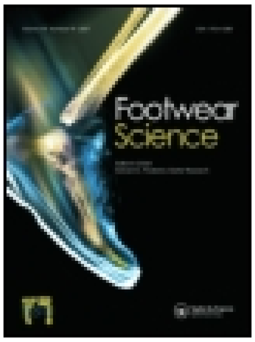

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Improvement of safety shoe fit - evaluation of dynamic foot structure

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Safety shoe development is based on static foot measures, which are transferred to last design. However, workplaces are not just static ('standing workplaces only'). The aim of the present study is to examine static and dynamic foot loading of workers to determine whether foot morphology changes between different loading situations. The results could be used to improve last and shoe design to improve the fit of safety shoes. 1024 workers at different industrial locations in Germany took part in the study. The DynaScan4D dynamic scanner system was used to measure static and dynamic foot morphology during different phases of ground contact. All scan variables were selected based on measures required in the last development process. Cohen's d (effect size) was calculated to identify individual differences between maximum values during the stance phase of walking and static values in standing. Stepwise multiple linear regression analysis was performed to identify possible influencing variables with regard to differences between static and dynamic values. Several foot measures showed relevant differences between dynamic and static loading. Interestingly, most length, width, height, and angular measures increased during dynamic loading (compared to static loading), whereas all circumference measures decreased. None of the tested variables (age, BMI, gender) predicted the differences between the two loading situations. Most dynamic changes are practical relevant changes between static and dynamic loading. Regarding the fit of safety shoes, it seems appropriate to adapt these changes to the last or shoe design.

Keywords: shoe fit; dynamic foot scanning; safety shoe; workplace; ergonomics

Introduction

Safety footwear plays an important role in preventing injuries at the workplace, such as compressions, impacts, punctures, as well as slipping. To fulfil this role, safety shoes must meet basic requirements including toe-protection and slip resistance, but also penetration resistance and isolation, depending on the area of application, which is defined by norms (EN ISO 20345:2011 and EN ISO 20347:2012). Almost all safety shoes are, therefore, equipped with hard toe caps, protective uppers, puncture-resistant and anti-slip outsoles, and encapsulating backs. These safety aspects alter shoe characteristics in terms of shoe mass and sole flexibility, which directly affect the workers' comfort and gait (Dobson, Riddiford-Harland, Bell, & Steele, 2017). The workplace presents the unique situation of the legal requirement to wear safety shoes and the duration they must be worn (approximately 8 h hours per day for several days per week).

The above-described circumstances might be one reason why safety shoes are often associated with work-related pain and injuries at the lower back, the ankle, the hallux, and the metatarsal heads (Hofgärtner, 2007). This is supported by a survey by Marr and Quine (1993), in which 91% of the subjects wearing safety shoes suffered from foot problems. Furthermore, pain and injuries seem to be related to poor concentration ('danger of accidents') and productivity. Thus, well-fitting safety shoes are an important component of safety and health.

Another aspect linking safety shoes to pain and injuries might be the last design of safety footwear, which can have a general mismatch of foot anatomy and last design, as described by Dobson et al. (2017) comparing the foot shape of coal miners with the shape of their boots. These findings might manifest observations that there are still no well-fitting shoe lasts (Kouchi, 1998; Richter and Schaefer, 2009; Witana, Feng, & Goonetilleke, 2004). Furthermore, as last development and design are generally based on static foot measures and designers' manual craft experience, deficits in dynamic foot function (different standing situations and walking) add to this problem. As described above, safety

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shoes are worn approximately 8 h per day and for several days per week. Thus, poorly fitting shoes negatively influence foot morphology, function, and biomechanical qualities (D'Aout, Pataky, De Clercq, & Aerts, 2009; Wunderlich & Cavanagh, 2001; Zipfel & Berger, 2007), as well as the onset of pain and injuries.

Three-dimensional (3D) information about static and dynamic foot deformation during standing and walking seems to be of great importance for proper footwear fit (D'Aout et al., 2009; Kimura, Mochimaru, & Kanade, 2008; Krauss, Valiant, Horstmann, & Grau, 2010; Morio, Lake, Gueguen, Rao, & Baly, 2009). Generating this information is still challenging and only a few research teams have found solutions for how to capture dynamic foot function in standing and walking (Coudert, Vacher, Smits, & Van der Zande, 2006; Fritz, Schmeltzpfenning, Plank, Hein, & Grau, 2013; Kimura et al., 2008; Kouchi, Kimura, & Mochimaru, 2009).

There is no doubt that the foot changes its shape under different loading situations during standing and walking (Coudert, et al., 2006; Kouchi et al., 2009; Leardini et al., 2007). Researchers analysed the movement of foot bones during walking and slow running and found that all examined joints moved and that these movements were higher than expected in some joints (Lundgren et al., 2008; Nester et al., 2007). Changes in different static loading situations, such as foot length, width of rearfoot and forefoot, and height of arch and instep, were reported with regard to foot shape (Tsung, Zhang, Mak, & Wong, 2004; Xiong, Goonetilleke, Zhao, Li, & Witana, 2009). Differences between 3 D static and dynamic foot shape were only reported in children (Barisch-Fritz, Plank, & Grau, 2016; Barisch-Fritz, Schmeltzpfenning, Plank, & Grau, 2014). These changes were especially great for forefoot width and midfoot girth measures (Barisch-Fritz et al., 2014). Kouchi et al. (2009) compared to static and dynamic situations in adults and found statistically significant differences in heel width, instep height, width of forefoot, and medial ball length. However, only a low sampling rate of 14 Hz was used to analyse differences between static and dynamic (Kouchi et al., 2009).

Nevertheless, there are foot shape deformation characteristics during dynamic loading (walking) in adult feet that are necessary and would be beneficial if incorporated in footwear to improve fit. This would be particularly beneficial in a working environment that has highly specific and varying requirements (numerous work places with different requirements of the workers) that are often physically demanding, especially for the feet (e.g. lifting and carrying heavy loads).

Several research groups have presented different measurement systems for dynamic three-dimensional foot scanning (Coudert et al., 2006; Kimura et al., 2008; Kouchi et al., 2009; Schmeltzpfenning, Plank, Krauss, Aswendt, & Grau, 2009; Wang, Saito, Kimura, Mochimaru, & Kanade, 2006). However, most studies focus on feasibility (Kimura et al., 2008; Wang et al., 2006) and thus do not provide comprehensive results to improve footwear fit. The technology first described by Schmeltzpfenning et al. (2009) seems to be appropriate to examine the above-described issues.

Two main aspects are important for providing a wide range of workers with well-fitting shoes. First, specific foot measures (different length, width, height, and circumference measures) from workers at different work places that optimally describe foot morphology, need to be measured and evaluated with regard to their changes from static to dynamic loading. Second, a possible influence of anthropometric data (e.g. age, gender, or BMI) on possible differences between static and dynamic loading needs to be examined. Research on static foot morphology has identified gender as an influencing variable (Krauss et al., 2010), as well as body weight, ethnicity, and age (Hawes and Sovak, 1994; Kouchi, 1998; Mauch, Grau, Krauss, Maiwald, & Horstmann, 2008; Wunderlich and Cavanagh, 2001).

The aim of the present study is to examine static and dynamic foot loading of workers at different work places to determine whether foot morphology changes between the different loading situations. The results could be used to improve last and shoe design to improve the fit of safety shoes.

The following research questions will be examined:

(1) Is there a difference between static and dynamic loading of workers' feet?
(2) Do anthropometric variables, static foot measures and gender have a relationship towards the difference between static and dynamic loading?

Methods

Participants and design

The study was approved by the Ethics Committee of the university clinic. Overall, 1024 workers at different industrial locations in Germany took part in the study. The worker population comprised both genders and included a wide range of ages (16–74 years), weight (44–151 kg), height (1.53–2.02 m), and BMI (16.48–47.05 kg/m^2). All participants were informed about the aims and contents of the research project prior to conducting the study. Exclusion criteria were pain and problems that affected normal gait, especially injuries at the lower extremities, serious foot deformities, or neurological disorders that had an influence on participants' balance.

The DynaScan4D was used to measure static and dynamic foot morphology (Barisch-Fritz et al., 2014; Barisch-Fritz et al., 2016; Schmeltzpfenning et al., 2009). One foot of each worker was randomly chosen and

Table 1. Description of final sample size.

	N	Age [Years]	Body mass [kg]	Size [cm]	BMI [kg/m^2]	Foot length [mm]	Shoe size [EU]
Men	592	32.9 ± 15.4	82.7 ± 14.6	179.1 ± 6.8	25.8 ± 4.2	272.7 ± 11.7	43 ± 2
Women	320	36.3 ± 16.3	67.2 ± 13.1	165.8 ± 11.0	24.3 ± 4.4	247.9 ± 11.2	39 ± 2
Total	912	34.1 ± 15.8	77.2 ± 15.9	174.4 ± 10.6	25.2 ± 4.3	264.0 ± 16.5	41 ± 2

All values are mean values ± standard deviation.

measured statically during half weight-bearing standing (HWB). They were then measured dynamically during walking at a predefined speed (5 km/h ± 5%). All participants were allowed to accustom themselves with the requirements (velocity, landing on the glass plate) to assure normal gait during the measurements. Finally, three valid trials were captured for further evaluation.

Age and gender were documented, in addition to the static and dynamic scan data. Body weight was measured on an electronic bathroom scale and body height was determined using a stadiometer. Body mass index (BMI) was calculated from the weight and height measures.

The final sample is described in Table 1. 912 participants were included in the evaluation. 112 participants were excluded for different reasons. The main reason for exclusion was low scan quality (holes in the surface patterns) due to alignment problems with the shutter time. High sensitivity of the DynaScan4D system with regard to ambient light at the different industry locations, dysfunction of the trigger, and deficits adjusting to skin (color, hairy feet) were responsible for further drop-outs.

Measurement system

Static and dynamic foot morphologies were recorded using the DynaScan4D system (Barisch-Fritz et al., 2014; Barisch-Fritz et al., 2016; Schmeltzpfenning et al., 2009). The system is based on the principle of full-field triangulation by structured light projection. The system comprised 5 scanner units (z-Snapper, Vialux GmbH, Chemnitz, Germany) that were attached to a walkway (4.6 m long and 0.8 m high). One scanner unit was placed below a glass plate (0.6 × 0.4 m), two scanner units at the right side and two at the left side (Barisch-Fritz et al., 2014; Barisch-Fritz et al., 2016; Schmeltzpfenning, Plank, Krauss, Aswendt, & Grau, 2010). Each scanner unit consisted of one high-speed camera (Pike F-032 B/W, Allied Vision, Stadtroda, Germany) and a projector. The sampling frequency of each camera was 205 frames per second, the resolution 640 × 480. The projector was equipped with digital light technology including a Digital Micromirror Device (DMDTM, Texas Instruments Inc., Dallas, TX, USA). A precise synchronization of camera and projector and the maximum DMDTM speed were achieved using a special accessory light modulator developed by VIALUX (Höfling and Ahl, 2004). Elevation information was calculated according to Frankowski, Chen, and Huth (2000). A strain gauge was used to trigger scanning of the walking sequence; light cells were used to monitor walking velocity.

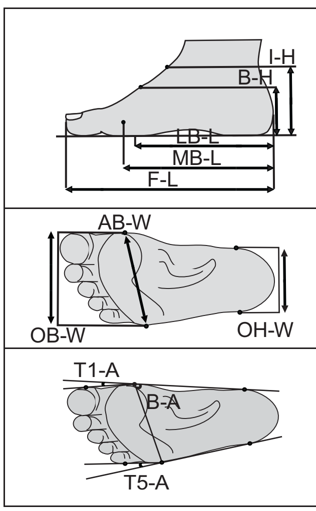
The final frequency for dynamic foot scanning was 46 Hz, which was achieved using reduced spatial resolution (4 × 4 binning mode). The captured measurement volume was 55 × 35 × 25 cm. The test for system accuracy was reported by Barisch-Fritz et al. (2016). The measurement error (root mean square error, RMSE) was 0.23 mm for the static scans and 0.89 mm for the dynamic scans.

Analysis of data and statistics

Recording, processing, and storage of the measured foot scans were performed using the DynaScan4D software. The dynamic foot measures were recorded during different phases of ground contact (see Figure 1) according to characteristics described by Blanc, Balmer, Landis, & Vingerhoets (1999) and Barisch-Fritz et al. (2014). All foot scans were aligned along the x-axis, a line connecting the most medial point at the heel and the metatarsal head 1 (MTH 1). After a coordination meeting with a German last manufacturer, all scan variables were selected based on measures required in the last development process (Mitchell, Jones, & Newman, 1995). These are displayed in Figures 2(a,b). The different girth measures in this study depend on the shoe size and were defined according to a last-making device (Behrens, Alfeld, Germany) that provides the distance relative to the heel where the girth has to be measured for each shoe size. This would enable a smooth transfer of results into the last development process. All foot measures were calculated for each static scan and for each frame of the dynamic scan during the respective loading phase. Mean values of three dynamic walking trials were used to evaluate the scans. The maximum value (MaxDyn) of each variable during the stance phase of walking was recorded from the dynamic scans and compared to the static value of the respective variable.

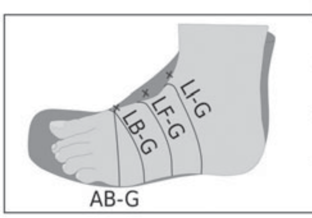
Figure 1. Measurement phases for different foot measures during ground contact (MTH = metatarsal head).

(a)



Denotation		Description
I-H	Instep Height	Highest point of the foot at 50% of foot length
B-H	Ball Height	Highest point of the foot at the golden ratio (61.8% of foot length)
F-L	Foot Length	Distance between most posterior point of the heel and foremost point of the longest toe
MB-L	Medial Ball Length	Distance between most posterior point of the heel and most medial point of MTH1
LB-L	Lateral Ball Length	Distance between most posterior point of the heel and most lateral point of MTH5
AB-W	Anatomical Ball Width	Distance between most medial point of MTH1 and most lateral point of MTH5
OB-W	Orthogonal Ball Width	Distance between most lateral and most medial point of the forefoot measured orthogonally
OH-W	Orthogonal Heel Width	Distance between most lateral and medial point if the heel measured orthogonally between 14 and 20% of foot length
B-A	Ball Angle	Angle between the connecting line of MTH1 and MTH5 and the x-axis
T1-A	Toe1 Angle	Angle between the connecting line of most medial point of the heeland MTH1 and the connecting line of most medial point of Toe1 and MTH1
T5-A	Toe5 Angle	Angle between the connecting line of most lateral point of the heel and MTH5 and the connecting line of most lateral point of Toe5 and MTH5

(b)



Denotation		Description
AB-G	Anatomical Ball Girth	Girth around the anatomical landmarks MTH1 and MTH5
LB-G	Last Ball Girth	Girth around the first point detected on the last at an angle of 22° relative to the vertical
LF-G	Last Fore Girth	Girth around the second point detected on the last at an angle of 22° relative to the vertical
LI-G	Last Instep Girth	Girth around the third point detected on the last at an angle of 22° relative to the vertical

Figure 2. (a) Description of height, width and angular variables of static and dynamic foot scans. (b) Description of girth variables of static and dynamic foot scans.

Normality for all foot measures (static and dynamic) was tested using the Shapiro–Wilk Test. Cohen's d (effect size) was calculated to analyse magnitude of differences between maximum values (MaxDyn) during the stance phase of walking and static values in standing (HWB). Multiple regression analysis was calculated for each foot measure for both genders to assess the predictability of differences between static and dynamic values (HWB-MaxDyn) by the variables age, BMI, foot length, and HWB. Best models were chosen after stepwise

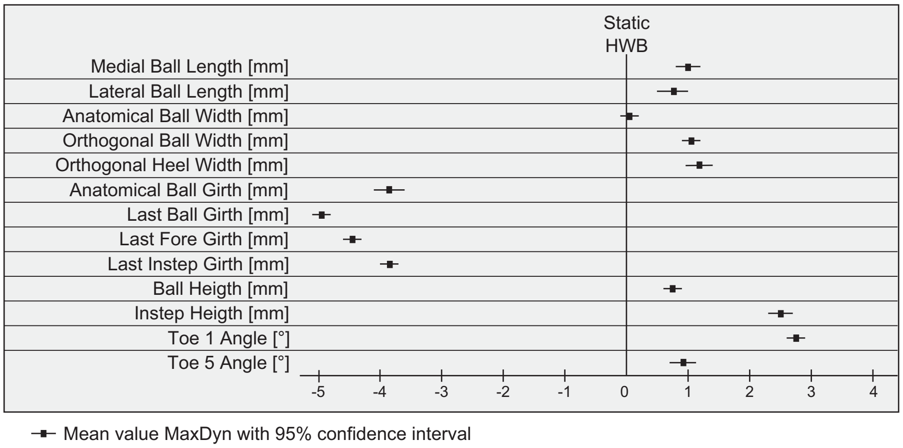


Figure 3. Differences between maximum dynamic (MaxDyn) and static half-weight bearing (HWB) values (positive values show an increase, negative values a decrease in size; $n = 912$).

Table 2. Characteristics of the measured variables.

Foot measure		MaxDyn (mm)	HWB (mm)	Mean difference [mm]	95% CI difference [mm]	[mm]	Cohen's d
F-L	Foot length	263.9 ± 16.8	264.1 ± 16.7	−0.02	−2.05	1.70	−0.01
MB-L	Medial ball length	190.2 ± 12.3	189.2 ± 12.0	1.00	0.81	1.15	0.08
LB-L	Lateral ball length	159.7 ± 11.5	158.9 ± 10.5	0.80	0.44	1.01	0.07
AB-W	Anatomical ball width	104.0 ± 7.1	103.9 ± 7.0	0.10	−0.06	0.15	0.01
OB-W	Orthogonal ball width	101.4 ± 6.6	100.4 ± 6.6	1.00	0.92	1.08	0.15
OH-W	Orthogonal heel width	70.9 ± 5.5	69.8 ± 5.5	1.10	1.05	1.19	0.21
AB-G	Anatomical ball girth	240.3 ± 16.8	244.1 ± 16.7	−3.80	−3.97	−3.61	−0.23
LB-G	Last ball girth	235.9 ± 15.5	240.8 ± 15.5	−4.90	−5.05	−4.79	−0.32
LF-G	Last fore girth	238.1 ± 16.5	242.5 ± 16.3	−4.40	−4.60	−4.33	−0.27
LI-G	Last instep girth	248.0 ± 18.3	251.8 ± 18.0	−3.81	−3.95	−3.68	−0.21
B-H	Ball height	52.7 ± 4.2	51.8 ± 4.1	0.90	0.76	0.95	0.21
I-H	Instep height	69.5 ± 5.9	66.9 ± 5.6	2.60	2.45	2.66	0.45
B-A	Ball angle	73.7 ± 4.1	73.0 ± 3.2	0.70	0.58	0.94	0.19
T1-A	Toe 1 angle	8.4 ± 4.9	5.6 ± 4.8	2.80	2.58	2.93	0.58
T5-A	Toe 5 angle	14.5 ± 4.8	13.6 ± 4.3	0.90	0.73	1.12	0.20

Angular values are in degree; MaxDyn: maximum dynamic value; HWB: static half weight bearing value; 95% CI: 95% confidence interval; $n = 912$.

procedure and adjusted R^2 were reported. Repeatability of the measured values were taken from Barisch-Fritz et al. (2014).

Results

Difference between static and dynamic loading of workers' feet

The results comparing static and dynamic measures are displayed in Figure 3 and Table 2. Several foot measures show relevant differences (Cohen's $d > 0.2$) between dynamic and static loading. Interestingly, most length, width, height, and angular measures increased during dynamic loading (compared to static loading), whereas all circumference measures decreased. Orthogonal ball width and overall foot length did not change between the two loading situations.

Possible influencing factors on differences between static and dynamic loading

Possible influencing factors on differences between static and dynamic loading are displayed in Table 3. The models, which were calculated for each foot measure, provide rather small values of the explained variance (R^2).

Table 3. Possible influencing factors on difference between dynamic and static values.

	Influences on difference MaxDyn-HWB				
Difference: Static-Dynamic	Age [years]	BMI [kg/m^2]	Foot Length [mm]	HWB [mm]	R^2
Instep height					0
Ball height					0
Medial ball length			<0.001	<0.001	0.04
Lateral ball length	<0.001	<0.001	<0.001	<0.001	0.08
Orthogonal ball width				<0.001	0.01
Orthogonal heel width	<0.001				0.03
Last ball girth	<0.001	<0.001	0.003		0.08
Last fore instep girth	<0.001	<0.001	<0.001		0.10
Last instep girth	<0.001	<0.001	<0.001		0.11
Ball angle	<0.001	<0.001		<0.001	0.07
Toe1 angle				<0.001	0.05
Toe5 angle	<0.001			0.004	0.04

MaxDyn: maximum dynamic value; HWB: static half weight bearing value; $n = 912$.

The values of R^2 range from 0 to 0.11, thus none of the tested variables predicted the differences between the two loading situations. Gender also did not predict differences.

Discussion

Difference between static and dynamic loading of workers' feet

The goal of the present study was to evaluate possible differences in foot morphology between static and dynamic loading. In general, statistically significant differences were found for most foot measures, although some increased and some decreased from static to dynamic loading.

The practical relevance of these findings will be discussed with regard to two main concerns. First, the increment in length from one shoe size (length) to the next is 6.66 mm of French scale (Rossi and Tennant, 2013). Half a shoe size (3.3 mm in the French Scale) is assumed to be relevant with regard to foot length measures. Therefore, a difference between static and dynamic foot length measures that exceeds the value of half a shoe size is regarded as relevant for footwear (last) construction. The increment from one shoe size to the next with regard to girth measures is 5 mm in the French Scale (Joneja and Fan, 2013). The relationship of ball girth and ball width is mostly standardized as 60:40 (Maier and Killmann, 2003). Thus, if the same principle is applied to foot girth and width measures, that half an increment is relevant, a difference between static and dynamic loading of 2.5 mm for girth measures and 1 mm for width measures is relevant for footwear (last) construction. Second, possible relevant differences between static and dynamic loading depends on the repeatability (measured by root mean square error, RMSE) of the calculated foot measures (Barisch-Fritz et al., 2014). If the differences of foot measures between static and dynamic loading exceed the RMSE of the respective foot measure, it is assumed to be relevant.

In this study, the main foot length measures are represented by MB-L and LB-L. MB-L is the main representative of foot length extension, as no lengthening from the metatarsal heads towards the toes could be shown in previous studies (Cashmere, Smith, & Hunt, 1999; Schmeltzpfenning et al., 2009). Both measures (mean values) violate the above-described concerns: they are less than half a shoe size for lengthening and smaller than the respective RMSE value (Barisch-Fritz et al., 2014). Therefore, these differences are not relevant with regard to footwear construction. However, it seems that there is a lengthening of MB-L and LB-L via the longitudinal arches, an expected extension of the foot, as shown in previous studies (Lundgren et al., 2008; Scott and Winter, 1993). Interestingly, foot length did not change between static and dynamic loading. The reason for this might be that F-L may not represent the maximum extension because of a shortened measurement phase, as it was observed from toe strike to heel off, which was rather short in many of the measured subjects. It can be assumed that most body weight has already shifted to the forefoot when the toes touch the ground.

Both of the above-mentioned criteria have been fulfilled (change >1 mm widening and exceeding RMSE value) for width measures (OB-W and OH-W). Therefore, the differences between static and dynamic loading are practically relevant for safety footwear (last) construction, mainly to improve fit. This means that lasts need to be adjusted (widened) in the respective areas or resilient upper materials should be used to match foot shape under dynamic loading. The deformation (widening) in adult feet has been described by Schmeltzpfenning et al. (2010), but was never considered in footwear construction. Heel widening can be explained by the compression of the fat pad underneath the heel, whereas forefoot widening might be explained by the relative movement of the metatarsal joints under loading. This confirms previous studies by Lundgren et al. (2008) and Wolf et al. (2008). With regard to shoe construction, a too narrow forefoot might be more critical to foot structures than a too narrow heel.

The decrease of all girth measures during dynamic loading is also practically relevant for footwear (last) construction (change >2.5 mm and exceeding RMSE value). This decrease was reported by Barisch-Fritz et al. (2014) in children's feet and is comparable in size to this study. The decrease might be a consequence of contractions of intrinsic and extrinsic muscles during walking, as supposed by Gefen et al. (2000) and Scott et al. (1993). To improve safety shoe fit, changes need to be made to the last (reduction of volume) and/or the upper (flexible material and/or functional elements that 'follow' the volume changes during the different loading situations). Improvement of lacings could also make a contribution to better fit, especially for workplaces where in a standing position. Nonetheless, all girth measures are crucial with regard to shoe fit and thus changes in volume during dynamic loading need to be considered.

Toe angles are also important with regard to shoe fit. T1-A change (more pointed during walking) seems to be practically relevant (exceeding RMSE value), whereas T5-A is within the repeatability error. This change was reported by Barisch-Fritz et al. (2014) in children's feet. Even though T1-A is more pointed under dynamic loading, which would result in a more pointed forefoot shape of the last, this cannot be recommended from a physiological point of view, as the last would push the toes aside during standing. Further, it would not be reasonable as safety shoes typically use stiff protection caps.

Possible influencing factors on differences between static and dynamic loading

A stepwise multiple linear regression analysis was conducted to give an overview of possible predictors for the difference between static and dynamic loading. As shown in Table 3, the magnitude of the explained variances (R^2) was small for the calculated models, even if there seemed to be statistically significant influence of some of the variables. Unclear remains if the patterns of influencing variables are different between the genders. With regard to the study by Barisch-Fritz et al. (2014) in children's and adolescents' feet, it can be speculated that the influence of gender might be neglected. Regarding safety footwear construction, it seems that adaptations to the last and/or the shoe to improve fit can be implemented without further considerations, such as gender or any anthropometric influences.

Practical relevance and conclusions

Width and girth measures show practical and relevant changes between static and dynamic loading. It seems appropriate to adapt these changes to the last or shoe design, as well as new materials to improve the fit of safety shoes. This transfer can probably be implemented without considering gender, age, or body mass. However, these adjustments must be discussed individually, dependent on the characteristics of different workplaces (purely standing, more standing, more walking). Improving safety shoe fit will support workers' health in general, as well as support safety prevention at the workplace.

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