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COMPREHENSIVE REVIEW OF FOOT MEASUREMENTS TERMINOLOGY IN USE

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COMPREHENSIVE REVIEW OF FOOT MEASUREMENTS TERMINOLOGY IN USE

ABSTRACT

Digital foot measurements are typically obtained from foot scanners or digital measuring software providers and they are consumed (or used) by footwear brands, orthotic workshops, size recommendation platforms, or even directly by footwear and orthotics users. IEEE SA Industry Connections (IC) 3D Body Processing (3DBP) Footwear Subgroup recommends that each digital foot measurement provider make measurement definitions publicly available for foot measurement data consumers. Foot scanning companies are providing measuring software that follow different definitions. This is particularly problematic in the case of key references, such as the foot axis. Many measurements are dependent upon the definition of the foot axis, giving rise to different values assigned to the same designation. This compilation will facilitate the comparison across definitions for measurement data consumers and help them make informed decisions.

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1. RECOMMENDATION

Digital foot measurements are typically obtained from foot scanners or digital measuring software providers and they are consumed (or used) by footwear brands, orthotic workshops, size recommendation platforms or even directly by footwear and orthotics users. The recent large-scale installations of foot scanners into footwear retail makes it possible to collect large data sets of customer foot data. These data sets provide new opportunities for footwear brands to use the data when designing and grading footwear.

IEEE SA Industry Connections (IC) 3D Body Processing (3DBP) Footwear Subgroup recommends that each digital foot measurement provider make measurement definitions publicly available for foot measurement data consumers.

Why is it important that foot measurement definitions be publicly available? Mainly, it is to help data consumers make informed decisions. For instance:

- Brands need to understand the process used to obtain measurements if the brand is tying their process to a particular measurement input technology.
- Shoe-size recommendation platforms utilizing more than one input device (e.g., scanner smartphone app, or traditional manual approaches) need to understand the definitions underlying the methods or risk misinterpreting the output.
- A user may wish to use his/her acquired measurements with a specific device/technology and use them in different contexts, such as selecting footwear by stated size online or selecting foot orthotics.
- A researcher wishing to compare results between different foot scanning projects needs to understand the process used to obtain those measurements.

2. INTRODUCTION

Measurements of the human body based on manual methods have a long history and were standardized long before whole body scanners were developed. Manual measurements and scan-derived measurements are based on common definitions. Both methods use the same body-oriented coordinate system based on mid-sagittal plane, vertical direction, and bilateral direction. Several different foot-oriented coordinate systems (or foot axis) have been used.

The relative symmetry of the human body made this possible. However, human feet are asymmetrical to a degree that is important for proper fitting footwear and, unlike the body, standardized foot measurement definitions for shoe sizing are scarce, and just few standardization bodies addressed them (e.g., JIS S 5037:1998 [1]). Three-dimensional (3D) foot scanners have been available since the late nineties while the first international ISO standard was released in 2015 (ISO/TS 19408:2015 [2]). Existing standards of foot measurements are intended for manual measurements. Scan-derived foot measurements can be defined using a coordinate system (or foot axis) based on landmarks that are not practical for manual measurements.

These facts resulted in several foot scanning companies providing measuring software that follow different definitions. This is particularly problematic in the case of key references, such as the foot axis. Many

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measurements are dependent upon the definition of the foot axis, giving rise to different values assigned to the same designation.

This paper will not be presenting a comparison between manual and scanned measurements or about the reliability of traditional or digital methods, since there is extensive literature addressing these topics (Ballester et al., 2017 [3], [4]; Butler, R. J. et al., 2008 [5]; De Mits, S. et al., 2010 and 2011 [6], [7]; Gordon C. C. et al., 1989 [8]; ISO 20685-1:2018 [9], Kouchi, M. et al., 1996 [10], 1999 [11] and 2014 [12]; Kouchi, M., and Mochimaru, M., 2006 [13] and 2011 [14]; Laughton, C. et al., 2002 [15]; Lee, Y. C. et al., 2014 [16]; Liu, W. et al., 1999 [17]; Mall, N. A. et al., 2005 [18] and 2007 [19]; Pohl, M. B. and Farr, L., 2010 [20]; Telfer, S., and Woodburn, J., 2010 [21]; Williams, D. S., and McClay, I. S., 2000 [22]; Witana, C. P. et al., 2006 [23]).

This paper gathers a compilation of foot measurement definitions and related terminology made by the IEEE IC 3DBP Footwear Subgroup. This compilation includes terms and definitions from standards (i.e., ISO/TS 19408:2015 [2], JIS S 5037:1998 [1]) and from the main foot measurement suppliers: SATRA [24], I-Ware Laboratory Co., Ltd. (I-Ware) [25], Volumental [26] [27], Instituto de Biomecánica de Valencia (IBV) [28], TryFit [29], TechMed 3D [30], Bodyform3D [31], and Aetrex [32], [33], [34], [35]. Measurements from ISO 8559-1:2017 [36], ISO 7250-1:2017 [37], and ASTM D5219-15 [38] are deliberately excluded because they are focused on full body dimensions and the foot definitions are either included in ISO/TS 19408:2015 [2] or are too vaguely defined. This compilation will facilitate the comparison across definitions for measurement data consumers. If other companies or standards organizations would like to be included in a future paper, please contact the authors.

This document focuses on static foot measurements. Dynamic foot measurements are not covered. Shoe last measurements, even those similar in names to foot measurements are not covered.

This paper is organized into two sections: Section 3 includes a review of terms related to foot measurements; Section 4 identifies gaps in current standards and industry practices and concludes with possible future work.

3. TERMS AND DEFINITIONS

This section is structured into three subsections:

- Section 3.1 includes the definition of measuring or scanning conditions that have an important impact on foot shape, and therefore on measurement definitions.
- Section 3.2 provides key anatomical references, features, planes, and lines that are used to define foot measurements.
- Section 3.3 includes foot measurement definitions found in standards and/or utilized by foot scanner and digital foot processing technologies.

For clarity and to facilitate comparisons, original definitions with images provided by each measurement provider have been rewritten and grouped to show the differences between them.

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3.1. FOOT SCANNING CONDITIONS AFFECTING FOOT SHAPE

3.1.1. ATTIRE

When being measured or scanned, the foot can be barefoot, wearing a sock, a thin hose or a compression stocking. Foot attire thickness will affect measurements. Moreover, compression can induce shape changes, especially in the forefoot. Note that even with thin hose, toes are compressed with the result that toe angle measurements and sometimes foot length are affected. Some scanning solutions require the user to wear a patterned sock to digitize it.

It is recommended that each scanning or foot measuring technology state if the use of socks is supported or required. TABLE 1 summarizes the requirements and recommendations made by different measurement providers in this regard.

TABLE 1 Requirements and recommendations for attire made by different measurement providers

Provider	Requirements/recommendations	Other conditions supported
ISO/TS 19408:2015	Barefoot required	Thin hose that does not significantly affect the dimensions of the foot.
Aetrex	Barefoot recommended	Any type of hose or sock is supported. For any thickness beyond a thin hose, the person should be informed hose or sock choices will impact final dimensions of foot measurement.
Bodyform3D	Barefoot recommended	Very thin hose that is not shiny and does not affect the dimensions of the foot.
IBV, SATRA, I-Ware, and TechMed 3D	Barefoot recommended	Thin hose that does not significantly affect the dimensions of the foot.
TryFit	Any color thin socks recommended	Thin hose that does not significantly affect the dimensions of the foot.
Volumental	Barefoot or thin socks recommended	Other socks of any color and pattern.

3.1.2. POSTURE AND WEIGHT BEARING

Foot structure includes soft and hard parts that are flexible and articulated. Foot shape changes during activity (e.g., gait cycle) but also between different loading or weight bearing conditions in static postures. These shape changes affect foot measurements (Yamazaki N., 1999 [39]; Tsung et al., 2003 [40]; Houston et al., 2006 [41]; Xiong et al., 2006 [42]; Ballester et al., 2019 [43]).

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These differences can be as large or larger as shoe size grading intervals. It is therefore important that measurement consumers are aware of the conditions under which the foot was measured to account for its application (e.g., made-to-measure or size recommendation).

Procedures used to scan feet may consist of:

- Full-weight bearing (FWB): the user stands erect on one foot on a flat surface.
- Half-weight bearing (HWB): the user stands erect distributing body weight equally on both feet on a flat surface. This is the most commonly used condition for footwear applications.
- Non-weight bearing (NWB): foot is in the air when measured not supporting any body weight. Foot pose is not usually standardized. This condition is sometimes used in clinical applications. This condition is challenging to digitize because the user should remain still during the scanning process.
- Partial-weight bearing, sitting (SWB): the user sits on a chair resting most of his/her body weight on the chair and the foot lies on a flat surface.
- Partial-weight bearing, inclined plane (IWB): the user sits on a chair resting most of his/her body weight on the chair and the foot lies on a flat surface inclined at some degree (FIGURE 1).

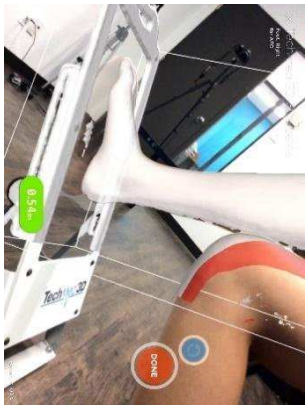
It is recommended that, at least, each scanning or foot measuring technology state the weight bearing conditions required or recommended, especially if support is involved. Ideally, the weight bearing condition should be provided as metadata. TABLE 2 summarizes the requirements and recommendations made by different measurement providers in this regard.

TABLE 2 Requirements and recommendations for weight bearing made by different measurement providers

Provider	Requirements/recommendations	Other conditions supported
ISO/TS 19408:2015, JIS S 5037:1998, SATRA and Aetrex	HWB required	
Bodyform3D	NWB recommended	FWB
I-Ware	HWB recommended	NWB, FWB, SWB (knee and ankle joints have to be 90°), IWB
IBV	HWB recommended	FWB, SWB
TechMed3D	FWB, HWB, NWB, SWB, IWB supported. No particular recommendation or requirement	
TryFit and Volumental	HWB recommended	

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FIGURE 1 Example of other weight bearing conditions (IWB)
Foot positioning optimization module to allow scanning the dorsum of the foot at the same time as the plantar surface, developed by TechMed 3D.

3.1.3. USE OF PHYSICAL MARKERS OR STICKERS

Foot measurements are defined using landmarks. Scan-derived measurements are calculated using landmark positions and surface data. Landmark positions are automatically calculated in some software, while with other software, users put marker stickers at manually determined landmark positions which are automatically detected. Different types of errors are involved in landmark positions obtained by the two types of methods. Automated landmarking includes errors in estimating landmark positions, while using physical markers includes errors in detecting marker positions and the artifact caused by the physical markers (Kouchi and Mochimaru, 2011 [14]).

It is recommended that each scanning or foot measuring technology state if the use of markers is required/recommended or supported or required. TABLE 3 summarizes the requirements and recommendations made by different measurement providers in this regard.

TABLE 3 Requirements and recommendations for marker use made by different measurement providers

Provider	Requirements/recommendations	Other conditions supported
Aetrex, Bodyform3D, IBV, SATRA, TryFit, Volumental	Markerless	
I-Ware	Markers recommended for detecting landmarks on bones and for more precise measurements	Markerless
TechMed 3D	Markerless	Markers with Bodyscan scanner

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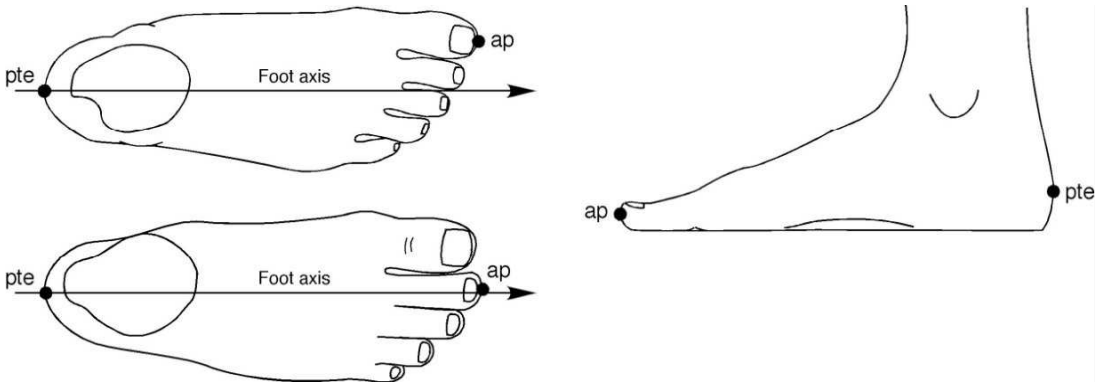
3.2. KEY ANATOMICAL REFERENCES

Anatomical references are used in measurement definitions. Such references are typically points, lines, planes and sections. Different contexts (e.g., academic, health, or footwear) and different measurement providers use different terminology to refer to the same foot anatomical features. Similar terminology can also have slightly different definitions, as utilized by the different measurement providers.

Anatomical features are used in this paper for being the most concise and unambiguous way to designate a reference.

3.2.1. ACROPODION (AP)

It is the end of the most prominent toe. It is also designated as: “furthest toe,” “foremost point of the foot,” or “tip of the longest toe.” See FIGURE 2.



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FIGURE 2 Acropodion (ap) (Section 3.2.1) and pternion (pte) (Section 3.2.2)

3.2.2. PTERNION (PTE)

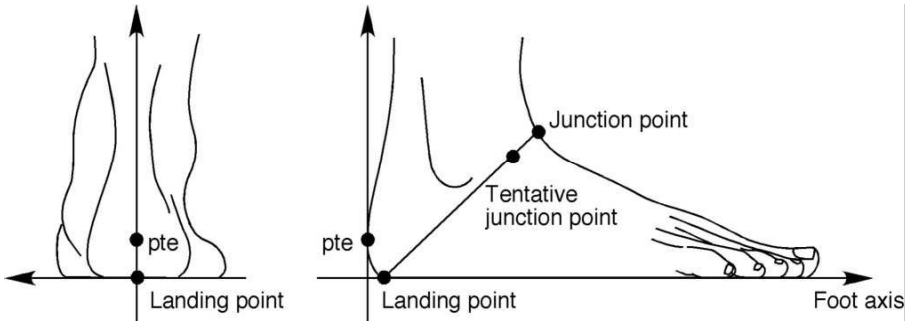
It is the maximum point of the heel curve. It is also designated as the “center of the back of the heel,” “back of the heel,” “rearmost point of the foot,” or “furthest point of the back of the heel.” See FIGURE 2.

3.2.3. LANDING POINT

It is the rearmost transition point of the weight-bearing surface to the posterior non-weight-bearing surface of the heel. This is the point where the dorsal surface of the heel meets the sole of the foot. It is also designated as “rearmost point of the foot sole/plant/tread.” See FIGURE 3.

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FIGURE 3 Landing point (Section 3.2.3), tentative junction point (Section 3.2.4), and junction point (Section 3.2.5). pte: pternion. Actual position of junction point may depend on the definition of the foot axis

3.2.4. TENTATIVE JUNCTION POINT

It is the crossing point of the skin crease at the ankle and the tendon of the toe extensor muscle to the 5th toe. The tendon is easily visible when the toes are dorsiflexed. The skin crease at the ankle is easily visible when the knee and ankle joints are bent while standing. See FIGURE 3.

3.2.5. JUNCTION POINT

The point furthest from the landing point on the cross section that passes the landing point and tentative junction point and perpendicular to the sagittal plane including the foot axis. See FIGURE 3.

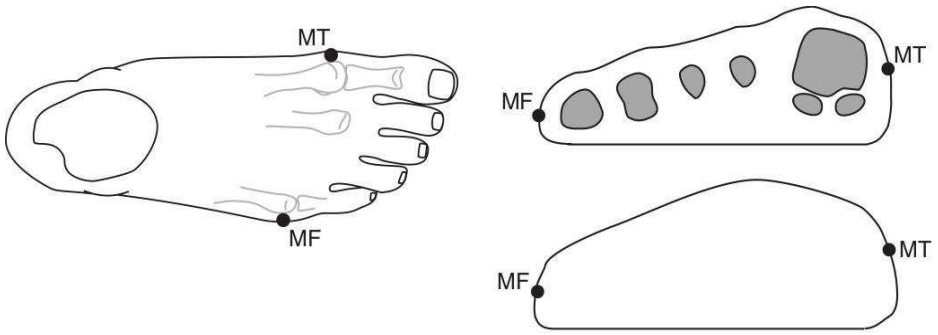
3.2.6. METATARSALE TIBIALE (MT)

It is the projection to the skin of the most medial point (outside swell) of the head of the first metatarsal bone. See FIGURE 4.

3.2.7. METATARSALE FIBULARE (MF)

It is the projection to the skin of the most lateral point (outside swell) of the head of the fifth metatarsal bone. See FIGURE 4.

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FIGURE 4 Metatarsale tibiale (MT, Section 3.2.6), metatarsale fibulare (MF, Section 3.2.7)

Note that MT is not always the most medial point on the ball of the foot section, or MF is not always the most lateral point on the ball of the foot section.

3.2.8. BALL OF THE FOOT SECTION

It is a cross section of the metatarsophalangeal (or metatarsal) joint of the foot. In most cases it is defined by passing through two points located, respectively, at first and fifth metatarsal heads. The metatarsal heads are relatively large (centimeters) and the location of the specific points used by each measurement provider can be different. TABLE 4 summarizes the definitions according to different measurement providers. See FIGURE 5.

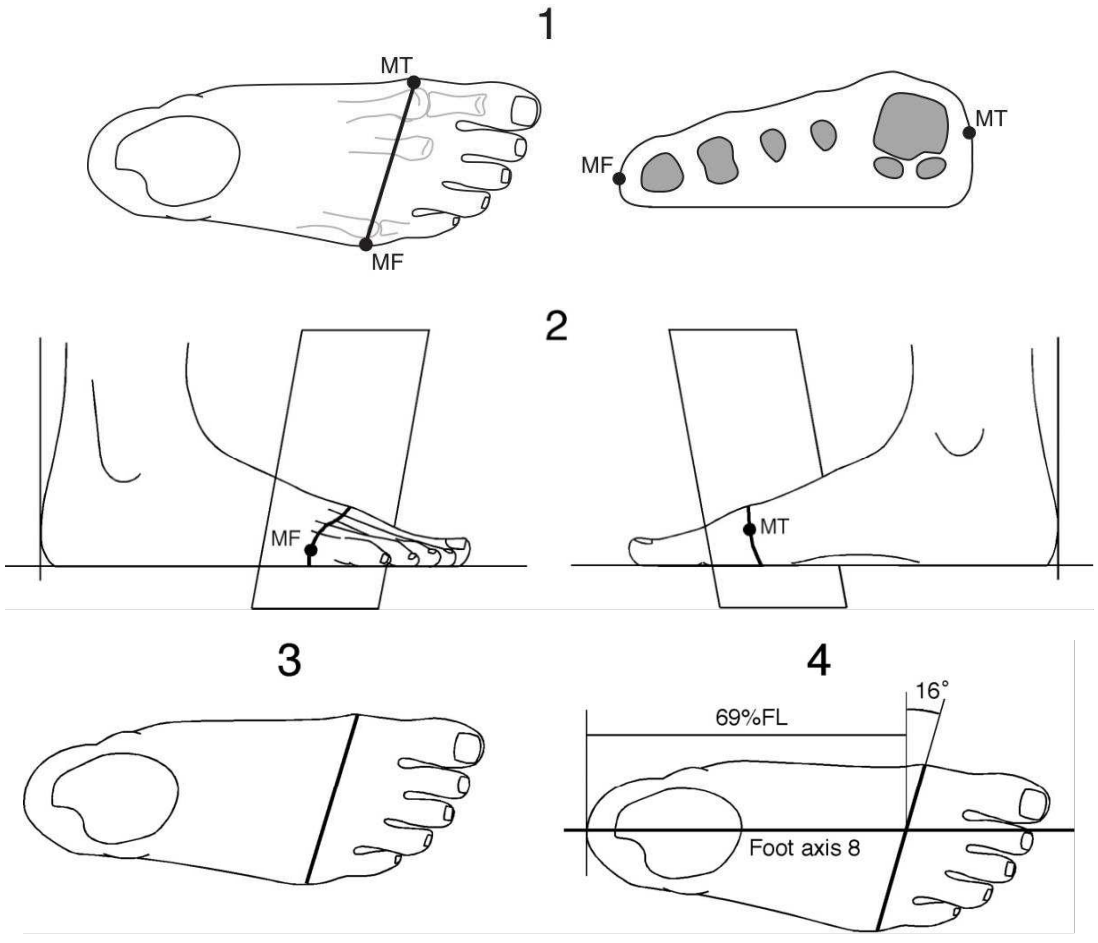
TABLE 4 Ball section definitions and providers that use them

#	Definition	Measurement providers*
1	Cross section of the foot perpendicular to the standing surface and passing metatarsale tibiale (MT) and metatarsale fibulare (MF).	JIS S 5037:1998, I-Ware, Bodyform3D, SATRA, IBV, TechMed 3D (method 1)
2	Cross section of the foot by a plane inclined 80˚ from the standing surface (horizontal plane) and passing metatarsale tibiale and metatarsale fibulare.	TechMed 3D (method 2)
3	Cross section of the foot perpendicular to the standing surface at the widest part of the ball of the foot, passing through the most medial and most lateral points of the metatarsal joint in the soft tissue.	Aetrex
4	Cross section of the foot perpendicular to the standing surface and passing through the 1st and 5th metatarsal heads, which is estimated as a plane that passes a point at 69% foot length (FL) on foot axis #8 (midpoint of the breadth at 10% FL – point at 66% FL and 40% width from medial side) and it is rotated around the vertical axis by 16°.	Volumental

* ISO 19408:2015 and TryFit do not have this definition.

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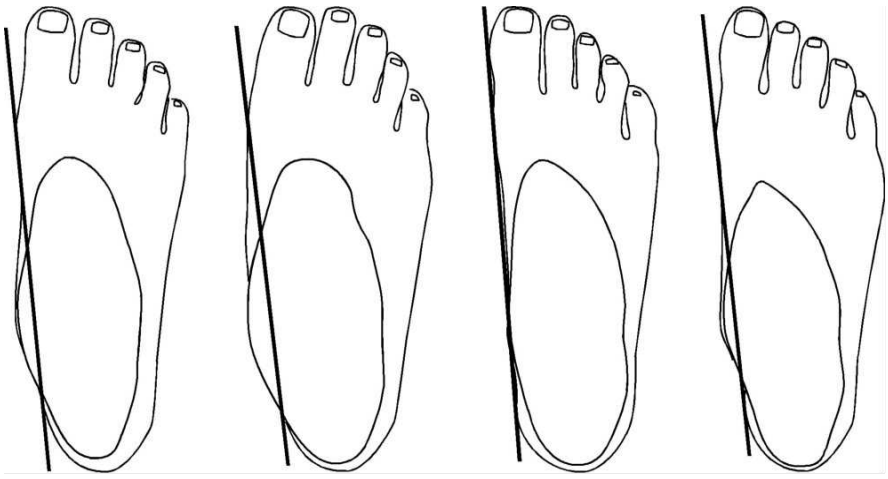
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FIGURE 5 Ball of the foot section (Section 3.2.8).
FL: foot length, MF: metatarsale fibulare, MT: metatarsale tibiale

3.2.9. MEDIAL TANGENT PLANE

It is the vertical plane tangential to the point of maximum inside heel swell (medial side) and the point of maximum swell at the first metatarsal head. It is also designated as an “inside tangent plane.” See FIGURE 6.

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FIGURE 6 Examples of medial tangent plane (Section 3.2.9). All feet are cut at the height of 40 mm.

3.2.10. FOOT AXIS

Foot axis is an imagined line indicating the longitudinal axis of the foot. It is also designated as “central line of foot,” “longitudinal axis of the foot,” “center axis,” or “central axis.” Usually it is defined using two points, one at the heel and the other at the forefoot and projected to the standing surface. Foot axis is used to define foot measurements. TABLE 5 summarizes the different definitions of this reference axis. See FIGURE 7.

TABLE 5 Foot axis definitions and providers that use them

#	Definition	Measurement providers
1	Intersection between inside tangent and standing surface (ground plane).	ISO/TS 19408:2015 (2.1.4 method 1), TechMed 3D (method 1)
2	Line connecting the projection on the ground plane of the pternion and the midpoint of the points defining the ball tread width (maximal swell of the first metatarsal as a point of the foot line touching the ground and maximal swell of the fifth metatarsal as a point of the foot line touching the ground).	ISO/TS 19408:2015 (2.1.1 method 2, 2.1.4 method 2b)
3	Line connecting the projections on the ground plane of the back of heel and tip of the second toe.	ISO/TS 19408:2015 (2.1.1 method 1, 2.1.4 method 2a), JIS S 5037:1998, TechMed 3D (method 2)
4	Line connecting the projections on the ground plane of the pternion and the midpoint between MT and MF.	SATRA, IBV

Table continues

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#	Definition	Measurement providers
5	Line connecting the projection on the ground plane of the pternion and the midpoint of the breadth of ball cross section.	I-Ware (method 1), Aetrex
6	Line connecting the projections on the ground plane of the pternion and the center of second metatarsal head in the dorsum of the foot.	I-Ware (method 2), Bodyform3D
7	Line connecting the projections on the ground plane of a point at heel (midpoint of the breadth at 10% of foot length) and a point at forefoot (midpoint of a point at 73% of foot length on medial side and a point 62% of foot length on lateral side).	TryFit (method 1)
8	Line connecting the midpoint of the heel breadth at 10% of foot length (height ≤ 30 mm) and the point that divides the forefoot breadth at 66% of foot length into 40% medial side and 60% lateral side.	Volumental
9	Line connecting the midpoint of the heel breadth at 10% of foot length (height ≤ 25 mm) and the point that divides the forefoot breadth at 68% of foot length into 40% medial side and 60% lateral side.	TryFit (method 2)

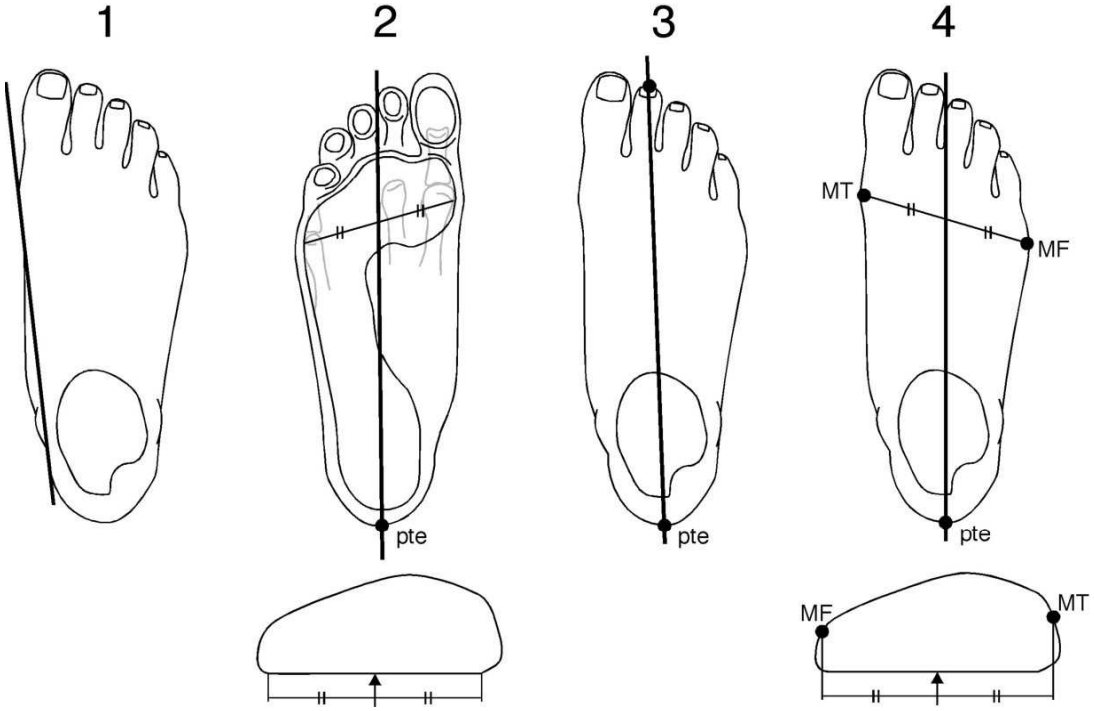
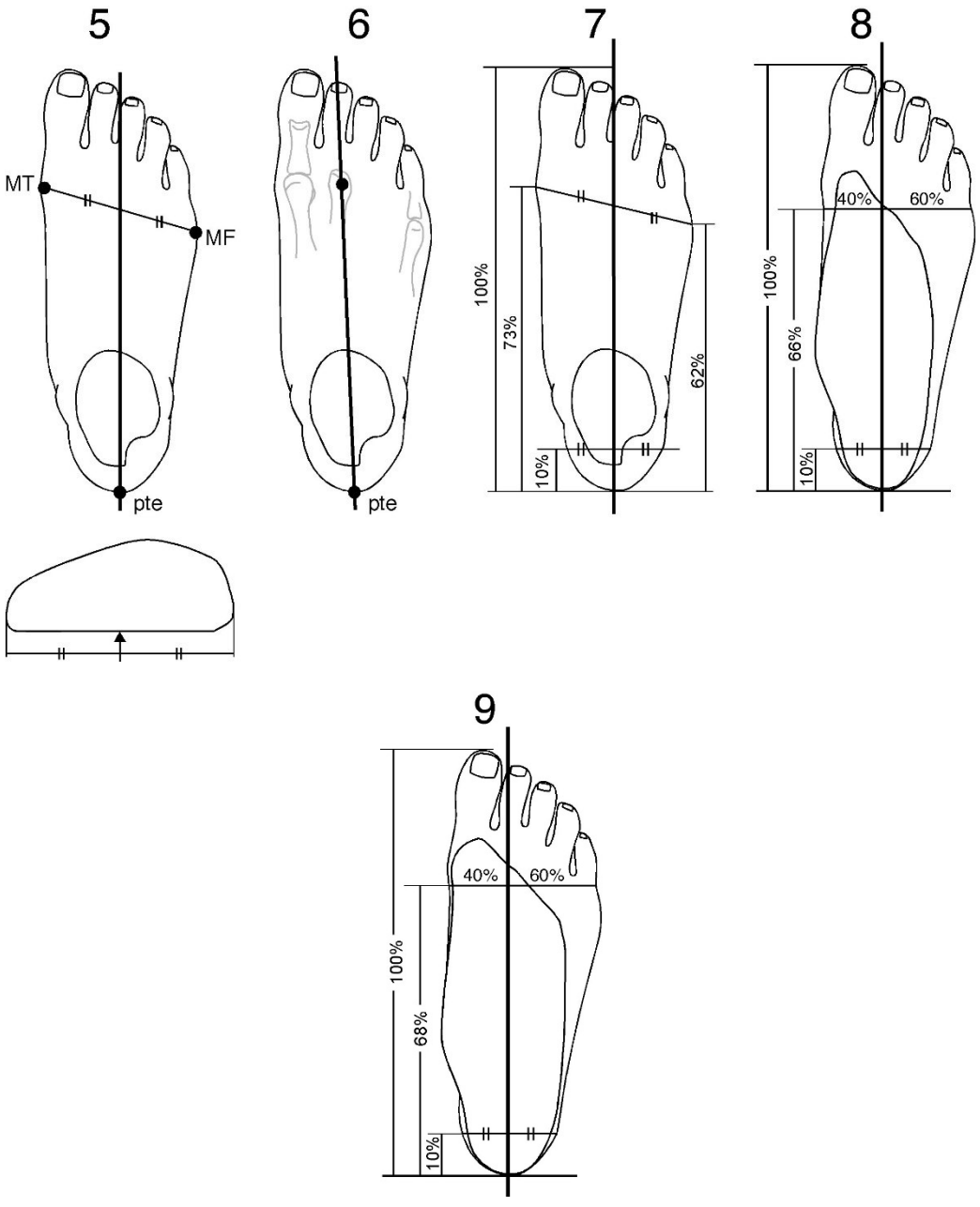


Figure 7 continues

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FIGURE 7 Foot axis (Section 3.2.10). MF: metatarsale fibulare, MT: metatarsale tibiale, pte: pternion. Foot in 8 is cut at the height of 30 mm. Foot in 9 is cut at height of 25 mm.

3.2.11. INSTEP POINT

It is the highest point of the dorsum of the foot at a specific position of the midfoot. TABLE 6 summarizes the different definitions. See FIGURE 8.

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