr>
<tr>
<td>LW-G</td>
<td>Last Waist Girth</td>
<td>Girth around the second point detected on the last at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
</tr>
<tr>
<td>LI-G</td>
<td>Last Instep Girth</td>
<td>Girth around the third point detected on the last at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
</tr>
<tr>
<td>Angles of the Foot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-A</td>
<td>Ball Angle</td>
<td>Angle between the connecting line of MTH1 and MTH5 and the x-axis.</td>
</tr>
<tr>
<td>T1-A</td>
<td>Toe1 Angle</td>
<td>Angle between the x-axis and the connecting line of most medial points of Toe 1 and MTH 1.</td>
</tr>
<tr>
<td>T5-A</td>
<td>Toe5 Angle</td>
<td>Angle between the connecting line of most lateral points of the heel and MTH 5 and the connecting line of most lateral points of Toe 5 and MTH 5.</td>
</tr>
</tbody>
</table>

Foot measures are illustrated in Figure 7.1.
As a result of the markerless scanning, the anatomical landmarks of first (MTH1) and fifth metatarsal heads (MTH5) were visually detected as the most medial or lateral points judging from the x-axis. All landmarks were determined by one operator, similar to Yamazaki et al. (2013) who defined anatomical landmarks on their dynamic model. The visual detection of anatomical landmarks entails some bias, but eliminates the disadvantage of moving soft tissue. The resulting error was calculated in this study design and used for discussing the relevance of the results.

The maximum of each foot measure is called MaxDyn. To realize the comparability of MaxDyn values, it was necessary to extract MaxDyn for each foot measure within a specified measurement phase. Furthermore, MaxDyn of each foot measure is relevant within a specific measurement phase. A measurement phase is relevant when most load is expected due to shifting body weight over the respective foot area (Gefen et al. 2000). The measurement phases were defined by characteristic instants according to Blanc et al. (1999). These characteristic instants were visually detected for each sequence of frames of the roll-over process (see Figure 7.2). Heel strike was defined as the instant when 70% of the heel surface had contact with the ground (Heel Strike). This threshold was visually detected from a plantar perspective. The same was defined for the contact of the MTHs (MTH1 Strike). This instant was standardized as the contact of MTH1 and MTH5 with the ground. Additionally, the instant when the toes hit the ground (Toes Strike) was determined. The instants of the take-off of the heel (Heel Off) and the MTHs (MTH1 Off) were defined as the instants where the heel and the MTHs were no longer in contact with the ground. Table 7.3 presents the measurement phase for each foot measure.

7.2.3 Statistical analysis

All foot measures were tested for normality by the Shapiro-Wilk Test (Shapiro and Wilk 1965). Foot length, width, height, and girth measures were normalized to the respective foot length (F-L). To test the differences between loaded static and dynamic foot measures, a one-way ANOVA with paired Students’ t-test was calculated. The level of significance was adjusted by Bonferroni correction (Bland and Altman 1995). As no relevant influence of gender, age, or body mass on the differences between static and dynamic foot morphology was found (Barisch-Fritz et al., 2013), the results of the foot measures normalized to F-L were merged.
Figure 7.2: Sequence of 30 frames of a standard dynamic foot scan
The repeatability of the procedure to calculate the foot measures was analysed to determine the error. This was in particular important for foot measures dependent on the visually detected landmarks MTH1 and MTH5. The visual detection of the anatomical landmarks and the calculation of the foot measures were conducted twice within a smaller sample of n=33 participants. Intra-tester reproducibility was calculated by intraclass correlation coefficient (ICC) as well as root mean squared error (RMSE) (Perini et al. 2005; Shrout and Fleiss 1979). The RMSE, also known as technical error of measurement, is a statistical indicator for the variance caused by error (Perini et al. 2005). It allows to better estimate the relevant differences compared to ICC because of the representation of absolute values in the same measurement unit. The statistical analyses were performed using JMP version 9.0.2 (SAS, Cary, USA) as well as SPSS version 20 (SPSS Inc. Chicago, IL, USA).

7.3 Results

7.3.1 Differences between static and dynamic foot measures

Table 7.4 presents mean values and standard deviations of absolute and relative foot measures and also F-ratios and p-values of each foot measure obtained by one-way ANOVA. The differences between the three situations HWB, FWB, and MaxDyn of absolute and relative foot measures indicated statistically significant differences, except for absolute F-L.
Table 7.4: Absolute and relative foot measures. The results of one-way ANOVA with comparison of HWB, FWB, and MaxDyn by paired Student’s t-test

<table>
<thead>
<tr>
<th>Absolute Foot Measure</th>
<th>N</th>
<th>HWB Mean ± SD</th>
<th>FWB Mean ± SD</th>
<th>MaxDyn Mean ± SD</th>
<th>One-way ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-H [mm]</td>
<td>2032</td>
<td>55.9 ± 6.2</td>
<td>56.1 ± 6.1</td>
<td>59.8 ± 6.9</td>
<td>220.8</td>
</tr>
<tr>
<td>B-H [mm]</td>
<td>2056</td>
<td>44.1 ± 4.6</td>
<td>44.2 ± 4.6</td>
<td>45.6 ± 4.9</td>
<td>65.5</td>
</tr>
<tr>
<td>F-L [mm]</td>
<td>1655</td>
<td>227.2 ± 21.9</td>
<td>227.1 ± 22.0</td>
<td>226.1 ± 22.1</td>
<td>1.3</td>
</tr>
<tr>
<td>MB-L [mm]</td>
<td>2036</td>
<td>165.2 ± 16.1</td>
<td>165.0 ± 16.0</td>
<td>166.6 ± 16.2</td>
<td>6.0</td>
</tr>
<tr>
<td>LB-L [mm]</td>
<td>2017</td>
<td>139.2 ± 13.0</td>
<td>138.5 ± 13.1</td>
<td>140.4 ± 13.1</td>
<td>10.6</td>
</tr>
<tr>
<td>AB-W [mm]</td>
<td>2047</td>
<td>88.7 ± 8.8</td>
<td>89.3 ± 8.8</td>
<td>90.1 ± 8.9</td>
<td>11.9</td>
</tr>
<tr>
<td>OB-W [mm]</td>
<td>2047</td>
<td>85.8 ± 7.9</td>
<td>86.3 ± 7.9</td>
<td>87.7 ± 8.0</td>
<td>30.3</td>
</tr>
<tr>
<td>OH-W [mm]</td>
<td>2047</td>
<td>59.6 ± 5.7</td>
<td>59.5 ± 5.8</td>
<td>60.0 ± 6.2</td>
<td>4.7</td>
</tr>
<tr>
<td>AB-G [% F-L]</td>
<td>2034</td>
<td>215.3 ± 20.6</td>
<td>216.3 ± 20.7</td>
<td>212.8 ± 20.8</td>
<td>14.7</td>
</tr>
<tr>
<td>LB-G [mm]</td>
<td>2032</td>
<td>206.4 ± 18.6</td>
<td>207.7 ± 18.7</td>
<td>202.3 ± 19.1</td>
<td>45.5</td>
</tr>
<tr>
<td>LW-G [mm]</td>
<td>2032</td>
<td>207.4 ± 19.4</td>
<td>208.1 ± 19.3</td>
<td>203.5 ± 19.6</td>
<td>32.5</td>
</tr>
<tr>
<td>LI-G [mm]</td>
<td>2031</td>
<td>214.8 ± 20.4</td>
<td>215.0 ± 20.4</td>
<td>211.4 ± 20.4</td>
<td>19.9</td>
</tr>
<tr>
<td>B-A [']</td>
<td>2033</td>
<td>73.1 ± 3.1</td>
<td>72.7 ± 3.0</td>
<td>74.6 ± 3.3</td>
<td>189.7</td>
</tr>
<tr>
<td>T1-A [']</td>
<td>2051</td>
<td>3.9 ± 4.9</td>
<td>3.6 ± 4.9</td>
<td>7.5 ± 5.0</td>
<td>506.0</td>
</tr>
<tr>
<td>TS-A [']</td>
<td>2051</td>
<td>9.6 ± 4.8</td>
<td>10.0 ± 4.7</td>
<td>11.6 ± 4.9</td>
<td>130.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Foot Measure</th>
<th>N</th>
<th>HWB Mean ± SD</th>
<th>FWB Mean ± SD</th>
<th>MaxDyn Mean ± SD</th>
<th>One-way ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-H [% F-L]</td>
<td>2032</td>
<td>24.6 ± 1.8</td>
<td>24.8 ± 1.8</td>
<td>26.4 ± 2.5</td>
<td>424.8</td>
</tr>
<tr>
<td>B-H [% F-L]</td>
<td>2056</td>
<td>19.5 ± 1.4</td>
<td>19.6 ± 1.4</td>
<td>20.1 ± 1.5</td>
<td>132.3</td>
</tr>
<tr>
<td>MB-L [% F-L]</td>
<td>2036</td>
<td>72.7 ± 1.4</td>
<td>72.7 ± 1.4</td>
<td>73.3 ± 1.5</td>
<td>144.6</td>
</tr>
<tr>
<td>LB-L [% F-L]</td>
<td>2017</td>
<td>61.4 ± 2.1</td>
<td>61.1 ± 2.2</td>
<td>62.0 ± 2.2</td>
<td>79.8</td>
</tr>
<tr>
<td>AB-W [% F-L]</td>
<td>2047</td>
<td>39.1 ± 2.0</td>
<td>37.4 ± 2.0</td>
<td>39.7 ± 2.1</td>
<td>44.7</td>
</tr>
<tr>
<td>OB-W [% F-L]</td>
<td>2047</td>
<td>37.9 ± 1.9</td>
<td>38.1 ± 2.0</td>
<td>38.7 ± 2.1</td>
<td>96.8</td>
</tr>
<tr>
<td>OH-W [% F-L]</td>
<td>2047</td>
<td>26.4 ± 1.8</td>
<td>26.3 ± 1.8</td>
<td>26.5 ± 1.9</td>
<td>8.6</td>
</tr>
<tr>
<td>AB-G [% F-L]</td>
<td>2034</td>
<td>90.6 ± 4.5</td>
<td>95.4 ± 4.5</td>
<td>93.9 ± 4.7</td>
<td>59.0</td>
</tr>
<tr>
<td>LB-G [% F-L]</td>
<td>2032</td>
<td>91.2 ± 4.4</td>
<td>91.8 ± 4.4</td>
<td>89.3 ± 4.6</td>
<td>159.5</td>
</tr>
<tr>
<td>LW-G [% F-L]</td>
<td>2032</td>
<td>91.7 ± 4.7</td>
<td>92.0 ± 4.7</td>
<td>89.9 ± 4.9</td>
<td>105.5</td>
</tr>
<tr>
<td>LI-G [% F-L]</td>
<td>2031</td>
<td>94.9 ± 4.5</td>
<td>95.0 ± 4.5</td>
<td>93.4 ± 4.8</td>
<td>76.4</td>
</tr>
</tbody>
</table>

Abbreviations of foot measures see Table 7.1 and Table 7.3: HWB = half weight-bearing; FWB = full weight-bearing; MaxDyn = maximum during walking; SD = standard deviation; DF = degrees of freedom; p-value = result of paired Student’s t-test
7 Differences between static and dynamic 3D foot morphology in developing feet

The mean differences and confidence intervals (CI) with Bonferroni correction for the relative foot length, width, height, and girth measures and the absolute foot angles are presented in Table 5. The differences between the two static situations HWB and FWB were statistically significant for instep height (I-H), lateral ball length (LB-L), anatomical ball width (AB-W), orthogonal ball width (OB-W), anatomical ball girth (AB-G), last ball girth (LB-G), ball angle (B-A), and toe 5 angle (T5-A). The mean differences for the relative foot measures ranged from 0.2 to 0.6% of F-L. A negative significant difference of -0.3% of F-L was found for LB-L. The difference between HWB and FWB of ball height (B-H), medial ball length (MB-L), orthogonal heel width (OH-W), last waist girth (LW-G), last instep girth (LI-G), and toe 1 angle (T1-A) were not statistically significant.

The differences between MaxDyn and HWB, and MaxDyn and FWB of all relative foot measures and all absolute foot angles were statistically significant. The differences for length, width, and height measures between MaxDyn and HWB were positively ranging from 0.2 to 1.7% of F-L. Smallest mean differences were found for OH-W (0.2% FL), followed by LB-L (0.5% FL), AB-W (0.6% FL), MB-L (0.7% FL), B-H (0.7% FL) and OB-W (0.8% FL). The highest mean difference was found for I-H (1.7% FL). The mean differences of foot girth measures featured negative values of -1.9% (LB-G), -1.7% (LW-G), -1.5% (LI-G), and -1.1% of F-L (AB-G).

The differences between MaxDyn and FWB were similar to the differences between MaxDyn and HWB. Mean differences of foot length, width, and height measures were positively ranging from 0.2 to 1.6% of F-L. The smallest mean difference was also found for OH-W and the highest for I-H. Negative differences, in the same order of the differences between MaxDyn and HWB, were found for all foot girth measures ranging from -2.4 to -1.5% of F-L.

The differences for absolute T1-A and T5-A were 3.9° and 2.2° for MaxDyn-HWB, and 4.2° and 1.8° for MaxDyn-FWB, respectively. The differences in B-A were 1.5° for MaxDyn-HWB and 1.8° for MaxDyn-FWB.
<table>
<thead>
<tr>
<th>Foot Measure</th>
<th>N</th>
<th>FWB-HWB</th>
<th>MaxDyn-HWB</th>
<th>MaxDyn-FWB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Difference</td>
<td>CI</td>
<td>p-value</td>
<td>Mean Difference</td>
</tr>
<tr>
<td>I-H [% F-L]</td>
<td>2032</td>
<td>0.2</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>B-H [% F-L]</td>
<td>2056</td>
<td>0.1</td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>MB-L [% F-L]</td>
<td>2036</td>
<td>-0.1</td>
<td>-0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>LB-L [% F-L]</td>
<td>2017</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.2</td>
</tr>
<tr>
<td>AB-W [% F-L]</td>
<td>2047</td>
<td>0.3</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>OB-W [% F-L]</td>
<td>2047</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>OH-W [% F-L]</td>
<td>2047</td>
<td>-0.1</td>
<td>-0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>AB-G [% F-L]</td>
<td>2034</td>
<td>0.4</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>LB-G [% F-L]</td>
<td>2032</td>
<td>0.6</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>LW-G [% F-L]</td>
<td>2032</td>
<td>0.3</td>
<td>-0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>LI-G [% F-L]</td>
<td>2031</td>
<td>0.1</td>
<td>-0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>B-A [°]</td>
<td>2033</td>
<td>-0.3</td>
<td>-0.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>T1-A [°]</td>
<td>2051</td>
<td>-0.3</td>
<td>-0.7</td>
<td>-0.1</td>
</tr>
<tr>
<td>T5-A [°]</td>
<td>2051</td>
<td>0.4</td>
<td>0.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Abbreviations of foot measures see Figure 7.1 and Table 7.3: HWB = half weight-bearing; FWB = full weight-bearing; MaxDyn = maximum during walking; CI = confidence interval with Bonferroni correction; p-value = result of paired Students’ t-test.
7.3.2 Repeatability of measurements

The repeatability of all foot measures is shown in Table 7.6. The ICC values of all automatically analysed foot measures were close to one. There were no differences between values of ICC analysed in static or dynamic situations. The ICC values of all foot measures depending on the anatomical landmarks MTH1 and MTH5 (MB-L, LB-L, AB-W, AG-W, B-A, T1-A, T5-A) deviated from one. Smallest values were found for B-A in FWB 0.710 with a 95% confidence interval of 0.484-0.847.

Values of RMSE were close to zero for all measures not depending on manually detected MTH1 and MTH5. Measures based on the anatomical landmarks showed RMSE values deviant from zero. Values of MB-L ranged from 1.8 mm (FWB) to 2.3 mm (MaxDyn), and for LB-L from 1.9 mm (MaxDyn) to 2.4 mm in FWB. RMSE values of the angles B-A, T1-A, and T5-A ranged from 0.4° (T1-A, HWB) to 2.4° (T1-A, MaxDyn).
Table 7.6: Intra-tester reliability of the calculation of the foot measures (including measures based on the visually detected anatomical landmarks MTH1 and MTH5). Supplemented by the absolute differences between MaxDyn and static HWB and the half increments based on shoe grading (French Scale).

<table>
<thead>
<tr>
<th>Foot Measure</th>
<th>HWB</th>
<th></th>
<th></th>
<th></th>
<th>FWB</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>MaxDyn [mean of 3 trials]</th>
<th>MaxDyn - HWB Mean ± SD</th>
<th>Half increment French Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>ICC</td>
<td>95 % CI</td>
<td>RMSE</td>
<td>N</td>
<td>ICC</td>
<td>95 % CI</td>
<td>RMSE</td>
<td>N</td>
<td>ICC</td>
<td>95 % CI</td>
<td>RMSE</td>
</tr>
<tr>
<td>T1-A</td>
<td>32</td>
<td>0.992</td>
<td>0.996</td>
<td>0.4°</td>
<td>32</td>
<td>0.964</td>
<td>0.978</td>
<td>1°</td>
<td>26</td>
<td>0.987</td>
<td>0.994</td>
<td>2.4°</td>
</tr>
<tr>
<td>T5-A</td>
<td>32</td>
<td>0.987</td>
<td>0.994</td>
<td>0.5°</td>
<td>32</td>
<td>0.959</td>
<td>0.980</td>
<td>0.9°</td>
<td>26</td>
<td>0.965</td>
<td>0.984</td>
<td>1.1°</td>
</tr>
<tr>
<td>I-H</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>0.999</td>
</tr>
<tr>
<td>B-H</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>0.998</td>
</tr>
<tr>
<td>F-L</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>M1-B</td>
<td>32</td>
<td>0.978</td>
<td>0.986</td>
<td>0.989</td>
<td>2.3 mm</td>
<td>32</td>
<td>0.995</td>
<td>0.990</td>
<td>0.998</td>
<td>1.8 mm</td>
<td>26</td>
<td>0.992</td>
</tr>
<tr>
<td>L1-B</td>
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<td>0.979</td>
<td>0.997</td>
<td>0.990</td>
<td>2.0 mm</td>
<td>32</td>
<td>0.955</td>
<td>0.911</td>
<td>0.978</td>
<td>2.4 mm</td>
<td>26</td>
<td>0.993</td>
</tr>
<tr>
<td>A1-W</td>
<td>32</td>
<td>0.996</td>
<td>0.991</td>
<td>0.998</td>
<td>0.6 mm</td>
<td>32</td>
<td>0.989</td>
<td>0.978</td>
<td>0.995</td>
<td>0.9 mm</td>
<td>26</td>
<td>0.996</td>
</tr>
<tr>
<td>O1-W</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>O2-W</td>
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<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>A1-B</td>
<td>32</td>
<td>0.997</td>
<td>0.994</td>
<td>0.999</td>
<td>1.1 mm</td>
<td>32</td>
<td>0.994</td>
<td>0.988</td>
<td>0.997</td>
<td>1.6 mm</td>
<td>26</td>
<td>0.997</td>
</tr>
<tr>
<td>L1-B</td>
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<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>L1-W</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>L1-G</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>32</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0 mm</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>B-A</td>
<td>32</td>
<td>0.837</td>
<td>0.695</td>
<td>0.916</td>
<td>1.7°</td>
<td>32</td>
<td>0.710</td>
<td>0.484</td>
<td>0.847</td>
<td>2.0°</td>
<td>26</td>
<td>0.814</td>
</tr>
<tr>
<td>T1-A</td>
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<td>0.993</td>
<td>0.996</td>
<td>0.4°</td>
<td>32</td>
<td>0.956</td>
<td>0.912</td>
<td>0.978</td>
<td>1°</td>
<td>26</td>
<td>0.874</td>
</tr>
<tr>
<td>T5-A</td>
<td>32</td>
<td>0.987</td>
<td>0.974</td>
<td>0.994</td>
<td>0.5°</td>
<td>32</td>
<td>0.959</td>
<td>0.918</td>
<td>0.980</td>
<td>0.9°</td>
<td>26</td>
<td>0.965</td>
</tr>
</tbody>
</table>

Abbreviations of foot measures see Figure 7.1 and Table 7.3; HWB = half weight-bearing; FWB = full weight-bearing; MaxDyn = maximum during walking; ICC = intraclass correlation coefficient; CI = 95 % confidence interval; RMSE = Root Mean Square Error; SD = standard deviation; MaxDyn-HWB (mean and SD) is given for the whole group and can serve as a reference point to discuss the practical relevance.
7 Differences between static and dynamic 3D foot morphology in developing feet

7.4 Discussion

7.4.1 Static and dynamic differences

The aim of the present study was to identify differences between loaded static and dynamic foot morphology. The foot morphology, which was calculated for the three situations HWB, FWB and MaxDyn, was studied for a large sample size of developing feet. Results of one-way ANOVA showed that the differences between the three situations were statistically significant for all foot measures except for F-L. Regarding the comparison between static HWB as well as FWB and MaxDyn, it can be concluded that there are significant differences between static and dynamic foot morphology.

The practical relevance of the calculated differences was evaluated with respect to two main concerns. First, the increment from one shoe size to the next was put in relation to the differences between static and dynamic foot measures. The increment for shoe length comprises 6.66 mm of French Scale (Rossi and Tennant 2011). The difference of a half shoe size (3.33 mm of French Scale) is regarded as relevant difference for foot length measures. Relevant difference means that if the differences between static and dynamic situations of foot length measures exceed this value, the difference must be considered in footwear construction. From one shoe size to the next, the increment of the girth of a last is arithmetically graded by 5 mm in the French Scale (Joneja and Kit 2013). The relation of LB-G and OB-W is often specified as 60:40 (Maier and Killmann 2003). The same principle, that half of the increment is relevant, is applied to foot girth and width measures. Thus, a difference of 2.5 mm for girth measures and 1.0 mm for ball width is practically relevant (see Table 7.6).

Second, the relevance of the detected differences depends on the repeatability of the calculated foot measures (see Table 7.6). In this context, the RMSE of MaxDyn of the foot measures is important. It reflects errors due to visually detected landmarks. The differences between MaxDyn and HWB are considered as practically relevant if they exceed the values of RMSE of the foot measure.

In the present study, the differences between HWB and FWB were rather small for all foot measures. Furthermore, these differences were smaller than the values regarded as practically relevant. In the case of LB-G, the mean difference between HWB and FWB was 0.6 % of F-L. For a foot length of 225 mm the difference is 1.4 mm. According to the first concern, this difference is not practically relevant. This also holds for the other
foot measures (see Table 7.5 and Table 7.6).

All differences between MaxDyn and HWB, as well as FWB were statistically significant. The differences of F-L are demonstrated by MB-L and LB-L. MB-L is representative for the extension of the foot, as no extension from metatarsals ahead is expected (Cashmere, Smith and Hunt 1999; Schmeltzpfenning et al. 2009). The mean values of the differences between MaxDyn and HWB of MB-L and LB-L were smaller than the RMSE which means that the practical relevance is limited and must be carefully discussed. However, there is a tendency that MaxDyn of MB-L and LB-L exceed static loaded values. Based on the structural characteristics of the medial longitudinal arch, an extension of the foot was expected. The results showed this medial extension, as it has been reported before, from early stance phase to foot flat (Scott and Winter 1993). To the best of our knowledge, it has not been reported that LB-L increases during stance phase in a similar manner like MB-L. This result confirms the results of bone pin analyses, where considerable capacity for motion of the lateral arch has been found (Lundgren et al. 2008). At the same time, high standard deviations in both measures indicate strong individual variability. This is possibly caused by high individuality of gait and overall low reproducibility of children’s gait (Hausdorff et al. 1999). This may also interact with the weaker repeatability of this foot measure due to the dependency on visually detected landmarks.

The extension of the foot during walking was expected and has already been considered in footwear construction. Thus, the last has to be longer than the foot. This additional space primarily has to account for the extension of the foot. This extension was found for MB-L but was not visible regarding the entire foot length (F-L). The values of F-L showed small differences. However, the dynamic captured F-L may not represent the actual maximum during walking because of a shortened measurement phase. F-L was observed from Toes Strike to Heel Off, which was a very short phase in the case of several participants (see Figure 7.2). It can be assumed that most of body weight is already shifted to the forefoot when the toes touch the ground. Therefore, the actual maximum extension of F-L was not captured and thus not included in our considerations.

During walking, high forces and also peak pressure has been found beneath the heel of the foot (Rodgers 1995). These higher forces raise the expectations for a marked deformation of the heel width. The results of this study showed rather small differences between static and dynamic heel width. These findings are in line with cadaveric studies that have detected a non-linear viscoelastic behaviour (Wearing et al. 2009). This non-
linear viscoelastic behavior means that the soft tissue initially deforms to a significantly higher extent when force exerts. This deformation does not continue in the same manner with increasing force. Therefore, most deformation of the heel can be expected between non weight-bearing and half weight-bearing, which has been detected in healthy adults (Tsung et al. 2003). The deformation was small between half and full weight bearing. Consequently, the higher forces during the dynamic situation do not further deform the heel.

Even if the deformation of the forefoot during walking can be expected and has been observed in adult feet (Schmeltzpffenning et al. 2010), it is not considered in footwear construction. Furthermore, the actual dimension of the deformation in developing feet is unknown. The differences between static and dynamic OB-W of the current study can be regarded as practically relevant. The reason is that the reproducibility of this measure was very high because of its independence of the anatomical landmarks MTH1 and MTH5. Furthermore, it is essential for the construction of a last and a mean difference of 0.8% of F-L in OB-W is very important with respect to the improvement of footwear fit. The pronounced widening of the forefoot during walking can be explained by its special composition. In contrast to the heel, the forefoot is composed of several bones and joints in combination with fat pads. Studies with bone pins have concluded that internal movement (as a function of rotations) increases within the joints distal to the rearfoot. Especially, the increased movements within the cuboid-fifth metatarsal joint, which has been found to be larger than previously assumed, can contribute to the broadening of the forefoot (Lundgren et al. 2008; Wolf et al. 2008a).

The reduction of the girth measures was not expected. Due to the flattening of the arch and thus the midfoot, only a deferment but no increase or decrease of the girth measures within the midfoot was expected. The smaller maximum values of all foot girth measures, during stance phase of walking compared to static situations, has not been reported before. It might be a consequence of contractions of intrinsic and extrinsic muscles during walking (Gefen et al. 2000; Scott and Winter 1993). The reproducibility of the girth measures LB-G, LW-G, and LI-G was very high, thus their differences were practically relevant. The foot girth measures are important for well-fitting footwear and even more important for last construction. The increase of the dynamic values of I-H and B-H also reflects the assumption of muscular activity within the midfoot during walking. The difference between static and dynamic I-H was very high and points to the function
of the medial longitudinal arch. I-H is also an automatically calculated measure and thus practically relevant.

The angles of the foot are also important for the fit of footwear. B-A is important to locate the flexible line of a shoe. This ensures the natural dorsiflexion of the foot. The change of the foot angles during walking has not been analysed before. B-A was expected to become more acute-angled due to extension of the medial ball length. However, B-A was more obtuse-angled during walking which is in line with the forward motion of MTH5. However, the RMSEs of MaxDyn for all foot angles were quite large because of their dependency on MTH1 and MTH5. Thus, the increase of T1-A and T5-A must be cautiously discussed. However, there is a tendency that the forefoot is more pointed during walking. An implementation of this finding would result in a more pointed forefoot shape of the last which would push aside the toes during standing. This cannot be recommended from a physiological point of view.

7.4.2 Limitations of the study

There are several limitations of the present study. Most of them are related to the highly innovative measurement system and the challenge of processing the data. The prototype system provides solutions for several technical difficulties. Currently, the system is sensitive for changes in the environment (e.g. skin colour, ambient light). This sensitivity results in a high dropout rate. However, the final sample size is still representative. The software of the DynaScan4D was used to process the data. The automatically detected and calculated foot measures showed high values of repeatability, even for the dynamic values. However, the repeatability of foot measures dependant on the visually detected anatomical landmarks was rather low, even if values of ICC were acceptable. Preferably, all measures should be automatically detected, which will be the aim of further improvements of the system. At present, the recorded 3D scan of the foot is reduced to discrete measures. However, complete 3D information exists and can be used for future research.

Even if there were limitations in accuracy of the system and repeatability of the foot measures based on visually detected landmarks, the reliability was better than reported by Cheng et al. (1997) who have measured 2829 children and adolescents with a digital foot measuring device in static situation. The findings of the current study were critically discussed and can be used, in part, for last construction to improve the fit of footwear in dynamic situations.
7.4.3 Conclusion

The present study aimed to identify differences between loaded static and dynamic foot morphology of developing feet. With respect to the increments of last grading and the calculation of the repeatability, the practically relevant differences can be summarised as follows:

- Foot measures calculated in FWB situation differed from the maximum during walking. Thus, FWB is not a quasi-dynamic situation and cannot be used to assess dynamic foot morphology.

- Both static and dynamic foot measures must be considered for last construction. Thus, for the construction of footwear for developing feet, thresholds or areas that account for the differences between static and dynamic situations must be defined. Additionally, resilient materials should be used to account for these differences.

- Dynamic MB-L is important to appropriately consider the required amount of the allowance in front of the toes. This allowance is currently based on the experience of last designers. However, MB-L must be carefully regarded as the RMSE reached values up to 2.3 mm. Furthermore, to calculate the toe allowance additional information about the space for growing and the in-shoe movement must be considered. This was not in scope of this study.

- The mean increase of OB-W from HWB to MaxDyn was 0.8% of F-L, which must be considered in last construction. This part of the foot is highly sensitive to external influences.

- The increase in OH-W from HWB to MaxDyn is negligible for footwear construction.

- All girth measures decreased in the dynamic situation. This is important in terms of “holding” the foot during the roll over process to prevent slipping forward and resulting compression of the toes. Resilient materials and improved lacings can help improve the required hold and also account for the higher dynamic values of B-H and I-H.

- As the dynamic values of T1-A and T5-A exceeded the static values, it is not recommended to consider them for last construction. The base for construction of
T1-A and T5-A should be the static values to protect against increased lateral and medial pressure. Thus, the “toe box” should be more rounded.

- Previous suggestions to fit a shoe in the static loaded situation (Cheng et al. 1997) are in line with our findings. However, dynamic characteristics must be known and implemented in footwear design.

These results can be transferred into last construction and must be considered when it comes to the choice of upper materials or lacing. The recommendations can improve the dynamic fit of footwear and thus help to maintain a physiological development of feet.

Acknowledgement

We would like to thank all the helping hands who made the recording of this huge sample possible and Lisa Peterson for her linguistic assistance.

Reference List


7.4 Discussion


7.4 Discussion


Effects of gender, age, and body mass on dynamic foot morphology and dynamic deformation

Summary: The effect of anthropometric variables on dynamic foot morphology of developing feet has not been evaluated before. However, effect can be hypothesized as they have been identified on static foot morphology. This original article is concerned with the effects of gender, age, and body mass on the maximum during dynamic situation as well as the difference between dynamic maximum and static half weight-bearing. Thus, this article examines hypothesis 3.

Published in: Footwear Science, Online since 09/2013

DOI: 10.1080/19424280.2013.834982
8 The effects of gender, age, and body mass on dynamic foot shape and foot deformation in children and adolescents

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(Received May 16, 2013; accepted August 12, 2013)

Abstract

Purpose: The aim of the present study is to identify influences of gender, age, and body mass on the dynamic foot morphology and foot deformation of maturing feet. Only, advancements in scanner technology allow for record foot morphology during walking.

Methods: Static and dynamic foot morphology of 2554 participants (6-16 years) were measured with DynaScan4D. Different foot measures corresponding to measures used in last construction were defined. Influences of gender, age, and body mass were calculated within the whole sample by multiple linear regression analysis and within matched groups by Student’s t-test.

Results: The results of multiple linear regression analysis show similar patterns in boys and girls. The explained variance ($R^2$) of the differences between static and dynamic foot morphology is low. $R^2$ is higher for the maximum dynamic foot measures where the
respective static value mainly predicts the dynamic value. Relative maximum dynamic values of foot height, width, and girth are higher in overweight, younger, and male participants. The deformation of the instep height and the angle of the fifth toe differ between overweight and normal weight participants. Between boys and girls as well as children and adolescents there are differences in the deformation of the ball area.

**Conclusion:** There are effects of gender, age, and body mass on dynamic foot morphology and deformation. The differences are small regarding the high variability. Thus, dynamic adjustments are applicable without customizing to gender, age, and body mass. However, it is important to account for the high variability and for static and dynamic situations. This must be discussed with focus on resilient materials. These results can improve footwear design and thus contribute to a healthy foot development.

**Keywords:** 3-D deformation; Children’s footwear; 3-D scanning; dynamic foot morphology; footwear

### 8.1 Introduction

Shoes have to function as a safeguard to protect our feet daily, especially during locomotion. However, shoe design is mainly based on static foot measurements or on experiences of last designers gathered over centuries. To optimize the fit of shoes, dynamic characteristics of the foot are important and often requested (Kimura et al., 2009; Tsung et al., 2003). Technical advancements in three-dimensional (3D) scanner technology allow recording of the foot during natural walking (Coudert et al., 2006; Kimura et al., 2009; Schmeltzpfenning et al., 2009; Wang et al., 2006). Different studies focused on the feasibility as well as potentials and limitations of several scanner systems (Kimura et al., 2009; Wang et al., 2006). However, no study has examined the effects of gender, age, and body mass on dynamic foot morphology in maturing feet.

Shoe fit is in particular important for maturing feet. Predominantly, shoes for children and adolescents should not affect physiological maturation. Several effects of shoes on gait characteristics but also foot structure and function have been reported (Wegener et al., 2011; Wolf et al., 2008). Therefore, ill-fitting shoes are associated with different pathologic deformities like hallux valgus, hammer toes, or pes planus (Klein et al., 2009; Rao and Joseph, 1992; Staheli, 1991).
8.1 Introduction

Even if the external foot shape of a new-born can be taken for an adult's foot, essential structural and functional characteristics are different and have to mature gradually. The morphogenesis of the foot starts in the embryonic and foetal states when converting from an organ for grabbing to an organ for weight-bearing (Fritz and Mauch, 2013). Main changes in foot shape and functionality occur with increased forces due to upright standing and walking (Maier et al., 1980). The foot matures during childhood and adolescence according to a predefined genetic program. At the same time, the maturing foot is prone to environmental influences, like shoes (Hennig and Rosenbaum, 1991; Hennig et al., 1994; LeVeau and Bernhardt, 1984).

Different studies have examined developmental differences according to age and gender (Anderson et al., 1956; Cheng et al., 1997; Mauch, 2007). Most commonly, the development of foot length was analysed. Main findings are that at the age of five to twelve years boys have on average two mm longer feet than girls (Walther et al., 2005). Final foot length is reached in girls by the age of 12 to 13 years. Whereas, boy’s foot growth stops approximately two years later (Anderson et al., 1956; Cheng et al., 1997; Gould et al., 1990; Maier and Killmann, 2003; Walther et al., 2005). The whole foot morphology of children aged between three and five years showed no differences according to gender. This was found by Mickle et al. who normalised the foot measures to foot length. However, they found a thicker fat pad under the midfoot in boys and concluded that feet of boys and girls do not differ structurally but the feet of boys manifest a retard in maturation (Mickle et al., 2008).

Feet are already large at the time of birth (Dimeglio, 2001) to be prepared carrying future body weight. In particular during puberty, the body weight quickly increases (Debrunner, 1965; Maier and Killmann, 2003). However, what about heavy load before puberty? Many studies have tried to identify differences between feet of overweight and normal weight children (Dowling et al., 2001; Mauch et al., 2008; Riddiford-Harland et al., 2000). Some authors analysed differences in static foot morphology (Dowling et al., 2001; Mauch et al., 2008), or static and dynamic plantar pressure (Dowling et al., 2001; Filippin et al., 2007; Jiménez-Ormeno et al., 2013; Mickle et al., 2006a). Other studies focused on differences in characteristics of gait identified by time-space parametric, kinematic or electromyographic analysis (Hills et al., 2002; McGraw et al., 2000; Nantel et al., 2006; Speiser et al., 2005).
Significant differences between overweight and normal weight children were found for static foot structure (Dowling et al., 2001; Hills et al., 2002; Mauch et al., 2008; Morrison et al., 2007; Riddiford-Harland et al., 2000). The contact area of overweight participants, over which the higher forces due to overweight are transmitted, was identified and found to be larger than in normal weight participants (Nyska et al., 1997). As a result, plantar pressure values are not increased in overweight children (Dowling et al., 2001; Filippin et al., 2007; Nyska et al., 1997).

Previous research does not highlight whether it is necessary to offer customized shoes for special groups according to age, gender, or body mass. A foot type classification by cluster analysis of static foot measures showed that the voluminous foot type is more frequent in overweight children (Mauch et al., 2009). However, influences on the dynamic foot morphology as well as the differences between static and dynamic foot morphology have not been evaluated. Furthermore, the transfer of previously identified influences into footwear construction in terms of customization to different subgroups has not been conducted. This is in particular important for feet that are not fully matured because the stiffness and resistance of all soft tissues and full ossification is not attained before late adolescence (Maier and Killmann, 2003; Walther et al., 2005).

The aim of the present study is to identify influences of gender, age, and body mass in maturing feet. The core hypothesis is that gender, age, and body mass are influences on the dynamic foot morphology as well as on the differences between static and dynamic foot morphology. It is important to identify these influences in order to know if footwear should account for these influencing variables. This may improve the dynamic fit of footwear for maturing feet. In consideration of these results, footwear designers and paediatrics as well as parents can support a physiological development of children’s and adolescents’ feet.

8.2 Methods

8.2.1 Final sample size and matched groups

The study was approved by the ethics committee of the University Clinic of Tuebingen (Germany). The measurements took place between April 2010 and December 2011. 2554 children and adolescents, aged between six and 16 years, participated in the study. The children and adolescents were recruited with the assistance of 15 schools in the
southern part of Germany. The measurements took place in each school, where children and adolescents could freely decide whether to participate. In the preliminary stage, all children and adolescents as well as their parents were informed by their teachers and received written information about aims and contents of the study. Exclusion criteria comprised all kinds of problems influencing normal gait, like injuries or diseases of the lower extremities, serious foot deformities, or diagnosed neurological deficits concerning balance. Further pre-condition was the written consent of one legal guardian.

The final sample size is dependent on each foot measure and comprises 2056 to 2071. The reasons for excluding participants were diverse. In some cases the quality of the scans was not sufficient to analyse the targeted foot measures. Reasons for insufficient quality of the scan data comprised measurement problems due to wrong alignment of shutter time and saving processes as well as trigger function. Other problems were caused by high sensitivity of the scanner system to ambient light or deficits to adjust to skin type. In other cases anthropometric or scanned data was missing.

From this pool, three matched groups were formed to compare differences due to age, gender, or body mass (see Table 8.1). This procedure was used before by other studies that analysed influences on foot variables (Dowling et al., 2001; Fritz et al., 2013). The matched groups were formed by individually creating pairs of participants. If one participant could not be matched to a counterpart it was excluded. The criteria for assigning the participants were the following:

- **Male versus female:** Comparison of male and female participants, matched according to foot length, age, and BMI-percentile.

- **Overweight versus normal weight:** Comparison of overweight ($\geq 90^{th}$ BMI-percentile) and normal weight ($35^{th}$ BMI-percentile $\leq$ mean normal weight $\geq 65^{th}$ BMI-percentile), matched according to foot length, age, and gender.

- **Younger versus older:** Comparison of pre-pubescent children (6-9 years) and pubescent adolescents (12-16 years), matched according to gender and BMI-percentile. In this case, foot length was not a matching criterion because of the high correlation to age.
Table 8.1: Characteristics of the whole sample and the matched groups

<table>
<thead>
<tr>
<th>Group Characteristics</th>
<th>N</th>
<th>Age [years]</th>
<th>Body Height [m]</th>
<th>Body Weight [kg]</th>
<th>BMI-Percentile</th>
<th>Shoe Size [Paris Point]</th>
<th>Foot Length [mm]</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole sample</td>
<td>2554</td>
<td>10.6 (2.5)</td>
<td>1.45 (0.16)</td>
<td>38.9 (13.9)</td>
<td>52.0 (29.0)</td>
<td>36 (4)</td>
<td>228.3 (24.6)</td>
<td>♂ 1285 ♂ 1269</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>490</td>
<td>10.1 (2.2)</td>
<td>1.41 (0.13)</td>
<td>36.1 (11.1)</td>
<td>51.6 (28.8)</td>
<td>35 (3)</td>
<td>224.6 (20.6)</td>
<td>♂ 490</td>
</tr>
<tr>
<td>Female</td>
<td>490</td>
<td>10.3 (2.2)</td>
<td>1.44 (0.15)</td>
<td>37.5 (12.8)</td>
<td>51.4 (28.8)</td>
<td>35 (3)</td>
<td>224.6 (20.6)</td>
<td>♂ 490</td>
</tr>
<tr>
<td>BMI-Percentile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overweight</td>
<td>253</td>
<td>10.8 (2.5)</td>
<td>1.50 (0.15)</td>
<td>54.8 (17.2)</td>
<td>95.6 (3.0)</td>
<td>37 (3)</td>
<td>236.9 (20.0)</td>
<td>♂ 112 ♂ 141</td>
</tr>
<tr>
<td>Normal Weight</td>
<td>253</td>
<td>11.0 (2.4)</td>
<td>1.49 (0.15)</td>
<td>40.3 (11.0)</td>
<td>49.6 (9.3)</td>
<td>37 (3)</td>
<td>236.7 (21.7)</td>
<td>♂ 112 ♂ 141</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-16 years</td>
<td>478</td>
<td>13.9 (1.0)</td>
<td>1.63 (0.09)</td>
<td>53.8 (12.5)</td>
<td>52.1 (29.2)</td>
<td>39 (3)</td>
<td>250.1 (16.1)</td>
<td>♂ 251 ♂ 227</td>
</tr>
<tr>
<td>6-9 years</td>
<td>478</td>
<td>7.6 (1.0)</td>
<td>1.29 (0.08)</td>
<td>27.1 (6.0)</td>
<td>52.1 (28.2)</td>
<td>32 (2)</td>
<td>203.4 (14.4)</td>
<td>♂ 251 ♂ 227</td>
</tr>
</tbody>
</table>

Mean values of anthropometric values with the standard deviation (SD) in brackets.
8.2 Methods

8.2.2 Measurement system

The dynamic and static foot morphology was measured with the scanner system DynaScan4D. This system, which is based on the principle of full-field triangulation by structured light projection, was developed at the University of Tuebingen (Germany). In order to capture objects during locomotion, five scanner units have been used that are synchronized by a special software program. The scanner units (z-Snapper, ViALUX GmbH, Chemnitz, Germany) are installed on a 4.6 m long and 0.8 m high walkway; two scanner systems on the right, two on the left side and one below under a 0.6 x 0.4 m glass plate (Schmeltzpfenning et al., 2010). Each scanner unit is composed of a projecting and a recording (Pike F-032 B/W, Allied Vision, Stadtroda, Germany) device. The cameras record 205 frames per second with a resolution of 640 x 480. The projecting devices, based on digital light processor technology, include the Digital Micromirror Device (DMD™, Texas Instruments Inc., USA). ViALUX has developed a special accessory light modulator package that guarantees, amongst other things, maximum DMD™ speed and precise synchronization of camera and projector (Hoefling and Ahl, 2004). The calculation of the elevation information is realized according the equations of Frankowski et al. (Frankowski et al., 2000).

The measurement frequency comprises 46 Hz. This high frequency is achieved by a reduced spatial resolution (4x4 binning mode). The captured scenery has a volume of approximately 55 x 35 x 25 cm. To merge the recording of the five scanner units, the system is calibrated in advance. This guarantees that the recordings of the five scanners are in a single coordinate system. The accuracy of the system was tested by recording a bowl in static condition with full resolution and in dynamic condition with a 4x4 binning mode and a velocity of 0.8 m/s. The error (calculated as root mean square error or technical error of measurement) is for the static condition 0.23 mm and for the dynamic condition 0.89 mm. The repeatability of the foot measures that are independent of the anatomical landmarks metatarsal head one (MTH1) and five (MTH5) is less than 0.4 mm.

A strain gauge controls the capturing of the 3D shape of the foot. Light barriers are used to detect the walking speed of the participants. To reduce interruption due to different illumination conditions, the surrounding area is shaded and synthetic light is used.
8 The effects of gender, age, and body mass on dynamic foot shape and foot deformation

![Figure 8.1: Analysed foot measure](image)

8.2.3 Measurement procedure

One foot per child was randomly determined as recommended by Menz (Menz, 2004). This is confirmed by other studies that have found no statistically significant or practically relevant difference between right or left feet for children and adolescents as well as for adults (Cheng et al., 1997; Xiong et al., 2009). One static scan was recorded in full weight-bearing (FWB) and one in half weight-bearing (HWB). The participants had to stand still on the determined foot, looking straight and gripping the handrail with both hands to capture the foot in FWB. The other foot was lifted backwards. For the static HWB situation, participants had to stand on both feet. To ensure equal weight distribution, the participants were instructed to flex and subsequently extend their knees.

At least three valid dynamic scans were recorded during walking after a period of familiarisation. The participants had to walk over the walkway with specified walking speed adjusted to body height. The starting point was varied to guarantee that they trod centrally on the glass plate.

The secondary measures age, gender, body weight, and body height were determined. Body height was measured with a stadiometer and body weight using an electronic bathroom scale, both without shoes and in lightweight clothing. Body mass index (BMI, weight [kg]/height [m²]) was calculated and normalised to the gender- and age-dependant reference data of German children (Kromeyer-Hauschild et al., 2001). The resultant BMI percentiles were used to define overweight (BMI ≥ 90th percentile), normal weight (10th ≤ BMI < 90th percentile) and underweight (BMI < 10th percentile). These classification is based on BMI cut-offs an was recommended before for children and adolescents (Freedman and Sherry, 2009; Poskitt, 1995).
8.2.4 Analysis Procedure

The DynaScan4D software was used to capture and store the 3D foot scans. Further processing to calculate and analyse the foot measures was also realized within this software. It aligns the foot scans to the x-axis which is the connecting line between the most medial point of heel and MTH1. Foot measures that are commonly used in last design were defined and analysed. The foot girth measures were taken on the points that are usually marked on the last by a last marking device (Behrens, Germany). All foot measures are illustrated in Figure 8.1 and described in Table 8.2.
<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>Description</th>
<th>Measurement Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-H Instep Height</td>
<td>Highest point of the foot at 50% of foot length (measured on a cross section perpendicular to the x-axis).</td>
<td>MTH1 Strike - Heel Off</td>
</tr>
<tr>
<td>B-H Ball Height</td>
<td>Highest point of the foot at 61.8% (a.k.a. golden ratio) of foot length (measured on a cross section perpendicular to the x-axis).</td>
<td></td>
</tr>
<tr>
<td>F-L Foot Length</td>
<td>Distance between most posterior point of the heel and foremost point of the longest toe parallel to the x-axis.</td>
<td>Toes Strike - Heel Off</td>
</tr>
<tr>
<td>M-Bl Medial Ball Length</td>
<td>Distance between most posterior point of the heel and most medial point of MTH1 parallel to the x-axis.</td>
<td>MTH1 Strike - Heel Off</td>
</tr>
<tr>
<td>LB-L Lateral Ball Length</td>
<td>Distance between most posterior point of the heel and most lateral point of MTH5 parallel to the x-axis.</td>
<td></td>
</tr>
<tr>
<td>AB-W Anatomical Ball Width</td>
<td>Distance between most medial point of MTH1 and most lateral point of MTH5.</td>
<td>MTH1 Strike - Heel Off</td>
</tr>
<tr>
<td>OB-W Orthogonal Ball Width</td>
<td>Distance between most lateral and medial point of the forefoot measured orthogonally to the x-axis.</td>
<td></td>
</tr>
<tr>
<td>OH-W Orthogonal Heel Width</td>
<td>Distance between most lateral and medial point of the heel measured orthogonally to the x-axis between 14-20% of foot length.</td>
<td>Heel Strike - Heel Off</td>
</tr>
<tr>
<td>AB-G Anatomical Ball Girth</td>
<td>Girth around the anatomical landmarks MTH1 and MTH5 (perpendicular to the x-axis).</td>
<td>MTH1 Strike - Heel Off</td>
</tr>
<tr>
<td>LB-G Last Ball Girth</td>
<td>Girth around the first point (usually detected on the last by Behrens last marking device) at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
<td></td>
</tr>
<tr>
<td>LW-G Last Waist Girth</td>
<td>Girth around the second point at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
<td></td>
</tr>
<tr>
<td>LI-G Last Instep Girth</td>
<td>Girth around the third point at an angle of 22° relative to the vertical (perpendicular to the x-axis).</td>
<td></td>
</tr>
<tr>
<td>B-A Ball Angle</td>
<td>Angle between the connecting line of MTH1 and MTH5 and the x-axis.</td>
<td>MTH1 Strike - Heel Off</td>
</tr>
<tr>
<td>T1-A Toe1 Angle</td>
<td>Angle between the x-axis and the connecting line of most medial points of Toe 1 and MTH1.</td>
<td></td>
</tr>
<tr>
<td>T5-A Toe5 Angle</td>
<td>Angle between the connecting line of most lateral points of the heel and MTH5 and the connecting line of most lateral points of Toe 5 and MTH5.</td>
<td></td>
</tr>
</tbody>
</table>

Foot measures are illustrated in Figure 8.1.
8.2 Methods

All foot measures were calculated for static HWB as well as dynamic condition. The dynamic values were evaluated within defined phases during the roll-over process in which most load and therefore most deformation is expected (Gefen et al., 2000). Characteristic positions according to Blanc et al. were manually determined (Blanc et al., 1999), to standardize the measurement phases. The first position is the striking of the heel on the glass plate (Heel Strike). This position was standardized as the second frame of heel contact, to ensure that not only a small part of the heel has contact to the ground (Gefen et al., 2000). The second position is the contact of the metatarsal heads (MTH1 Strike) standardized as the complete contact of MTH1 and MTH5. Additionally, the position when the toes hit the ground (Toes Strike) and the position when heel (Heel Off) and metatarsal heads (MTH1 Off) take off were detected. The take-off was standardized as the second frame of rising when the heel or metatarsal heads were no longer completely loaded.

The marker-less scanning system provides the advantage that bias due to soft tissue movement is eliminated. However, some anatomical landmarks are important to calculate foot measures. Therefore, MTH1 and MTH5 were visually detected. The possible bias due to this procedure must be considered for further interpretation and application of the measures dependent on MTH1 and MTH5. All foot measures independent of the visually detected landmarks showed high values of reliability.

To achieve the aim of the study, the maximum of each foot measure (MaxDyn) was detected during the respective measurement phase. The mean of three dynamic trials was used and compared with the foot measures of static HWB by calculation of the difference. In the following this difference is abbreviated as MaxDyn-HWB for each foot measure. The foot size has an effect on the comparison as it is highly correlated to age. This effect was eliminated by normalisation of the foot measures to the foot length measured in HWB of the respective foot. As in other studies concerned with influences on foot measures, foot height, length, width, and girth measures were normalised to foot length (Jiménez-Ormeno et al., 2013; Mauch et al., 2008; Mauch et al., 2009; Mickle et al., 2008; Wunderlich and Cavanagh, 2001).

8.2.5 Statistical analysis

Normal distribution of each static and dynamic foot measure was tested by using the Shapiro-Wilk Test (Shapiro and Wilk, 1965). A multiple linear regression analysis was
conducted to identify influences of the anthropometric continuous variables, on the outcome measures MaxDyn and MaxDyn-HWB for each foot measure. The multiple linear regression analysis was calculated separately for male and female participants as an explorative procedure to obtain information about the magnitude of the effects as well as the relationship between different variables (Aiken et al., 1991). The variables age, BMI-percentile, and the respective static value were added to the model by the stepwise forward method. The critical p-value for inclusion of variables was \( p \leq 0.25 \). The model was calculated according to equation (1). The target values are symbolized by \( Y \) and comprise MaxDyn and MaxDyn-HWB, respectively. \( X_i \) \((i=1, n)\) are the influencing variables.

\[
E\left(\frac{Y}{X}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon
\]

The differences between the matched groups were analysed by Student's t-test for independent samples. All analyses were performed by using JMP Version 9.0.2 (SAS, Cary, USA).

### 8.3 Results

The sample comprises children and adolescents aged between six and 16 years, 49% male and 51% female. 12.6% are overweight and obese, 80.2% were normal weight, and 7.2% underweight. The calculated shoe sizes (measured foot length + allowance) range from 26 to 45 Paris Point.

#### 8.3.1 Multiple linear regression analysis

The results of the multiple linear regression analysis for male and female participants are presented in Table 8.3 and Table 8.4, respectively. The models, which were calculated for each foot measure, provide rather small values of the explained variance (\( R^2 \)). The values of \( R^2 \) comprise 0 to 0.22 regarding the differences between static and dynamic foot measures. The highest values were found in ball angle (B-A) for boys and girls.

\( R^2 \) of the models for MaxDyn of each foot measure was higher by trend. For both genders, the explained variance of T5-A and T1-A was high with \( R^2 \) of 0.70 (boys and girls) and 0.61 (boys) and 0.62 (girls), respectively. Whereas values of \( R^2 \) for foot length measures tend toward zero.
The results showed similar patterns for male and female participants regarding the variables influencing MaxDyn. Static values of the respective foot measures were included in most models for MayDyn in female and male participants.
Table 8.3: Results of multiple regression analysis within all male subjects

<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>Intercept</th>
<th>Static Value</th>
<th>BMI-Percentile</th>
<th>Age</th>
<th>Coefficient of Determination ((R^2))</th>
<th>Intercept</th>
<th>Static Value</th>
<th>BMI-Percentile</th>
<th>Age</th>
<th>Coefficient of Determination ((R^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Height I-H [%FL]</td>
<td>2.18*</td>
<td>-0.09*</td>
<td>0.01*</td>
<td>0.04</td>
<td>17.71*</td>
<td>0.29*</td>
<td>-0.68*</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot Height B-H [%FL]</td>
<td>1.57*</td>
<td>-0.04*</td>
<td>0.00*</td>
<td>0.06*</td>
<td>0.03</td>
<td>13.55*</td>
<td>0.26*</td>
<td>-0.47*</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>Foot Length MB-L [%FL]</td>
<td>5.60*</td>
<td>-0.05*</td>
<td>0.01*</td>
<td>0.28*</td>
<td>0.08</td>
<td>58.93*</td>
<td>0.06*</td>
<td>-0.01*</td>
<td>0.49*</td>
<td></td>
</tr>
<tr>
<td>Foot Length LB-L [%FL]</td>
<td>6.17*</td>
<td>-0.06*</td>
<td>0.01*</td>
<td>0.25*</td>
<td>0.08</td>
<td>58.93*</td>
<td>0.06*</td>
<td>-0.01*</td>
<td>0.49*</td>
<td></td>
</tr>
<tr>
<td>Foot Width AB-W [%FL]</td>
<td>2.39*</td>
<td>-0.02*</td>
<td>0.00*</td>
<td>0.04</td>
<td>0.03</td>
<td>30.42*</td>
<td>0.13*</td>
<td>0.01*</td>
<td>-0.58*</td>
<td>0.29</td>
</tr>
<tr>
<td>Foot Width OB-W [%FL]</td>
<td>2.05*</td>
<td>-0.02*</td>
<td>0.00*</td>
<td>0.04</td>
<td>0.03</td>
<td>32.04*</td>
<td>0.14*</td>
<td>0.01*</td>
<td>-0.65*</td>
<td>0.33</td>
</tr>
<tr>
<td>Foot Width OH-W [%FL]</td>
<td>1.91*</td>
<td>-0.06*</td>
<td>0.01*</td>
<td>0.13*</td>
<td>0.05</td>
<td>19.64*</td>
<td>0.21*</td>
<td>0.01*</td>
<td>-0.55*</td>
<td>0.38</td>
</tr>
<tr>
<td>Foot Girth AB-G [%FL]</td>
<td>2.33*</td>
<td>-0.03*</td>
<td>0.02*</td>
<td>0.19*</td>
<td>0.03</td>
<td>81.95*</td>
<td>0.10*</td>
<td>0.04*</td>
<td>-1.09*</td>
<td>0.31</td>
</tr>
<tr>
<td>Foot Girth LB-G [%FL]</td>
<td>-3.79*</td>
<td>-0.01*</td>
<td>0.01*</td>
<td>0.04</td>
<td>0.04</td>
<td>75.83*</td>
<td>0.13*</td>
<td>0.03*</td>
<td>-1.34*</td>
<td>0.36</td>
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<tr>
<td>Foot Girth LW-G [%FL]</td>
<td>-2.06*</td>
<td>0.01*</td>
<td>0.01*</td>
<td>0.04</td>
<td>0.04</td>
<td>77.39*</td>
<td>0.12*</td>
<td>0.05*</td>
<td>-1.29*</td>
<td>0.40</td>
</tr>
<tr>
<td>Foot Girth LI-G [%FL]</td>
<td>-1.83*</td>
<td>0.00*</td>
<td>0.00*</td>
<td>0.01</td>
<td>0.01</td>
<td>83.05*</td>
<td>0.09*</td>
<td>0.05*</td>
<td>-0.08*</td>
<td>0.37</td>
</tr>
<tr>
<td>Angles B-A [\°]</td>
<td>32.31*</td>
<td>-0.40*</td>
<td>-0.16*</td>
<td>0.17</td>
<td>0.03</td>
<td>32.31*</td>
<td>0.60*</td>
<td>-0.16*</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Angles T1-A [\°]</td>
<td>5.92*</td>
<td>-0.16*</td>
<td>-0.15*</td>
<td>0.08</td>
<td>0.08</td>
<td>5.92*</td>
<td>0.84*</td>
<td>-0.15*</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Angles T5-A [\°]</td>
<td>2.89*</td>
<td>-0.16*</td>
<td>0.01*</td>
<td>0.09</td>
<td>0.09</td>
<td>2.89*</td>
<td>0.84*</td>
<td>0.01*</td>
<td>0.70</td>
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</tr>
</tbody>
</table>

* = \(p < 0.05\) (significance of the statistical test); Critical \(p\)-value for inclusion of variables = \(p \leq 0.025\); Abbreviations of foot measures are listed in Table 8.2 and Figure 8.1; Static Value = Half Weight Bearing (HWB)
Table 8.4: Results of multiple regression analysis within all female subjects

<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>MaxDyn-HWB</th>
<th></th>
<th></th>
<th></th>
<th>Intercept</th>
<th>Static Value</th>
<th>BMI-Perc</th>
<th>Age</th>
<th>Coefficient of Determination (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
<td>[β]</td>
</tr>
<tr>
<td>Foot Height I-H [%FL]</td>
<td>3.26*</td>
<td>-0.13*</td>
<td>0.04</td>
<td>16.71*</td>
<td>0.29*</td>
<td>-0.58*</td>
<td>0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot Height B-H [%FL]</td>
<td>1.57*</td>
<td>-0.02*</td>
<td>0.01</td>
<td>12.65*</td>
<td>0.26*</td>
<td>-0.38*</td>
<td>0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot MB-L [%FL]</td>
<td>5.09*</td>
<td>-0.06*</td>
<td>0.25*</td>
<td>0.07</td>
<td>71.04*</td>
<td>0.02*</td>
<td>-0.10*</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Foot LB-L [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>58.15*</td>
<td>0.06*</td>
<td>-0.35*</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Foot Width AB-W [%FL]</td>
<td>2.10*</td>
<td>-0.01*</td>
<td>0.13*</td>
<td>0.05</td>
<td>30.09*</td>
<td>0.17*</td>
<td>-0.51*</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Foot Width OB-W [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>69.08*</td>
<td>0.15*</td>
<td>-0.50*</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Foot Width OH-W [%FL]</td>
<td>2.06*</td>
<td>-0.01*</td>
<td>0.01</td>
<td>0.07</td>
<td>38.64*</td>
<td>0.17*</td>
<td>-0.41*</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Foot Girth AB-G [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>74.38*</td>
<td>0.13*</td>
<td>-1.03*</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Foot Girth LB-G [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>70.61*</td>
<td>0.14*</td>
<td>-1.14*</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Foot Girth LW-G [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>69.60*</td>
<td>0.15*</td>
<td>-1.11*</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Foot Girth LI-G [%FL]</td>
<td>1.01*</td>
<td>-0.04*</td>
<td>0.01</td>
<td>0.07</td>
<td>79.59*</td>
<td>0.10*</td>
<td>-0.92</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Angles B-A [°]</td>
<td>38.31*</td>
<td>-0.48*</td>
<td>-0.17*</td>
<td>0.22</td>
<td>38.31*</td>
<td>0.52*</td>
<td>-0.17*</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Angles T1-A [°]</td>
<td>5.93*</td>
<td>-0.19*</td>
<td>-0.16*</td>
<td>0.11</td>
<td>5.93*</td>
<td>0.81*</td>
<td>-0.16*</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Angles T5-A [°]</td>
<td>3.44*</td>
<td>-0.15*</td>
<td>0.07</td>
<td>3.44*</td>
<td>0.85*</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = p < 0.05 (significance of the statistical test); Critical p-value for inclusion of variables = p ≤ 0.025;
Abbreviations of foot measures are listed in Table 8.2 and Figure 8.1;
Static Value = Half Weight Bearing (HWB)
8.3.2 Differences between overweight and normal weight participants

Table 8.5 presents the differences between overweight and normal weight children/adolescents. Statistically significant differences were found in MaxDyn of foot height, width, and girth measures as well as the foot angles B-A and T5-A. MaxDyn values of foot height, width and girth measures are higher in overweight participants. MaxDyn values of B-A and T5-A are greater in overweight participants. No differences were found in MaxDyn of foot length measures. Statistically significant differences were only found in MaxDyn-HWB of I-H and T5-A, with greater differences in overweight participants.
Table 8.5: Differences in relative dynamic foot measure and foot deformation between overweight and normal weight subjects

<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>Normal Weight</th>
<th>Overweight</th>
<th>Mean Difference</th>
<th>95% CI</th>
<th>p-value</th>
<th>Normal Weight</th>
<th>Overweight</th>
<th>Mean Difference</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Height</td>
<td>1.89 (2.05)</td>
<td>2.44 (2.37)</td>
<td>0.56</td>
<td>0.16</td>
<td>0.95</td>
<td>0.006</td>
<td>26.29 (2.80)</td>
<td>27.92 (3.00)</td>
<td>1.63</td>
<td>1.12</td>
</tr>
<tr>
<td>B-H [%FL]</td>
<td>0.85 (1.00)</td>
<td>0.82 (0.78)</td>
<td>-0.04</td>
<td>-0.19</td>
<td>0.12</td>
<td>0.657</td>
<td>20.06 (1.55)</td>
<td>21.18 (1.53)</td>
<td>1.12</td>
<td>0.85</td>
</tr>
<tr>
<td>Foot Length</td>
<td>0.58 (1.60)</td>
<td>0.73 (1.38)</td>
<td>0.16</td>
<td>-0.11</td>
<td>0.42</td>
<td>0.246</td>
<td>73.23 (1.59)</td>
<td>73.46 (1.55)</td>
<td>0.23</td>
<td>-0.05</td>
</tr>
<tr>
<td>MB-L [%FL]</td>
<td>0.41 (1.94)</td>
<td>0.63 (2.01)</td>
<td>0.22</td>
<td>-0.13</td>
<td>0.56</td>
<td>0.221</td>
<td>61.70 (2.11)</td>
<td>62.01 (2.27)</td>
<td>0.31</td>
<td>-0.08</td>
</tr>
<tr>
<td>LB-L [%FL]</td>
<td>0.58 (0.92)</td>
<td>0.71 (1.00)</td>
<td>0.13</td>
<td>-0.04</td>
<td>0.30</td>
<td>0.139</td>
<td>39.41 (1.94)</td>
<td>40.96 (1.93)</td>
<td>1.54</td>
<td>1.20</td>
</tr>
<tr>
<td>Foot Width</td>
<td>0.85 (0.71)</td>
<td>0.86 (1.03)</td>
<td>0.01</td>
<td>-0.14</td>
<td>0.17</td>
<td>0.876</td>
<td>38.39 (1.95)</td>
<td>39.91 (1.91)</td>
<td>1.51</td>
<td>1.17</td>
</tr>
<tr>
<td>OB-W [%FL]</td>
<td>0.22 (1.04)</td>
<td>0.16 (1.04)</td>
<td>-0.07</td>
<td>-0.25</td>
<td>0.11</td>
<td>0.456</td>
<td>26.26 (1.63)</td>
<td>27.87 (1.74)</td>
<td>1.61</td>
<td>1.32</td>
</tr>
<tr>
<td>OH-W [%FL]</td>
<td>-0.73 (2.92)</td>
<td>-0.81 (1.60)</td>
<td>-0.07</td>
<td>-0.49</td>
<td>0.34</td>
<td>0.729</td>
<td>93.32 (4.48)</td>
<td>97.68 (4.16)</td>
<td>4.36</td>
<td>3.60</td>
</tr>
<tr>
<td>Foot Girth</td>
<td>-1.61 (1.56)</td>
<td>-1.39 (1.10)</td>
<td>0.23</td>
<td>-0.01</td>
<td>0.46</td>
<td>0.063</td>
<td>88.61 (4.12)</td>
<td>92.93 (3.95)</td>
<td>4.31</td>
<td>3.60</td>
</tr>
<tr>
<td>LB-G [%FL]</td>
<td>-1.53 (1.66)</td>
<td>-1.48 (1.46)</td>
<td>0.05</td>
<td>-0.23</td>
<td>0.33</td>
<td>0.719</td>
<td>88.93 (4.10)</td>
<td>94.69 (4.30)</td>
<td>5.76</td>
<td>5.02</td>
</tr>
<tr>
<td>LW-G [%FL]</td>
<td>-1.30 (2.31)</td>
<td>-1.19 (1.68)</td>
<td>0.11</td>
<td>-0.25</td>
<td>0.46</td>
<td>0.544</td>
<td>92.61 (4.27)</td>
<td>98.23 (4.31)</td>
<td>5.62</td>
<td>4.87</td>
</tr>
<tr>
<td>Angles B-A</td>
<td>1.35 (3.00)</td>
<td>1.68 (3.34)</td>
<td>0.33</td>
<td>-0.23</td>
<td>0.89</td>
<td>0.244</td>
<td>74.14 (3.58)</td>
<td>75.10 (3.42)</td>
<td>0.96</td>
<td>0.35</td>
</tr>
<tr>
<td>T1-A [°]</td>
<td>3.46 (3.93)</td>
<td>3.86 (3.77)</td>
<td>0.40</td>
<td>-0.29</td>
<td>1.09</td>
<td>0.253</td>
<td>6.97 (5.07)</td>
<td>7.79 (4.93)</td>
<td>0.83</td>
<td>-0.07</td>
</tr>
<tr>
<td>T5-A [°]</td>
<td>2.16 (3.31)</td>
<td>2.89 (3.46)</td>
<td>0.73</td>
<td>0.13</td>
<td>1.33</td>
<td>0.017</td>
<td>11.94 (4.73)</td>
<td>12.86 (4.33)</td>
<td>0.91</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Mean values and standard deviation (SD) in brackets of MaxDyn-HWB = foot deformation and MaxDyn = maximum value during walking; 95% CI = 95% confidence interval; Abbreviations of foot measure are listed in Table 8.2 and Figure 8.1.
8 The effects of gender, age, and body mass on dynamic foot shape and foot deformation

8.3.3 Differences between children and adolescents

The differences in foot measures between children’s (6-9 years) and adolescents’ feet (13-16 years) are shown in Table 8.6. Statistically significant differences were found between MaxDyn of all foot measures except T1-A and MB-L. Higher values in MaxDyn of foot height, width, and girth measures were found in children.

Children (6-9 years) showed higher values in MaxDyn-HWB of I-H, AB-W, LB-G, T1-A, and T5-A. The values for MaxDyn-HWB of LB-L were higher in adolescents. Children showed smaller dynamic OH-W compared to the static value, whereas adolescents showed higher dynamic values for OH-W (Table 8.6).
Table 8.6: Differences in relative dynamic foot measure and foot deformation between children and adolescents

<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>13-16 years</th>
<th>6-9 years</th>
<th>Mean Difference</th>
<th>95% CI</th>
<th>p-value</th>
<th>13-16 years</th>
<th>6-9 years</th>
<th>Mean Difference</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foot Height</strong></td>
<td>I-H [%FL]</td>
<td>1.64 (1.55)</td>
<td>3.02 (4.63)</td>
<td>1.38</td>
<td>0.94</td>
<td>1.82</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B-H [%FL]</td>
<td>0.68 (0.68)</td>
<td>0.65 (1.30)</td>
<td>-0.03</td>
<td>-0.17</td>
<td>0.10</td>
<td>0.635</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Foot Length</strong></td>
<td>MB-L [%FL]</td>
<td>0.69 (1.66)</td>
<td>0.70 (1.64)</td>
<td>0.02</td>
<td>0.20</td>
<td>0.23</td>
<td>0.889</td>
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</tr>
<tr>
<td></td>
<td>LB-L [%FL]</td>
<td>0.82 (2.26)</td>
<td>0.52 (2.03)</td>
<td>-0.30</td>
<td>-0.58</td>
<td>0.03</td>
<td>0.032</td>
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<td></td>
</tr>
<tr>
<td><strong>Foot Width</strong></td>
<td>AB-W [%FL]</td>
<td>0.47 (1.17)</td>
<td>0.71 (0.87)</td>
<td>0.25</td>
<td>0.11</td>
<td>0.38</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OB-W [%FL]</td>
<td>0.74 (0.98)</td>
<td>0.86 (1.30)</td>
<td>0.11</td>
<td>-0.03</td>
<td>0.26</td>
<td>0.128</td>
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</tr>
<tr>
<td></td>
<td>OH-W [%FL]</td>
<td>0.28 (1.07)</td>
<td>-0.11 (1.30)</td>
<td>-0.40</td>
<td>-0.55</td>
<td>-0.24</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Foot Girth</strong></td>
<td>AB-G [%FL]</td>
<td>-1.27 (1.98)</td>
<td>-1.09 (2.44)</td>
<td>0.18</td>
<td>-0.11</td>
<td>0.46</td>
<td>0.219</td>
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</tr>
<tr>
<td></td>
<td>LB-G [%FL]</td>
<td>-1.79 (2.08)</td>
<td>-2.39 (4.41)</td>
<td>-0.60</td>
<td>-1.04</td>
<td>-0.23</td>
<td>0.008</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>LW-G [%FL]</td>
<td>-1.80 (1.49)</td>
<td>-2.09 (3.86)</td>
<td>-0.29</td>
<td>-0.67</td>
<td>0.09</td>
<td>0.130</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Li-G [%FL]</td>
<td>-2.03 (2.46)</td>
<td>-2.44 (3.00)</td>
<td>-0.42</td>
<td>-0.75</td>
<td>0.04</td>
<td>0.080</td>
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</tr>
<tr>
<td><strong>Angles</strong></td>
<td>B-A [°]</td>
<td>1.65 (3.05)</td>
<td>1.71 (3.35)</td>
<td>0.06</td>
<td>-0.35</td>
<td>0.47</td>
<td>0.778</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T1-A [°]</td>
<td>3.18 (4.34)</td>
<td>5.47 (4.70)</td>
<td>2.29</td>
<td>1.70</td>
<td>2.87</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T5-A [°]</td>
<td>1.52 (5.42)</td>
<td>2.80 (3.84)</td>
<td>1.27</td>
<td>0.67</td>
<td>1.88</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean values and standard deviation (SD) in brackets of MaxDyn-HWB = foot deformation and MaxDyn = maximum value during walking; 95% CI = 95% confidence interval; Abbreviations of foot measure are listed in Table 8.2 and Figure 8.1
8.3.4 Differences between male and female participants

Gender-specific differences are presented in Table 8.7. Differences according to gender were found in MaxDyn of foot height, width, and girth measures as well as T1-A. Female participants showed smaller values in MaxDyn of foot height, width, and girth measures compared to their male counterparts. MaxDyn of T1-A in female participants is bigger than in males.

MaxDyn-HWB of B-H, MB-L, AB-G, and both measures of ball width (AB-W and OB-W) differ between male and female participants. In girls, higher values in MaxDyn-HWB of B-H and AB-G were found with negative values for MaxDyn-HWB of AB-G. MaxDyn-HWB of MB-L is smaller in female compared to male participants. MaxDyn-HWB of OB-W was higher in girls, whereas MaxDyn-HWB of AB-W was smaller in the same group.
### Table 8.7: Differences in relative dynamic foot measure and foot deformation between female and male subjects

<table>
<thead>
<tr>
<th>Foot Measures</th>
<th>MaxDyn-HWB</th>
<th>MaxDyn</th>
<th>95% CI</th>
<th>p-value</th>
<th>MaxDyn</th>
<th>95% CI</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>♂</td>
<td>♀</td>
<td>Mean Difference</td>
<td>95% CI</td>
<td>p-value</td>
<td>♂</td>
<td>♀</td>
</tr>
<tr>
<td>Foot Height</td>
<td>1.64 (1.62)</td>
<td>1.79 (1.77)</td>
<td>-0.15</td>
<td>-0.37</td>
<td>0.06</td>
<td>0.166</td>
<td>26.63 (2.48)</td>
</tr>
<tr>
<td>Foot B-H</td>
<td>0.57 (0.77)</td>
<td>0.71 (0.70)</td>
<td>-0.15</td>
<td>-0.24</td>
<td>-0.05</td>
<td>0.002</td>
<td>20.40 (1.48)</td>
</tr>
<tr>
<td>Foot MB-L</td>
<td>0.78 (1.55)</td>
<td>0.50 (1.38)</td>
<td>0.29</td>
<td>0.10</td>
<td>0.47</td>
<td>0.002</td>
<td>73.44 (1.56)</td>
</tr>
<tr>
<td>Foot LB-L</td>
<td>0.43 (2.03)</td>
<td>0.46 (1.83)</td>
<td>-0.03</td>
<td>-0.27</td>
<td>0.21</td>
<td>0.810</td>
<td>62.08 (2.32)</td>
</tr>
<tr>
<td>Foot Width</td>
<td>0.71 (0.86)</td>
<td>0.54 (0.81)</td>
<td>-0.17</td>
<td>0.07</td>
<td>0.28</td>
<td>0.002</td>
<td>40.05 (1.99)</td>
</tr>
<tr>
<td>Foot OB-W</td>
<td>0.78 (0.74)</td>
<td>0.91 (1.00)</td>
<td>-0.13</td>
<td>-0.24</td>
<td>-0.02</td>
<td>0.020</td>
<td>39.11 (2.01)</td>
</tr>
<tr>
<td>Foot OH-W</td>
<td>0.17 (1.00)</td>
<td>0.22 (1.26)</td>
<td>-0.05</td>
<td>-0.19</td>
<td>0.10</td>
<td>0.540</td>
<td>26.85 (1.79)</td>
</tr>
<tr>
<td>Foot AB-G</td>
<td>-0.90 (2.11)</td>
<td>-1.22 (1.87)</td>
<td>0.33</td>
<td>0.07</td>
<td>0.58</td>
<td>0.012</td>
<td>94.71 (4.58)</td>
</tr>
<tr>
<td>Foot LB-G</td>
<td>-1.84 (1.69)</td>
<td>-1.78 (1.96)</td>
<td>-0.06</td>
<td>-0.29</td>
<td>0.18</td>
<td>0.637</td>
<td>90.18 (4.47)</td>
</tr>
<tr>
<td>Foot LW-G</td>
<td>-1.63 (2.30)</td>
<td>-1.65 (1.42)</td>
<td>0.02</td>
<td>-0.22</td>
<td>0.27</td>
<td>0.137</td>
<td>91.12 (4.89)</td>
</tr>
<tr>
<td>Foot LI-G</td>
<td>-1.41 (2.07)</td>
<td>-1.46 (1.46)</td>
<td>0.04</td>
<td>-0.18</td>
<td>0.27</td>
<td>0.705</td>
<td>94.58 (4.59)</td>
</tr>
<tr>
<td>Angles B-A</td>
<td>1.39 (3.14)</td>
<td>1.72 (3.12)</td>
<td>-0.33</td>
<td>-0.73</td>
<td>0.07</td>
<td>0.103</td>
<td>74.92 (3.58)</td>
</tr>
<tr>
<td>Angles T1-A</td>
<td>4.13 (3.87)</td>
<td>3.66 (3.93)</td>
<td>0.47</td>
<td>-0.03</td>
<td>0.97</td>
<td>0.065</td>
<td>6.88 (5.07)</td>
</tr>
<tr>
<td>Angles T5-A</td>
<td>2.21 (3.32)</td>
<td>2.45 (3.41)</td>
<td>-0.24</td>
<td>-0.68</td>
<td>0.10</td>
<td>0.275</td>
<td>11.27 (4.56)</td>
</tr>
</tbody>
</table>

Mean values and standard deviation (SD) in brackets of MaxDyn-HWB = foot deformation and MaxDyn = maximum value during walking; 95% CI = 95% confidence interval; Abbreviations of foot measure are listed in Table 8.2 and Figure 8.1.
8.4 Discussion

8.4.1 Multiple linear regression analysis

The linear regression analysis was conducted to give a first overview of potential predictors for MaxDyn and MaxDyn-HWB as well as possible interactive effects (see Table 8.3 and Table 8.4). The magnitude of the explained variances ($R^2$) was small for the calculated models of MaxDyn-HWB. Therefore, the variance of MaxDyn-HWB cannot be sufficiently explained by the used variables. The explained variance in MaxDyn of foot measures showed higher values. For instance, 60-70% of the variance in MaxDyn of the angles of the first and fifth toe could be explained by the included variables.

In adults, values of explained variance were higher on average regarding dynamic plantar foot morphology (Fritz et al., 2013). According to the current data, the reasons for the discrepancy cannot be explained but should be analysed in following studies. One possible reason could be the very high standard deviation in foot measures of children as reported before (Kouchi, 1998; Mauch et al., 2009).

The patterns of influencing variables are similar for male and female. The respective static value provides the highest contribution for the explained variance of MaxDyn. Therefore, it can be concluded that for most instances dynamic foot morphology can be predicted by static values. This was also found in adults plantar foot shape (Fritz et al., 2013). Without confounding factors, the influences were identified in a second step within matched groups.

8.4.2 Differences between overweight and normal weight participants

There are differences between overweight and normal weight participants in MaxDyn of the foot measures normalised to foot length. Feet of overweight children and adolescents are higher, broader, and more voluminous in dynamic situation compared to their normal weight counterparts. This is in line with most results reported for static foot morphology (Mauch et al., 2008; Morrison et al., 2007). In contrast, some studies could not find statistically significant differences between overweight and normal weight children when normalising the foot measures to foot length (Jiménez-Ormeno et al., 2013).

The differences between static and dynamic foot morphology is higher for overweight participants. In particular, the increased values of the instep height (I-H) normalised to foot length are noticeable. The height at 50% of foot length divided by foot length is
8.4 Discussion

Often used to identify functionality of the medial longitudinal arch (Williams and McClay, 2000). Overweight participants showed higher maximum values of I-H during walking. This might be caused by increased adipose tissue. The higher value during walking compared to the lower value during standing is in contrast to the assumptions that the medial longitudinal arch flattens more in overweight children (Dowling et al., 2001; Mickle et al., 2006b; Riddiford-Harland et al., 2000). Thus, these findings tend to confirm studies which stated that an excess of adipose tissue is source of the supposed “flattening” and not a drop of the medial longitudinal arch (Mickle et al., 2006b; Morrison et al., 2007; Nass et al., 1999). However, by the use of this foot measure a clear statement cannot be given regarding the medial longitudinal arch. At this point, the criticism of the validity of used indices to estimate arch height and thus functionality of the foot must be reactivated (Hawes et al., 1992; McPoil and Cornwall, 2006; Wearing et al., 2006). To get a clearer understanding of the function of the medial longitudinal arch and their dependencies, bone pin or radiographical analysis would be beneficial. Furthermore, this study did not focus on the function of the medial longitudinal arch which is initially not important for footwear construction.

Another significant difference between normal weight and overweight participants is that the angle of the fifth toe (T5-A) is bigger in overweight participants, which means that the forefoot is pointier during walking. One possible reason is the additional fat tissue under MTH5 which deforms more during walking. This result must be interpreted carefully as the values of standard deviation are very high. An explanation of the higher differences and the variability of T5-A is given by Lundgren et al. (Lundgren et al., 2008). The authors found, using bone pin analysis, a considerable capacity of the motion on the lateral part of the foot which might be pronounced by increasing forces due to overweight (Lundgren et al., 2008).

8.4.3 Differences between children and adolescents

The influence of age on the foot morphology was previously analysed with respect to foot growth (Anderson et al., 1956; Debrunner, 1965). Previous research focused on associations between different foot measures normalised to foot length and age and found changing proportions of the foot (Gould et al., 1990; Kouchi, 1998). These changes in foot proportion are also obvious in MaxDyn as the static foot morphology is the main predictor for dynamic foot morphology. Our results confirm that feet of children are
relatively broader, higher, and more voluminous than feet of adolescents. This is most obvious in the girth around the instep (LI-G).

The novel findings considering the differences in static and dynamic foot morphology between children and adolescents must be discussed carefully because of the high standard deviations. I-H is higher during walking compared to static HWB in children. This was not reported before and is in contrast to statements that younger feet are softer and more deformable (Maier and Killmann, 2003). Further analysis on temporal and muscular information would be beneficial to interpret the results in terms of the functionality of the medial longitudinal arch. The differences in ball width measures in children are contrary to the differences in adolescents. It is possible that the anatomical ball width (AB-W), which is dependent on the anatomical landmarks MTH1 and MTH5 changes in a different pattern compared to the absolute orthogonal ball width (OB-W). Especially MTH5 changes in a different pattern in children compared to adolescents. The higher deformation of the angles T1-A and T5-A as well as last ball girth (LB-G) in children also suggest different deformation patterns within the area of the forefoot. The higher values for the orthogonal heel width (OH-W) in dynamic situations are also subjected to the high standard deviation which might be point to high variability of gait in children (Hausdorff et al., 1999).

8.4.4 Differences between male and female participants

Gender-specific differences have been subject of different studies in adults (Krauss et al., 2008; Zifchock et al., 2006) as well as children (Mauch et al., 2009; Mickle et al., 2008). In the present study MaxDyn of foot height, width, and girth measures normalised to foot length are greater for male participants. Similar results, even less distinctive, were reported in adults (Fritz et al., 2013; Krauss et al., 2008; Wunderlich and Cavanagh, 2001). In three to five year old children, Mickle et al. found no significant differences when normalising the foot measures to the respective foot length (Mickle et al., 2008).

Female participants have higher maximum dynamic values of the angle of the first toe. Even if the prevalence of hallux valgus was not studied, these results are in line with findings of Jerosch and Mamsch et al. who reported that more girls (10-12 years) have Hallux valgus deformations (Jerosch and Mamsch, 1998). In younger children (3-6.5 years) higher risk for Hallux valgus was found for boys (Klein et al., 2009). In adults, the prevalence of Hallux valgus increases with age and is more often observed in women.
(Nix et al., 2010). The responsibility of genetics or ill-fitting shoes is not completely explained.

Differences within MaxDyn-HWB are more pronounced in girls for ball height, orthogonal ball width, and anatomical ball girth. Less deformation can be found in anatomical ball width and medial ball length. The results point to a different deformation pattern of the forefoot in girls. Higher values of deformation were also found in women’s feet during stance phase (Fritz et al., 2013).

8.4.5 Practical relevance and conclusion

The core hypothesis of this study can be verified. The maximum dynamic values of relative foot height, width, and girth measures as well as angles of the foot are affected by gender, age, and body mass. The deformation (comparing static and dynamic situations) of the ball area showed different patterns in male compared to female participants as well as children compared to adolescents. The instep height of the feet of overweight participants does not decrease more than in feet of their normal weight counterparts. Furthermore, the differences between static and dynamic situation are not distinctively higher in overweight participants.

The differences between matched groups are small considering the mean values. On the other hand the variability within the foot measures is extremely high. Therefore, the transfer into footwear design is more complex. First of all, it is important to account for the high variability. One procedure to satisfy the high variability of feet is presented by Mauch et al. (Mauch et al., 2009). This procedure, based on a cluster analysis, can be still seen as the starting point of the implementation for the dynamic changes. Since, the dynamic values are best predicted by the respective static values, the cluster analysis could be primarily used to improve the static fit. In a second step further improvements can be achieved by defining areas where most deformation or variability of the deformation was found. According to our findings this is in particular the ball area.

The dynamic customization can be implemented without consideration of gender, age, or body mass. Therefore, the dynamic adjustments can be conducted in the same way for all subgroups. However, these adjustments must be discussed individually for each foot measure. With respect to the high variability within the foot measures, the meaning of mean values of deformation must be discussed. A mean deformation value of a normally distributed foot measure implies that it accounts for only approximately 50% of the
users. Thus, the threshold should be considered for each foot measure and it can be recommended to use different quantile values instead of mean values.

Another relevant aspect is that both static and dynamic values have to be considered. The static HWB is important in two ways: First, HWB represents the foot morphology during standing as one basic task of the foot that has to be unaffectedly allowed by the shoe. Second, this situation is also one part of walking named by the double support phase. Thus, the designer should not rely on consulting only one threshold for a foot measure of a special size when constructing a last. It is recommended to define an area for the location of MTH1 and MTH5. Furthermore, the broadening of the ball width must be allowed. This can be implemented by the insertion of resilient materials. These kinds of material could further accommodate the reduced girth measures of the midfoot during walking. In this context, the improvement of lacings can also make a contribution.

Future research should focus on the dynamic foot morphology and deformation to verify the findings of the study. Furthermore, it is important to improve the scanner technology in terms of high measurement frequency and simultaneously high spatial resolution. Especially, the reduced spatial resolution of the current scanner system must be mentioned as one limitation. However, the reproducibility of the automatically calculated foot measures is very high. It is only reduced in foot measures that depend on the anatomical landmarks MTH1 and MTH5. Thus, improved software systems are necessary to guarantee a high reliability of all foot measures.

Overall, the current study confirms the high potential of dynamic scanning with the aim to customize footwear to different requirements. Furthermore, the dynamic customisation of footwear contributes to a healthy foot development in children and adolescents which is important for the whole body and a physically active lifestyle.

References

8.4 Discussion


Maier, E. and Killmann, M., 2003. [Children's feet and children's shoes. Development
of children's legs and feet and the requirements for suitable shoes for their feet].
Munich: Verlag Neuer Merkur.
The effects of gender, age, and body mass on dynamic foot shape and foot deformation

Acta Paediatrica, 84, 961-963.


Schmeltzpfenning, T., et al., 2010. Dynamic foot scanning. Prospects and limitations of using synchronized 3D scanners to capture complete human foot shape while walking. 3rd International Conference on Applied Human Factors and Ergonomics. Louisville, USA.


9 Discussion

The discussion of this thesis focuses on the examination of the hypotheses and the research question. Section 9.1 presents comprehensive considerations and supplementary aspects with regard to the three hypotheses. Already discussed aspects that are relevant for the examination of the three hypotheses are only mentioned and it is referred to details within the three research articles. In Section 9.2, findings of this thesis are critically discussed along technical and non-technical limitations as well as consequences on the performance criteria. The findings, consolidated with the theoretical background, result in recommendations for footwear and footwear construction (see Section 9.3).

9.1 Research question and hypotheses

This section aims to prove the three hypotheses (see Table 9.1) that are addressed within the three research articles. The following subsections discuss each hypothesis in the following way. First, the key findings contributing to the hypothesis are summarized. Second, the contribution to research question is elaborated. Third, the relationship among the three hypotheses are detailed.

Table 9.1: Overview of the research question and the three hypotheses

<table>
<thead>
<tr>
<th>Research question:</th>
<th>How does foot morphology differ between static and dynamic situations?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis 1:</td>
<td>There are differences in dynamic foot morphology of adults according to age, gender, and body mass.</td>
</tr>
<tr>
<td>Hypothesis 2:</td>
<td>Dynamic foot morphology of developing feet differs from static foot morphology.</td>
</tr>
<tr>
<td>Hypothesis 3:</td>
<td>Gender, age, and body mass affect the dynamic foot morphology and the differences between static and dynamic foot morphology of developing feet.</td>
</tr>
</tbody>
</table>
9 Discussion

9.1.1 First hypothesis

The first hypothesis is verified by the adult sample which comprises 129 participants. Several differences are found according to age, gender, and body mass for the three-dimensionally measured plantar foot shape of adults. The dynamic foot morphology is evaluated by the absolute change (\(\Delta \text{Dyn}\)) of each foot measure within a specified phase and the maximum of the foot measure (MaxDyn) identified in the same phase. The findings of the influences on the dynamic foot morphology, presented in Chapter 6, are novel and complement existing research results on static foot morphology (Krauss et al., 2010; Wunderlich and Cavanagh, 2001; Zifchock et al., 2006). In the following, these findings are summarized for each analysis method.

The first analysis method, based on matched pairs, revealed complex relations between dynamic foot morphology and anthropometric variables. The differences according to age, gender, and body mass are not statistically significant for all dynamic plantar foot measures. There are no differences between men and women for the maximum dynamic values of all foot measures normalized to foot length. However, the width of the ball and arch deforms to a greater extent in women (discussed in Section 6.4.1). The maximum dynamic value of all plantar foot width measures is higher for overweight participants. This is discussed with respect to increased forces due to increased body mass and coexisting similar pressure distribution patterns as a result of a greater contact area. Furthermore, overweight participants show a wider range for the deformation of medial ball length, ball width as well as angles of the ball and toes. Thus, it can be concluded that their longitudinal arch flattens more and their ball width widens more (discussed in Section 6.4.2). The deformation of the ball angle of older participants is more pronounced during dynamic situations, compared to middle-aged participants. Furthermore, the maximum of the heel width of older participants is broader during walking (discussed in Section 6.4.3). All identified differences indicate that gender, age and body mass affect dynamic foot morphology and deformation. However, the influences must be individually considered, in particular as different areas of the foot are unequally affected.

A second statistical analysis, a multiple linear regression analysis, is used to evaluate possible relationships between the variables as well as their contribution to the explained variance. The explained variance is very low for the \(\Delta \text{Dyn}\) of all foot measures. Thus, this dimension cannot be sufficiently predicted by the used variables (see Section 6.3.2). The explained variance of the maximum of all foot measures is higher. The respective
9.1 Research question and hypotheses

Static value of each foot measures is main predictor of the value for the maximum during walking. Additionally, gender and body height contribute to the explained variance of measures that describe the arch as well as the lateral ball length.

These findings contribute to the research question in the following way. The differences and thus influences are more complex and not consistent regarding all plantar foot measures. In general, the detected influences are rather small. The contribution of the first research article to the research question is that influences of gender, age, and body mass are found for the dynamic foot morphology. The identified influences on the maximum values during walking area generally in line with literature findings for static foot morphology. With respect to these findings, it is essential to know the dimension of static foot morphology and the differences between static and dynamic situations. In terms of footwear fit it can be assumed that the implementation of these differences will improve the dynamic behaviour of footwear.

The findings of the first research article are important to understand the nature of interindividual differences of dynamic foot morphology. However, additional foot measures are necessary for the implementation in footwear. Especially, girth measures are important to improve the fit of footwear. Furthermore, the analysis procedure needs to be improved to generate highly reliable foot measures by automated procedures. Generally, the knowledge of foot deformation is most important for developing feet to contribute to a physiological foot development. Therefore, children and adolescents are recruited to evaluate the dynamic foot morphology which is presented in the second and third research article.

9.1.2 Second hypothesis

The second hypothesis is proven by a large sample of children and adolescents (n = 2554). For the underlying aim to identify differences that are relevant for footwear construction, foot measures, corresponding to measures usually used for last construction, are defined. To achieve a high reliability, most of the foot measures are automatically calculated.

The second hypothesis is verified for all foot measures except the measure of foot length (discussed in Section 7.4.1). The differences between static and dynamic 3D foot morphology of developing feet have not been evaluated before. Differences are found between dynamic situation and static half weight-bearing as well as full weight-bearing situation. The differences between the two static situations are not statistically significant. However, there are statistically significant differences between the foot measures
of standing and walking, which are relevant for the implementation. These differences can be summarized, at first, with respect to their direction, followed by their practical relevance. Regarding the direction of the differences, there are increased values during dynamic situations compared to loaded static situations in foot length, width, and height measures as well as angles of the ball. However, differences between static and dynamic heel width are small. The identified differences of medial and lateral ball length showed similar mean value, which has not been reported before (discussed in Section 7.4.1). The values of the angles increase in the dynamic situation. The ball angle is more obtuse-angled during walking. The increased angles of the toes indicate that the forefoot is pointier during the dynamic situation. Thus, the dynamic values of the toe angles cannot be used as a guideline for last construction. The consequence of using these dynamic values would be a permanent pressure during standing which would influence the physiological development. All midfoot girth measures are decreased in dynamic situations compared to loaded static situations. This is discussed with respect to muscular activity and it is related to higher values of the instep height during walking (discussed in Section 7.4.1).

In order to consider the relevant differences for implementation, the repeatability of each foot measure is calculated. This is conducted by a repeated performance of the analysis procedure. The intra-class correlation coefficient (ICC) and the root mean square error (RMSE) are calculated within a smaller sample. Information about the reliability as well as increments of the grading of shoes is evaluated to interpret the results in terms of their relevance for the implementation in footwear design (see Table 7.6, discussed in Section 7.4.1). The reliability of foot measures that are independent from visually detected anatomical landmarks is high. Furthermore, the reliability is still acceptable for the foot measures depending on the anatomical landmarks. The differences between static and dynamic values of orthogonal ball width and all midfoot girth measures are practically relevant. These measures are highly reliable and the magnitude of their differences comprise on average half of the grading increments (discussed in Section 7.4.1).

The second hypothesis is verified along the presented research article. Furthermore, the results are assessed regarding their practical relevance. The confirmation of the second hypothesis provides an essential contribution to the research question. There are relevant differences between static and dynamic foot morphology of developing feet. Up to now, differences between static and dynamic foot morphology have only been assumed
in footwear construction and mainly focused on foot length. The findings of this research article show that all foot measures differ between static and dynamic situations. Thus, dynamic customization is important to improve the dynamic fit of footwear.

The findings of the second research article provide important information to improve the dynamic fit of footwear for developing feet. However, the high variance within each foot measure does not allow to directly implement the results. Prior to that, it must be clarified if there are influences on the dynamic deformation that can explain the variance. As some influences of gender, age, and body mass were found within the adult sample, these influences have to be analysed within the sample of children and adolescents. The third research article analyses these influences to finally clarify if the customization must be adjusted to gender, age, or body mass.

9.1.3 Third hypothesis

The influences of gender, age, and body mass on the differences between static and dynamic foot morphology are very important to decide if dynamic customization must be further specified according to these anthropometric variables. The influences are identified by two different statistical procedures: First, a comparison of matched pairs and second, a multiple linear regression analysis. The multiple linear regression analysis is calculated within the whole sample. In addition, matched pairs are formed out of the whole sample according to gender, age, and body mass (see Section 8.2.1 and Section 8.2.5).

The third hypothesis is verified according to the results of the third research article. There are influences of gender, age, and body mass on the dynamic foot morphology and the differences between static and dynamic foot morphology. However, these influences must be individually regarded and assessed for each foot measure (discussed in Section 8.4). Furthermore, the high variance within each foot measure has to be considered. The explained variance of the differences between static and dynamic foot measures is small. Thus, the relevance of the identified influences is reduced and it can be concluded that the dynamic customization can be conducted without consideration of gender, age, or body mass. The comparisons of the matched pairs show that there are different patterns of deformation of the ball area especially between male and female as well as children and adolescents. The differences of the maximum value during walking between male and female, overweight and normal weight, and younger and older subgroups are more distinctive. This can be further explained with consideration of the
results of the multiple linear regression analysis. The respective static value is included in each model and the conclusion is that the static value best predicts the dynamic value (discussed in Section 8.4.1). This explains the similar influences of gender, age, and body mass on static and dynamic foot morphology. The conclusion is that the static loaded situation is still important for fitting footwear.

The contribution to the research question is that these findings explain the nature of the differences from a more qualitative point of view. The variance of the differences between the static and dynamic foot morphology could not be sufficiently explained. Possibly, there are other variables that can explain this variance. The more practical conclusion is that the dynamic customization can be conducted without consideration of gender, age, and body mass. However, the variance must be reflected for example by the application of resilient materials.

The findings of the influences are also more complex, similar to the identified influences within the adults sample. In addition to the second research article, these results allow formulating comprehensive recommendations for the construction of footwear for developing feet (presented in Section 9.3).

9.2 Limitations

Content of this chapter is a critical assessment of the overall results. This is carried out with regard to technical limitations but also non-technical limitations. All aspects are used to assess the consequences for quality criteria.

9.2.1 Technical limitations

The results of this study must be critically discussed, particularly, in view of the scanner system and its limitations. The main limitation of the current system is the reduced spatial resolution which is chosen to guarantee the high measurement frequency. The used binning mode results in a reduced density of the calculated points of the point cloud. Thus, it can be assumed that some information might be lost. However, the accuracy of the current system is very high as presented in Appendix A.3 (see Table A.1). Furthermore, the calculation of the root mean square error (or technical error of measurement) in different spatial resolution modulations provides reliable results. This analysis is performed by measuring a bowling ball in static situation as well as dynamic situations with
9.2 Limitations

controlled and varied velocity (see Table A.1). Thus, the validity and reliability of the scanner system is high and allows the conclusion that the lost information due to reduced spatial resolution is negligible.

The results of the comparison of different spatial resolutions and measurement situations show a trend of a higher variance with increasing velocity of the bowling ball. This is also obvious in the dynamic sequences of the recorded feet. The quality of the 3D point clouds is reduced when feet move faster. This is the case when the forefoot heads to touch the ground and also when the hindfoot takes off. Thus, the interpretation of foot measures is only legitimated when the respective area is on the ground and thus movement velocity is lower. This is in line with information, needed for dynamic customization of footwear. Hereby, the maximum deformation is relevant which is expected when the respective foot area has contact with the ground and body weight is operating on this area.

The technical limitations of the scanner system are also responsible for a high proportion of dropouts. In particular, the illumination of the feet is challenging and very sensitive for the colour of the skin. The solution for the captured samples was to individually adjust the illumination of each projector to each subject and situation to ensure best possible results. Therefore, considerable time was required to scan each foot and some obtained scans still showed limited quality. The modulation of the illumination could not be optimally performed for some subjects with dark coloured or irregularly tanned feet, which led to several dropouts.

The analysis procedure is automated for most of the foot measures. However, some measures depend on the anatomical landmarks MTH1 and MTH5. These landmarks are visually detected as a result of the decreased repeatability of the automated calculation. The repeatability is mainly reduced for the ball angle that relies on both visually detected landmarks (MTH1 and MTH5). Thus, the applicability of the findings regarding the ball angle is reduced which is taken into account for the formulation of the recommendations.

Another critical aspect is that calculated measures only provide a subset of the information, even if the 3D object is available. This can be legitimated by the aim to supply applicable results for last construction and to improve the fit of footwear. The typical procedure for the design of lasts is described in Section 3.1. This highlights the reliance to traditional handcraft. Thus, the focus of the defined measures was to derive practically relevant findings for implementation.
9 Discussion

The extraction of the maximum out of each dynamic trial must also be critically considered. This procedure possibly disregards some qualitative information about the changes during the dynamic phase. The reason for considering the maximum of each foot measure is that the main aim is to improve the dynamic fit of footwear. Goonetilleke et al. found that more pressure effects more discomfort (Goonetilleke et al., 1994). Thus, the maximum of deformation is relevant to improve the dynamic fit of footwear as it reflects the spatial need of the foot during walking.

Future challenge is to develop appropriate software that allows a more comprehensive interpretation of the roll-over process. For example, surface areas or volumes can provide additional information which can be used to improve material characteristics or allow the definition of areas where special material characteristics are required.

9.2.2 Non-technical limitations

In general, it is not predictable if the foot would feature the same dynamic characteristics when it is supported by a shoe that is constructed on the described findings. However, it can be assumed that especially improved material characteristics within the identified areas can reduce dynamic pressure and friction which is often seen as main reason for foot deformities or injuries.

Another limitation of the presented results is the high variance within the foot measures. This is a main challenge for the implementation of the results. Reasons for the high variance are presented in Section 2.4. A procedure to account for the high variability of feet and thus to improve the fit of footwear is based on static foot scans presented by Mauch et al. (Mauch et al., 2009). This is still regarded as the first step for the improvement of footwear fit. Building on these static foot types, the dynamic customization can further enhance footwear fit.

The aim of this thesis is to give recommendations for last construction. For this reason, the deficits of lasts have to be specified. Thus, comparisons between already improved lasts on the base of the mentioned procedure of Mauch et al. (Mauch et al., 2009) and children feet are conducted to ascertain deficits of lasts. The comparisons are performed for lasts of three different foot types for the sizes EU 33 and 37. Detailed findings are presented in the Appendix A.4 (see Table A.2 and Table A.3). In summary the differences are apparent for all shoe sizes and foot types and mainly concern the construction of MTH1 and MTH5, all girth measures, forefoot width and the design of
9.2 Limitations

the toe box (see Appendix A.4, Table A.2 and Table A.3). Especially, the differences of
the lateral ball length are alarming and may cause increased pressure along with changed
functional characteristics of the shoe. Another concern is the design of the toe box. The
more pointy shape of the shoe exert pressure toward the first and fifth toe. The girth
measures are increased on the lasts. This can be explained by the production-related needs
to remove the last from the manufactured shoe but also the opportunity to individually
adjust this area by lacings. Nonetheless, it is recalled that the girth measures are very
important for holding the foot within the shoe. This must be discussed together with
the allowance in front of the toes. The representative findings are particularly important
to confirm the necessity to give recommendation for last construction.

Nevertheless, it is essential to conduct constructive studies to evaluate the improve-
ment of the dynamic fit of footwear by the presented findings. These studies should
be designed for younger and older subjects to identify short-term as well as long-term
effects. Definitely, longitudinal studies in consideration with individual behaviour as well
as genetic dispositions are essential to identify and finally assess the effects of improved
footwear.

9.2.3 Evaluation of quality criteria

The quality criteria based on the classical test theory include objectivity, validity, and
reliability. Considering this classical test theory, it is attempted to derive the true value
on the base of the measurement value. The focus is on the accuracy of measurements,
i.e. the measurement error. Only a small measurement error allows the conclusion that
the method and as a consequence the approximation to the true value is reliable. The
three quality criteria are considered for the findings of this thesis.

The objectivity of the findings of this thesis is considered by standardizing several pro-
cesses prior to the measurements. The measurement protocol was defined and followed
for all measurements. Particular emphasis was placed on equal performance and instruc-
tions of walking and standing tasks. Furthermore, the recording of dynamic situations was
standardized by predefining walking speed which was adjusted to body height (Chapter 7,
Table 7.2). The subsequent examination of the foot measures was also standardized and
furthermore operated by one person. The objectivity was further improved regarding
the analysis procedure of the second sample of children and adolescents (see Chapter 7
and Chapter 8). Most of the analysed foot measures were automatically detected and
calculated to ensure the independency of tester. Therefore, it can be concluded that the objectivity of the obtained results is high.

The validity, as the question of the true value, was determined by recording a bowling ball in static and dynamic situations and calculating the root mean square error (RMSE), also known as technical error of measurement (TEM). The results presented in the Appendix A.3 (see Table A.1) show that the deviance of the measured girth of the bowling ball is rather small but depends on the situation as well as the modulations. As no comparable dynamic scanner system is available the validity of the foot measures must be indirectly estimated by the evaluation of reliability.

The reliability of the results is affected by the analysis procedure. Thus, the repeatability of the analyses procedure was examined. This is performed within a smaller sample and determined by ICC as well as RMSE (Chapter 7, Table 7.6). Regarding the values for ICC, the conclusion is that all foot measures offer a very high reliability. However, the findings must be more critically assessed by the consideration of the values for RMSE. The RMSE presents values in the same measuring unit as the respective foot measures. Thus, it can be concluded that the automatically calculated foot measures are highly reliable. Whereas, the foot measures depending on the visually detected anatomical landmarks MTH1 and MTH5 offer restricted reliability. The future aim must be to fully automate the calculation of all foot measures.

### 9.3 Recommendations for footwear

All three hypotheses provide an important contribution to better understand the differences between static and dynamic foot morphology and thus help to answer the research question. The design of the second and third study aimed to identify relevant differences for last and footwear construction. Thus, the recommendations for footwear and footwear construction are mainly derived by findings of the second and third research article. Furthermore, it can be stated that these improvements are most important for shoes of developing feet as they are especially prone to external influences.

The special requirements of footwear to satisfy the dynamic fit was already stated by Golding in 1902: "Boots that may be correct to stand in may not be correct to walk in." (Golding, 1902, p. 37). To improve the dynamic fit of footwear, the results of the study are used in combination with the theoretical background. The recommendations consider both the construction of lasts as well as the used material for footwear.


**Recommendation 1:** Dynamic foot morphology must be considered in footwear construction.

In general, the full weight-bearing situation cannot be used as a quasi-dynamic situation. There are changes between full weight-bearing and the maximum during walking for each foot measure. Thus, information about dynamic changes must be used to improve dynamic fit of footwear.

**Recommendation 2:** Static foot morphology is the starting point for improving footwear fit.

The results of the first and third research articles recommend using the static value as a starting point of the improvement of footwear fit. The static values are highly influenced by anthropometric variables like gender, age, and body mass and provide a high variability. The same applies to the maximum values of dynamic foot measures. Furthermore, these dynamic values can be best predicted by the static values and the variance of the differences between static and dynamic values cannot be explained by the same anthropometric variables. The recommended two-step procedure to achieve best footwear fit is to adopt the approach, based on cluster analysis, of Mauch et al. (Mauch, 2007; Mauch et al., 2009) to account for the variance of feet. The second step is the dynamic customization. This dynamic customization is specified in recommendation 5. This procedure is supposed to achieve best static and dynamic fit of footwear. Furthermore, it is in line with previous suggestions to fit shoes in loaded situations (Cheng et al., 1997).

**Recommendation 3:** Anthropometric variables must not be considered for dynamic customization.

There is no need to account for the anthropometric variables gender, age, or body mass to implement the examined dynamic changes. The variance of the differences between static and dynamic foot morphology cannot be explained by these variables. Therefore, the dynamic customization can be equally implemented for all shoes.

**Recommendation 4:** Mean values are not suitable to account for the variance of foot morphology.

The high variance of the values for the foot measures proposes to use alternatives to mean values. The presented results show that mean values cannot account for the variance within foot measures. This is even more obvious when comparing measures.
taken on a last with foot measures (see Appendix A.4, Table A.2 and Table A.3). To account for the variance of foot measures, thresholds must be defined using quantiles (i.e. percentiles). The reason to use quantiles instead of mean values is that there might be serious restrictions if values are used that cover about the half of the sample. This comes true when the foot measure is normally distributed, i.e. the median and the mean value are very close together. This must be individually considered for each foot measure. Furthermore, material characteristics must be taken into account for this discussion. Thus, “intelligent” materials could be used, which do not restrict feet that deform more but also support feet that do not need more space. This can point the way for future research and material development as well as testing of footwear.

**Recommendation 5:** Joint consideration of static and dynamic foot morphology for footwear construction.

Static and dynamic foot measures must be considered for the improvement of shoe lasts. Both situations are performed within the shoe and no situation should be impeded. Therefore, static loaded and dynamic values of each foot measure must be considered. It is important that the customization is discussed individually for each foot measure. The recommendations for improving footwear fit, based on consideration of foot deformation, are specified with respect to three aspects. First, the discrepancy between shoe lasts and children’s feet (see Appendix A.4, Table A.2 and Table A.3) is considered. Second, the tendency of the dynamic change compared to static foot morphology is reflected. Third, the relevance of the dynamic changes with regard to repeatability of foot measure as well as sizing and grading of footwear (discussed in Chapter 7, p. and Table 6, p. ) is taken into account.

**Recommendation 5.1:** MTH1 and MTH5 move forward during dynamic situations. Especially, MTH5 is located too far forward on lasts. The construction of MTH1 and MTH5 should base on a defined area to account for the static and dynamic situations. Furthermore, to cover the high variance for example 10th percentile of static foot measures and the 90th percentile of dynamic measures can be used.

**Recommendation 5.2:** The forefoot width increases during dynamic situations. The comparison of lasts and feet shows that in general the forefoot width is reduced on lasts. Furthermore, the widest part on the last is not located at the same area, compared to
the foot. Two solutions are feasible: First, the last is constructed on the base of the dynamic maximum (for example 90th percentile). Second, resilient materials, allowing the widening in this area, are used.

**Recommendation 5.3:** The midfoot girth measures are reduced during dynamic situations. On the last, all values of girth measures are higher than the values measured on the feet. To ensure the necessary hold within the shoe, this must be considered, either by using improved lacings or by resilient materials. These materials need excellent recovery properties to optimally support the foot during walking without exerting firm pressure during static loaded situation.

**Recommendation 5.4:** The toe angles increase during dynamic situations which means that the forefoot is more pointy during walking. The angles measured on lasts are further increased. The recommendation is to use static values to avoid high lateral pressure against the toes and thus a deflection of the toes in static loaded situations.

**Recommendation 5.5:** The heel width increases during walking. The changes between static loaded situation and maximum during walking are rather small. The discrepancy between the used lasts and the children’s feet is also small. The lasts should be constructed based on the maximum dynamic values of the heel width. However, the need for action is rather low.

**Recommendation 5.6:** Instep and ball height are generally higher during dynamic situations compared to static loaded situations. The height values are higher on lasts. The reason for that is the possible adjustment of this area due to lacing. Thus, this discrepancy is not alarming but should be considered with respect to used materials and lacings. The ball height must be considered with focus on resilient materials.

**Recommendation 6:** The allowance of about 12 mm is sufficient for all shoe sizes. The allowance is calculated for each shoe size and is presented in the Appendix A.5 (see Table A.4 and Table A.5). The sum of foot extension and advance as well as semi-annual growth rate is rather small and not influenced by foot length. However, the used mean values only account for approximately half of the sample (as the values are normally distributed). Thus, another calculation approach is used based on the 90th percentile.
These results are novel as it is the first approach to calculate the allowance out of scanned 3D data. The conclusion of this calculation is that the foot do not need that much space for extension and advance. However, the space for growing is very important and as a consequence the fit of children’s shoes must be regularly checked. The amount of the toe allowance is smaller than previously assumed. There is very little literature that gives data for the amount of the toe allowance. The suggestions from Maier and Killmann are generated from footprints and thus the approximated values are higher (Maier and Killmann, 2003).
10 Conclusion and perspectives

This thesis presents different aspects to answer the question of how foot morphology differs between static and dynamic situations. The answer to that question is significant from different perspectives: First, the findings contribute to the field of fundamental research, as there is still a lack of three-dimensional data for dynamic foot morphology. Second, the comparison of static and dynamic foot morphology can help to improve the fit of footwear and thus contribute to applied research in the field of footwear science. Recent advancements in scanner technology and the development of a dynamic foot scanner system (DynaScan4D) are preconditions for this thesis. Furthermore, literature based considerations are used to formulate the hypothesis but also to allow giving recommendations for the construction of lasts and footwear.

In Chapter 2, the anatomical and functional basics of the foot are described with focus on functional characteristics. In this context, the developmental processes are outlined which strongly interact with functional changes due to upright standing and walking. The challenge of "the shoe" that fits is reflected in the last section of this chapter which discusses the variety of foot shapes with reference to the inter-individual differences. Finally, known intra-individual differences are highlighted.

Chapter 3 presents fundamentals of footwear, starting with basic knowledge of how a shoe arises. Feet are as diverse as each fashion taste, thus, shoe manufacturers are compelled to produce different sizes. The aspects of sizing and grading are discussed with a view to standardization. Even if several sizes, widths, and shapes of shoes are available, not every foot is optimally supported by intent or grossly negligent behaviour. Thus, knowledge about the effects of shoes on feet but also knowledge about footwear fit is elaborated based on current literature. As it is stated that foot shape and shoe or last shape must be matched, it goes back to the point of measuring feet by basic methods but also current approaches of dynamic scanning.

On the base of the literature, three hypotheses are formulated in Chapter 4. These hypotheses provide relevant contributions to the research questions. The first hypothesis
10 Conclusion and perspectives

is that there are differences in dynamic foot morphology of adults according to age, gender, and body mass. This hypothesis was verified within Chapter 6. The analysis of 129 adult feet during walking showed that there are differences which must be differentiated.

The second hypothesis is verified within Chapter 7. Dynamic foot morphology of developing feet differs from static foot morphology. This was proven for all foot measures; however, the differences vary depending on the foot measure. The relevance of these differences was assessed with regard to the sizing and grading systems but also to the values for the error (RMSE).

In Chapter 8, the third hypothesis was evaluated. The hypothesis that gender, age, and body mass affect the dynamic foot morphology and the differences between static and dynamic foot morphology of developing feet was verified. However, the influences of anthropometric variables are more complex. In general, for the maximum during walking they are comparable to the influences on the static foot morphology. The variance of the difference between static and dynamic foot morphology cannot be sufficiently explained by gender, age, and body mass.

The confirmation of the hypotheses is summarized and the contribution to the research question is reflected in Chapter 9. This chapter additionally includes critical considerations of the results with reference to technical and non-technical limitations. Furthermore, the quality criteria, objectivity, validity, and reliability, are discussed. The results mainly obtained from the second sample (Chapter 7 and Chapter 8) in combination with literature review and practical aspects but also in consideration of the limitations are used to provide recommendations for the improvement of the dynamic fit of footwear.

The findings of this thesis are important to improve basic knowledge of foot deformation. Furthermore, the elaborated recommendations can contribute to further improvements for comfortable and functional footwear. Even if these findings must be validated by other scanner systems, it can be stated that they contribute to healthy feet which is essential during development.

A high potential to improve footwear fit might be reached by material characteristics which can be implemented in defined areas. To achieve this, the analysis approach of the 3D scan data must be further developed, i.e. description of surface deformation or calculation of volumes. However, the presented findings can encourage last designers and shoe manufacturers to implement these aspects and probably pursue new approaches for standardization.
The aim of further studies should be to evaluate the dynamic fit of footwear. For that reason, prototype shoes must be constructed and several standardized tests as well as surveys should be performed. In terms of detailed and reliable feedback, it is recommended to perform this evaluation of improved footwear with adolescents or adults. The reason for this can be found in the not fully matured sensor function of children’s feet which might confound the evaluation. Furthermore, a considerable scientific benefit would be to investigate the long term effect of these shoes. This is undoubtedly challenging but also profitable regarding the economic burdens of the health care systems, caused by foot problems.

This thesis shows an area of application for dynamic scanner systems in which beneficial findings were generated on the base of comprehensive samples. Additionally, it provides suggestions regarding further development of dynamic foot scanner systems. The calculation of the foot measures must be optimized, in terms of automation, to ensure the reliability of the foot measures. Furthermore, additional information about the quality of footwear for example by interpretation of the path of curves, or the assessment of the surface deformation of special areas can improve the understanding of foot deformation and the requirements within a shoe.

Regarding the scanner technology, it would be beneficial to supply a higher resolution but also a higher measurement frequency. These advancements would allow capturing faster and also highly demanding movements. To this end, further studies can provide a substantial contribution for functional footwear in the field of safety or sport shoes.

Finally, the findings of this thesis can contribute to the health of us all. Hopefully, some sensitising details serve suggestions to think about our feet before they are hurting and before serious health implications arise. From an evolutionary perspective, provocatively, it cannot be our aim that once our feet look like our shoes as “Nature does nothing in vain” as Aristotle (384-322 B.C.) said (Columbia World of Quotations, 1996).
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Appendix A

A.1 Information about the aim and content of the study for children and their parents
Information an die Kinder

Hallo,

läufst Du im Sommer auch gerne barfuß?

Aber für steinige Böden oder wenn es draußen nass und kalt ist, brauchen wir Schuhe um unsere Füße zu schützen. Die Schuhe sollten gut passen und nirgends drücken.

Denn Kinderfüße sind nicht wie die erwachsenen Füße. Sie sind noch nicht vollständig entwickelt und können durch falsche, nicht passende Schuhe geschädigt werden.

Am besten wäre ein Schuh, der sich beim Gehen, Hüpfen, Laufen richtig mit bewegt. Um heraus zu finden, wie sich die Füße bei der Bewegung verformen, möchten wir – eine Forschungsgruppe der Sportmedizin Tübingen – Deine Füße vermessen. Mit den gesammelten Informationen überlegen wir dann, wie ein guter Schuh aussehen und sich mit bewegen sollte.


Zum Schluss messen wir dann noch Deine Größe und Dein Gewicht und schauen, welche Schuhgröße Du hast.

Auf Dein Kommen freut sich
das Team der Fuß-Vermessung.
Entwicklung eines dynamischen Kinderschuhs.
Messung der Fußmorphologie in der Bewegung bei Kindern und Jugendlichen im Alter zwischen 6 und 16 Jahren.

Liebe Eltern,

der Forschungsbereich Biomechanik der Abteilung Sportmedizin der Universitätsklinik Tübingen führt unter der Leitung von Dr. Stefan Grau und Bettina Fritz eine wissenschaftliche Studie durch, die der Frage nachgeht, wie sich die Fußform während der Bewegung verändert und wie demnach ein „Dynamischer Kinderschuh“ aussehen sollte, der eine optimale Passform und Fußgesundheit gewährleisten kann.


Viele Menschen haben Probleme mit ihren Füßen, was nachweislich Auswirkungen auf den gesamten Körper haben kann. Das Tragen von Schuhen, die nicht optimal der Fußform entsprechen und möglicherweise eine Fehlbelastung während des Gehens provozieren, kann Fehlbildungen, Überlastungen und Schmerzen in Beinen und Rücken zur Folge haben. Mit der Teilnahme Ihres Kindes an der Studie können Sie einen kleinen Beitrag dazu leisten, die Fußgesundheit von Kindern zu wahren.

Im Zeitraum vom ______ bis ______ sind in _______ Kinder im _______ Klassenverband in die Studie eingebunden. Die Daten werden im Zeitverlauf regelmäßig in einem Umkreis von Lehrern ausgewertet. Hier werden der Spezifitätsuntersuchung im Rahmen der Schulleitung und den Lehrern, die die Füße von Schülern und Schülerinnen der __ Klasse vermessen.


Für die Untersuchung werden zunächst Körpergewicht und Körpergröße gemessen, sowie die aktuelle Schuhgröße dokumentiert. Die eigentliche Messung findet auf

Die während der Studie erhobenen Daten werden ohne Verwendung des Namens (anonym) in unsere Datenbank aufgenommen und dort gespeichert. Die gespeicherten Daten können nur von der Studienleitung und den zuständigen Untersuchern eingesehen werden, die bezüglich der Daten der Schweigepflicht unterliegen.

Wir möchten Sie bitten, uns mit der beiliegenden Erklärung (Abschnitt unten) Ihre Einverständnis zu geben, die Daten Ihres Kindes ohne Namensnennung (anonym) auf elektronischen Datenträgern und Fragebögen aufzeichnen zu dürfen. Sie erlauben uns damit zugleich, dass wir mit den Ergebnissen im Hinblick auf die oben genannten Fragestellungen arbeiten dürfen und diese statistisch auswerten können. Die Weitergabe der erhobenen Daten an Dritte (d.h. Personen, die mit der weiteren Bearbeitung der Daten betraut sind), die Auswertung sowie eine mögliche Veröffentlichung der Ergebnisse erfolgt ausschließlich in anonymisierter Form (d.h. ein Personenbezug kann anhand dieser Daten ebenfalls nicht hergestellt werden).

Während der gesamten Untersuchung wird das Prinzip der Freiwilligkeit eingehalten. Wenn ein Kind/Jugendlicher, trotz vorliegender Einwilligungserklärung der Eltern, die Untersuchung nicht durchführen möchte wird die Untersuchung unmittelbar abgebrochen.

Mit freundlichen Grüßen

Bettina Fritz
A.1 Information about the aim and content of the study for children and their parents

Bitte geben Sie diesen Abschnitt bis zum _________ beim Klassenlehrer ab!

Einwilligungserklärung

Entwicklung eines dynamischen Kinderschuhs.
Messung der Fußmorphologie in der Bewegung bei Kindern und Jugendlichen im Alter zwischen 6 und 16 Jahren.


Ich erkläre mich damit einverstanden, dass mein Kind an der Studie teilnehmen darf.

Die im Rahmen dieser Studie erhobenen Daten von meinem Kind dürfen ohne Namensnennung auf Fragebögen und elektronischen Datenträgern aufgezeichnet werden.

Die Weitergabe der erhobenen Daten an Dritte (d. h. Personen, die mit der weiteren Bearbeitung der Daten betraut sind), die Auswertung sowie die Veröffentlichung der Daten erfolgt ausschließlich in anonymisierter Form (d. h., ein Personenbezug kann anhand dieser Daten nicht hergestellt werden).

__________________________  ________________________
Proband/in (Name, Vorname)  Klassenstufe

__________________________  ________________________
Ort, Datum  Unterschrift
A.2 Case report form
### DynaScan4D Messung bei Kindern und Jugendlichen

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- Schuhgröße (abgelesen): ❑ ❑ ❑
- Innenschuh-Länge (mm): ❑ ❑ ❑ ❑ ❑

**Auffälligkeiten (z.B. Hallux valgus, Rötung, Schwielen, Hornhaut)**

---

**Messprotokoll: DynaScan4D**

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<td>dynamisch_3</td>
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Bemerkungen:

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185
A.3 Comparison of measurements of a bowling ball with varying spatial resolution and several static and dynamic situations
**Table A.1: Measurement results of a bowling ball measured in static and dynamic situation with different spatial resolution**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Bowling ball circumference [mm]</th>
<th>Static Full resolution [mm]</th>
<th>2x2 binning mode [mm]</th>
<th>Dynamic 2x2 binning mode [mm]</th>
<th>Dynamic 4x4 binning mode [mm]</th>
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<td>30.42</td>
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<td>0.12</td>
<td>0.05</td>
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**SD = standard deviation; RMSE = root mean square error**
A.4 Comparison of last and foot measures

Comparison of foot measures taken on scanned lasts compared to the children's feet with the respective foot length. The type of the last as well as of each foot was determined by the procedure of Mauch et al. (Mauch et al. 2009).
Table A.2: Mean and standard deviation of the foot measures calculated from scanned lasts and children’s feet of shoe size EU 33

<table>
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<tr>
<th>Size [EU] Type</th>
<th>Side</th>
<th>HWB</th>
<th>FWB</th>
<th>MaxDyn</th>
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<td>mid</td>
<td>right</td>
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<td></td>
<td>21</td>
<td>26</td>
<td>20</td>
<td>22</td>
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<tr>
<td>Medial ball length [mm]</td>
<td>Last</td>
<td>148.6 ± 3.3</td>
<td>148.5 ± 3.2</td>
<td>149.0 ± 3.0</td>
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<tr>
<td>Lateral ball length [mm]</td>
<td>Last</td>
<td>129.0 ± 4.6</td>
<td>129.2 ± 3.2</td>
<td>128.8 ± 3.9</td>
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<tr>
<td>Orthog. ball width [mm]</td>
<td>Last</td>
<td>74.4 ± 3.9</td>
<td>74.4 ± 3.9</td>
<td>74.0 ± 3.9</td>
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<tr>
<td>Last ball girth [mm]</td>
<td>Last</td>
<td>184.6 ± 5.9</td>
<td>185.6 ± 5.1</td>
<td>185.6 ± 5.1</td>
</tr>
<tr>
<td>Last waist girth [mm]</td>
<td>Last</td>
<td>185.0 ± 6.9</td>
<td>185.0 ± 5.6</td>
<td>183.1 ± 6.2</td>
</tr>
<tr>
<td>Last instep girth [mm]</td>
<td>Last</td>
<td>180.6 ± 7.2</td>
<td>180.5 ± 5.3</td>
<td>180.1 ± 6.6</td>
</tr>
<tr>
<td>Ball angle [°]</td>
<td>Last</td>
<td>74.3 ± 3.3</td>
<td>74.0 ± 2.1</td>
<td>73.3 ± 3.2</td>
</tr>
<tr>
<td>Toe 1 angle [°]</td>
<td>Last</td>
<td>18.5 ± 4.4</td>
<td>18.5 ± 4.7</td>
<td>18.4 ± 4.7</td>
</tr>
<tr>
<td>Toe 5 angle [°]</td>
<td>Last</td>
<td>5.8 ± 3.7</td>
<td>5.8 ± 4.0</td>
<td>5.8 ± 3.9</td>
</tr>
</tbody>
</table>

Note: The table includes measurements for both left and right sides, with standard deviations provided.
| Type       | Side  | N  | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   | left | ±   | right | ±   |
|------------|-------|----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|------|-----|-------|-----|-----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A.5 Calculation of the allowance based on the three components semi-annual growth rate, foot advance and foot extension
### Table A.4: Toe allowance calculated on the base of mean values

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</table>

EU = European Scale aka French Scale
### Table A.5: Allowance calculated on the base of the 90th percentile

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<th>Shoe size [EU]</th>
<th>Foot length mm</th>
<th>semi-annual growth mm</th>
<th>90% quantile advance mm</th>
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</table>

EU = European Scale aka French Scale
Affidativ

I, Bettina Barisch-Fritz, born in Sigmaringen on 10th May 1982, hereby declare that I wrote this dissertation at hand on my own, that I did only use the sources and materials referred to and that each citation is made explicit. Moreover, I declare that I did neither use the dissertation in this or any other form as a thesis nor submit the work as a dissertation to another faculty.

Tübingen, 18th February 2014

Bettina Barisch-Fritz
Contributions to research articles

This thesis includes chapters that have been published as journal articles:


All three manuscripts were written by the candidate, Bettina Barisch-Fritz. For the first article, she contributed in data acquisition, statistical analysis and data interpretation. She was responsible for preparation and submission of the manuscript as well as responding to reviewer’s comments.

The second and third article arose under her full responsibility. She developed the study and analysis design, recruited the participants, and performed the data acquisition and analysis. She prepared and submitted the manuscripts and responded to reviewer’s comments.

Bettina Barisch-Fritz
Candidate
Curriculum vitae

Personal Data
Name: Bettina Barisch-Fritz
Date of birth: 10.05.1982
Location of birth: Sigmaringen

Education
1988 – 1992 Elementary School, Irndorf
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Academic Education
2002 – 2008 Diploma of Sport Science
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2010 – 2013 PhD studies in the field of Biomechanics
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2005 – 2006 Student Assistant at the Institute of Sports Science
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Danksagung

Der Dank geht an viele Menschen, die mich auf dem Weg der Promotion begleitet und unterstützt haben. Allen voran danke ich Prof. Dr. Thomas Milani für die Betreuung und Begutachtung der Dissertation. Mein Dank geht besonders an Prof. Dr. Stefan Grau, der mein Vorhaben zu promovieren entfesselt und vorangetrieben hat. Durch sein Vertrauen, seine Unterstützung und Motivation konnte ich viele wichtige Erfahrungen durch Kongresse aber auch durch den Forschungsaufenthalt in Australien sammeln.


Dem weiteren Team der Sportmedizin mit PD Dr. Inga Krauß, Dr. Tobias Hein, Dr. Benjamin Steinhilber, Georg Haupt, Regina Miller, Dr. Pia Janßen und allen anderen danke ich für das einzigartige Klima sowie fachliche und kritische Diskussionen. Prof. Dr. Andreas Nieß danke ich für die großartige Unterstützung, insbesondere für die Bereitstellung der benötigten Ressourcen während Messphasen. Hierbei gilt der Dank den vielen Bufdis, Hiwis, Praktikant/innen und Absolvent/innen, die mit viel Engagement und Tatendrang ermöglicht haben eine so große Stichprobe zu erfassen.

Herr Peter Lauer war ein wertvoller Diskussionspartner. Durch seine Offenheit und seine
Erfahrung ermöglichte er mir tiefe Einblicke in die Schuhindustrie.

Meinen Freunden, besonders den Tübinger Mädels, bin ich dankbar für ihr Verständnis während dieser Zeit. Die vielen gemeinsamen Unternehmungen haben mir Kraft und Bestätigung für meinen Weg gegeben.

Besonderer Dank geht an meine Eltern Herta und Rudolf, die mich immer unterstützt haben und immer für mich da sind.

Zuletzt danke ich der wichtigsten Person in meinem Leben, meinem Mann Dr. Marc Barisch, der diese Zeit am nächsten miterlebt hat. Er hat mich unglaublich unterstützt, methodisch und mental aber vor allem durch seine Liebe.