ARTICLE IN PRESS

Gait & Posture xxx (xxxx) xxx

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Effects of barefoot vs. shod walking during indoor and outdoor conditions in younger and older adults

Karsten Hollander [a], Evi Petersen [b,*], Astrid Zech [c], Daniel Hamacher [c]

[a] MSH Medical School Hamburg, Hamburg, Germany
[b] Department of Sports, Physical Education and Outdoor Life, University of South-Eastern Norway, Norway
[c] Department of Sport Science, Friedrich Schiller University Jena, Germany

ARTICLE INFO

Keywords:
Barefoot
Footwear
Gait variability
Local dynamic stability
Gait
Risk of falling

ABSTRACT

Background: Gait stability and variability measures in barefoot and shod locomotion are frequently investigated in younger but rarely in older adults. Moreover, most studies examine gait measures in laboratory settings instead of real-life settings.

Research questions: How are gait stability and variability parameters affected by footwear compared to barefoot walking in younger and older adults as well as under indoor vs. outdoor conditions?

Methods: Healthy younger (<35 years) and older adults (>65 years) participated in the randomised within-subject study design. Participants conducted consecutive 25 m walking trials barefoot and with standardised footwear inside and outside. Inertial measurement units were mounted on the participant's foot and used to calculate local dynamic stability (LDS), velocity and minimal toe clearance (MTC), stride length and stride time, including variabilities for these parameters. Linear mixed models were calculated.

Results: Data of 32 younger (17 female, 15 male, age: 30 ± 4 years) and 42 older participants (24 female, 18 male, age: 71 ± 4 years) were analysed. MTC variability was higher in shod conditions compared to barefoot ($p = 0.048$) and in outdoor conditions ($p < 0.001$). LDS was different between age groups ($p < 0.001$). Gait velocity and MTC were higher in shod and outdoor conditions (both $p < 0.001$). Stride length and time were higher in shod conditions (both $p < 0.001$) and different between outdoor vs. indoor (longer stride length and shorter stride time outdoor, both ($p < 0.001$) as well as age groups (shorter stride length ($p < 0.021$) and stride time in older adults ($p < 0.001$).

Significance: Results suggest that gait stability and variability in older and younger adults are acutely affected by footwear vs. barefoot and indoor vs. outdoor walking conditions, indicating a high adaptiveness of these parameters to different experimental conditions. Consequently, future studies should be careful with generalising results obtained under certain conditions. Findings stress the clinical potential of barefoot walking.

1. Introduction

Walking with footwear instead of barefoot is a relatively recent evolutionary development [1]. In preceding years, scientific interest has increased on how shod locomotion is different from barefoot locomotion and how it might affect clinically relevant gait mechanics [2].

When walking barefoot, humans typically use shorter step and stride length with an increased cadence compared to shod walking with alterations in gait mechanics [2]. No consensus exists on how gait velocity changes [2] but for older participants, it has been shown that barefoot walking was faster when compared to walking in socks, which has been discussed to be a more cautious gait [3]. Overall, however, only little research in the field of barefoot vs. shod locomotion in cohorts of older adults has been conducted [2]. In addition to changes in gait mechanics, habitual footwear use has been shown to influence foot morphology and peripheral sensation [4–6].

Gait-related parameters such as gait variability and local dynamic gait stability (LDS) have gained increasing attention in the last decade due to their association with gait instability and the risk of falling [7,8] but have rarely been analysed when comparing different footwear conditions. Gait variability is frequently measured as the intra-individual variability (e. g. standard deviation) of particular

---

* Corresponding author at: Department of Sports, Physical Education and Outdoor Life, University of South-Eastern Norway, Gullbringvegen 36, Bø i Telemark, 3800, Norway.

E-mail address: evi.petersen@usn.no (E. Petersen).

https://doi.org/10.1016/j.gaitpost.2021.04.024
Received 17 October 2020; Received in revised form 8 April 2021; Accepted 14 April 2021
Available online 15 April 2021

Please cite this article as: Karsten Hollander, *Gait & Posture*, https://doi.org/10.1016/j.gaitpost.2021.04.024

Fig. 1. Overview of the conditions: a) indoor vs. outdoor and b) barefoot vs. shod.

time-discrete gait parameters. Local dynamic gait stability (LDS) rates how small perturbations affect movement trajectories over time. Therefore, LDS reflects the ability of a complex dynamic system (e.g. the sensorimotor system of a human) to compensate for small perturbations [8]. It has been suggested that peripheral sensation is an influencing factor for gait stability or gait variability [9]. Therefore, one may assume that walking barefoot effects (local dynamic) gait stability or gait variability measures as seen for running [10,11]. This is also supported by recent studies, which compared barefoot walking with (minimalist) footwear [12–15]. Although few studies have investigated age effects in this context, Petersen et al. (2020) indicated that changes in gait parameters occur in both younger and older adults when walking barefoot and with minimalist footwear [12]. Furthermore, all existing studies were conducted in a laboratory setting. Thus, it is unclear if the observed footwear effects can be transferred to outdoor walking situations. Outdoor walking (with or without shoes) can induce different predictable and unpredictable perturbations to the locomotor system that have to be compensated in order to maintain a stable gait and to avoid falling. Laboratory settings eliminate such typical perturbations that might occur in real-life settings. This limits the external validity of the results. Recent developments in wearable technology enable out of laboratory measurement to represent a more real-life situation [16,17], which allows for gait analysis in more real-life settings.

The primary and exploratory aim of this study was to investigate the effects of barefoot vs. shod walking on gait stability and gait variability. To improve external validity, the gait analysis was conducted indoors and outdoors in young and older participants. In a secondary analysis, basic gait parameters (stride length, stride time, gait velocity and minimal toe clearance) were analysed.

2. Methods

2.1. Study design

For this study, a randomised within-subject study design with three factors was applied. Gait parameters of younger and older participants were collected. All participants walked under the conditions: 1) barefoot and with shoes both 2) indoors and outdoors. Reporting of this study adhered to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) statement for reporting observational studies [18]. The study followed the principles of the Helsinki Declaration and was approved by the local ethics committee (protocol no. FSV 16/13).

2.2. Participants and setting

Gait data were collected from 32 healthy younger and 42 healthy community-dwelling older participants from September to November 2016. Participant recruitment for this study was realised through advertising in the local newspaper and at a local sports club. Participants were included in the study if their age was $\leq$ 35 years for the younger group or $\geq$ 65 years for the older group. One of the main inclusion criteria was that participants had to be able to walk for five minutes without having to pause or to use assisting equipment, like a walking stick. We excluded participants from the study if they reported any motor-functional impairments that could affect gait performance, such as acute musculoskeletal disorders or neurological diseases. All subjects provided their written informed consent to their voluntary participation.

2.3. Experimental conditions and randomisation

We analysed the effects of the footwear condition (barefoot vs. shod walking), walking environment (indoors vs. outdoors), and the participants' age (younger vs. older adults). During the indoor walking condition, the participants walked on a 25 m track inside a standard sports hall with flat linoleum ground. The 25 m outdoor track was a sidewalk with a concrete surface with some minor perturbations, very similar to how a typical sidewalk would look like (Fig. 1). Consequently, the outdoor condition provided a rougher, less even, and colder surface. The lengths of both tracks were marked with cones and participants walked in a bidirectional manner. We made sure that other pedestrians could not cross the sidewalk in the outdoor condition during the time of testing. In each environmental condition, the participants walked barefoot and with standardised cushioned shoes (Asics Gel-Cumulus 18), which were new and provided by the research team. Fig. 1 provides an overview of both the environmental and footwear conditions.

The environmental and the shoe condition were block-randomised, using the research randomiser software (https://www.randomizer.org). Before testing, participants familiarised themselves with each gait condition by walking for one minute on the 25 m tracks. We applied this procedure to improve the reliability of the gait parameters [19]. In the following testing phase, gait kinematics were recorded for each gait condition while the participants walked for three minutes back and forth the 25 m tracks.

2.4. Instrumentation

To capture kinematic data, we attached wireless inertial sensors

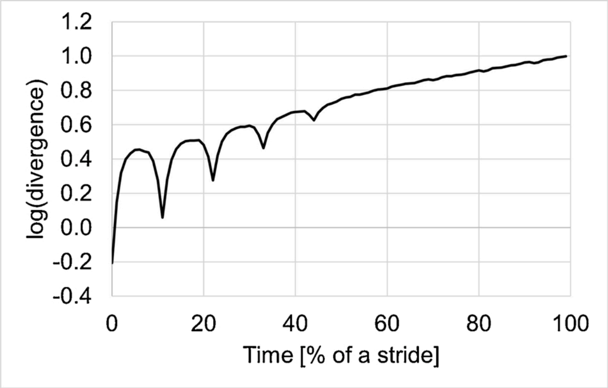

Fig. 2. Logarithmized divergence curve of one participant as an example.

(MTw2, Xsens Technologies B.V., Enschede, The Netherlands, range of measurement of angular velocity: ±1200 deg/s, sampling rate: 100 Hz) with medical tape to the participants' right forefoot.

2.5. Data processing and statistical methods

The first and the last bout of each walking condition, as well as the first and last 2.5 m of each bout, were excluded from the following data analysis to avoid possible transients. For each trial and walking condition, 90 strides were analysed. Thereafter, we calculated the gait parameters: stride length, stride time, and minimum toe clearance (MTC) as well as the intra-individual standard deviations of each parameter as gait variability measures. A detailed description and evaluation of the measurement system (inertial sensor and algorithms) are provided by Hamacher, Hamacher, Taylor, Singh and Schega [20]. Furthermore, we analysed local dynamic stability (LDS) by calculating the short-time largest Lyapunov exponent (λ). As kinematic data for the calculation, we used the three-dimensional angular velocity data (of the inertial sensor) as it depicts high effects discriminating younger vs. older adults [21]. We time-normalised the data of the 90 strides to 9000 samples. The state-space was then reconstructed with the embedding approach with a fixed time delay of 10 samples (mean across all participants) and an embedded dimension of dE = 12 (maximum across all participants). The time delay and the embedded dimension were determined as a result of the minimum mutual information analysis [22] and the global false nearest neighbour method [23], respectively. The λ was determined using Rosenstein's and co-workers' algorithm [24]. We tracked the Euclidean distance of each initially nearest neighbours in the state space over time. Thereafter, the mean of the logarithm of the divergence curve was calculated. λ was then defined as the slope of a linear fit through 0–50 time-normalised samples (a period of approximately 0.5 of the gait cycle, LDS 0–50 %), which is an implementation that was validated previously [20]. Additionally, in a secondary analysis, we calculated the slope through 0–0.03 (LDS 0–3 %) strides. While this does not represent the standard for analysing gait stability, this seems to be the first linear growth of the logarithm divergence curve (Fig. 2). This LDS 0–3 % reflects a much shorter time scale and, therefore, the immediate response to small perturbation. Furthermore, this shorter-time LDS has been proposed by Arno Schroll, who found this LDS to be more sensitive [25].

Taken together, as primary outcomes, gait variability measures of stride length, stride time, MTC, and LDS (0–50 %) were analysed. As secondary outcomes, the standard gait parameters stride length, stride time, MTC, gait velocity and LDS (0–3 %) are provided.

All statistical calculations were operated in IBM SPSS (V 21.0). Each gait measure was predicted with separate hierarchical linear models (2 levels, random intercepts). The three test conditions (age, shoe condition, environment), as well as all possible interaction effects, were included as fixed effects.

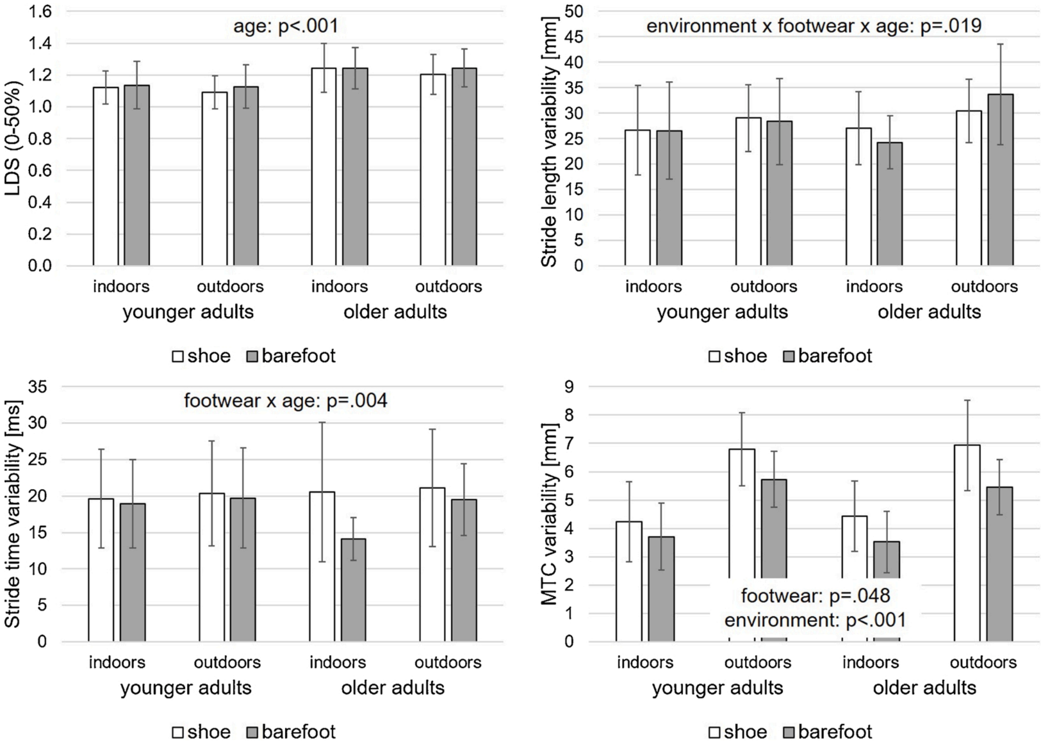

Fig. 3. Effects of footwear (shoe vs. barefoot), environment (indoor vs. outdoor) and age (younger vs. older adults) on the primary outcomes local dynamic stability (LDS 0–50 %), stride length variability stride time variability and minimum toe clearance (MTC) variability. The error bars represent the standard deviations.

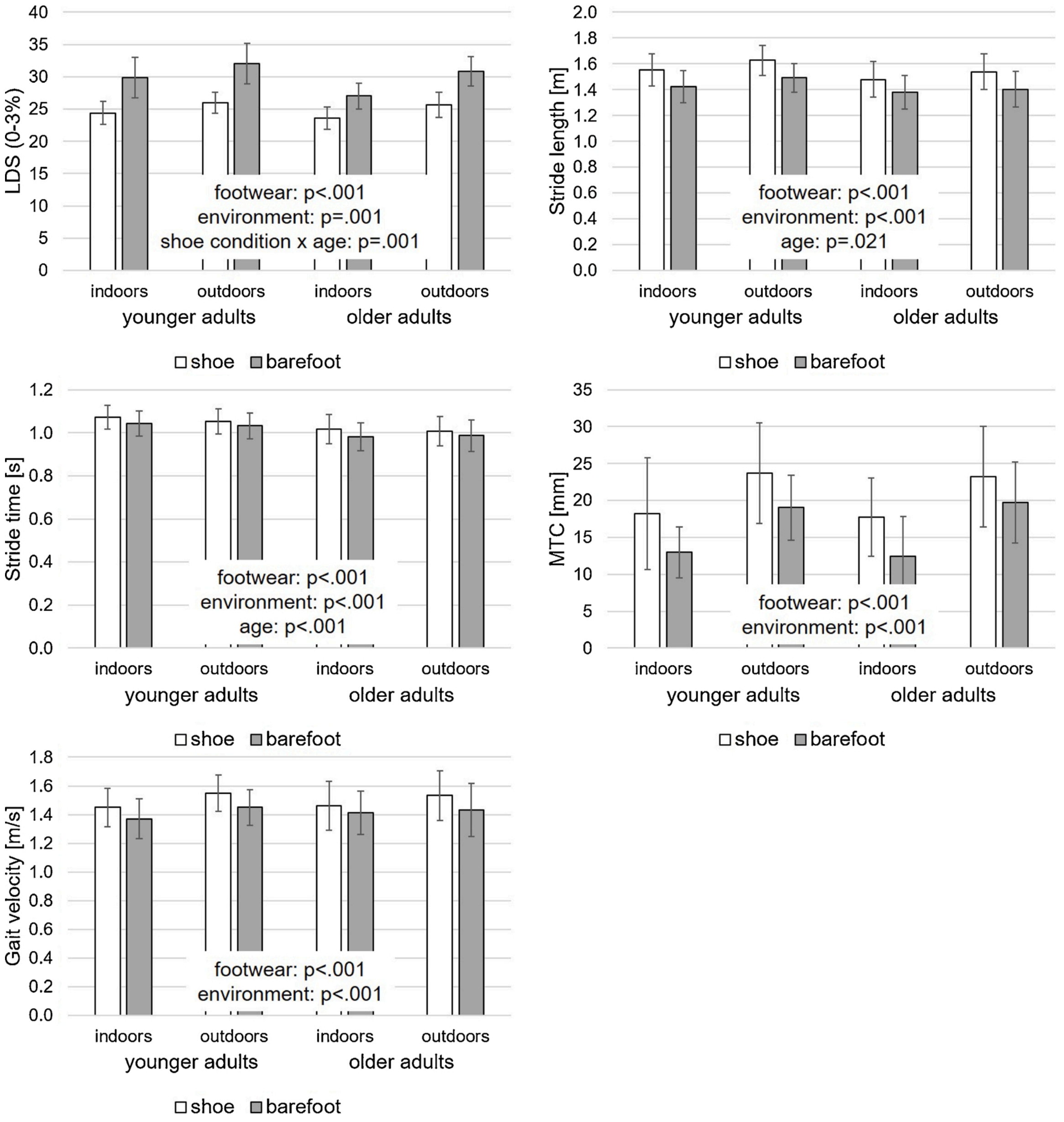

Fig. 4. Effects of footwear (shoe vs. barefoot), environment (indoor vs. outdoor) and age (younger vs. older adults) on the secondary outcomes local dynamic stability (LDS 0–3 %), stride length, stride time, minimum toe clearance (MTC) and gait velocity. The error bars represent the standard deviations.

3. Results

3.1. Participants

In the younger cohort, 32 participants (17 female, 15 male, age: 30 ± 4 years; height: 1.77 ± 0.11 m, weight: 72 ± 14 kg, BMI: 23 ± 2) were included of which one data was not able to be analysed due to technical problems. In the older cohort, 42 participants (24 female, 18 male, age: 71 ± 4 years; height: 1.69 ± 0.08 m, weight: 74 ± 14 kg BMI: 27 ± 4) were included of which all data sets were analysed for shod and indoors, 39 shod outdoors, 39 barefoot indoors and 35 barefoot outdoors. Reasons for non-participation were subjectively uncomfortable and cold conditions.

3.2. Primary outcomes: Gait stability and variability measures

Local dynamic stability (LDS 0−50 %) was statistically significantly different between age groups ($p < 0.001$, Fig. 3, Tables 1 and 2). Older adults had lower LDS (0−50 %, higher λ values) than younger adults.

The minimal toe clearance (MTC) variability was different between outdoor vs. indoor ($p < 0.001$) and footwear condition ($p = 0.048$) (Fig. 3, Tables 1 and 2). MTC variability was higher outdoors and in the shod conditions.

Stride length variability was affected by an outdoor vs. indoor x footwear x age interaction ($p = 0.019$): in older adults, the stride length variability decreased during the barefoot condition compared to the shod during indoor walking but increased during outdoor walking.

For stride time variability, we found a significant footwear x age interaction ($p = 0.004$, Fig. 3, Tables 1 and 2): only in older adults, the stride time variability decreased during barefoot walking compared to the shod walking condition.

3.3. Secondary outcomes: standard gait measures

The LDS (0−3 %) differed between outdoor vs. indoor ($p = 0.001$) and footwear ($p < 0.001$) (Fig. 4, Tables 1 and 3). LDS was lower (higher

Table 1
Discrete outcome parameters (mean and standard deviations) reported for younger and older adults, indoor and outdoor environment and both shoe conditions. LDS: local dynamic stability, MTC: minimum toe clearance.

		Younger adults				Older adults			
		indoors		outdoors		indoors		outdoors	
		shoe	barefoot	shoe	barefoot	shoe	barefoot	shoe	barefoot
	primary outcomes								
LDS (0–50 %)	Mean	1.12	1.14	1.09	1.13	1.24	1.24	1.20	1.24
	SD	0.10	0.15	0.10	0.14	0.15	0.13	0.13	0.12
stride length variability [mm]	Mean	26.69	26.54	29.07	28.36	27.00	24.28	30.43	33.69
	SD	8.81	9.54	6.54	8.41	7.16	5.19	6.27	9.91
stride time variability [ms]	Mean	19.63	18.93	20.40	19.73	20.53	14.11	21.11	19.52
	SD	6.75	6.06	7.19	6.89	9.53	2.96	8.08	4.93
MTC variability [mm]	Mean	4.23	3.70	6.80	5.73	4.43	3.52	6.93	5.45
	SD	1.41	1.18	1.29	0.98	1.25	1.09	1.60	0.98
	secondary outcomes								
LDS (0–3 %)	Mean	24.40	29.87	25.95	32.05	23.59	27.03	25.66	30.89
	SD	1.82	3.12	1.64	3.13	1.78	1.99	1.95	2.28
stride length [m]	Mean	1.55	1.42	1.63	1.49	1.48	1.38	1.54	1.40
	SD	0.12	0.12	0.12	0.11	0.14	0.13	0.14	0.14
stride time [m]	Mean	1.07	1.04	1.05	1.03	1.02	0.98	1.01	0.99
	SD	0.06	0.06	0.06	0.06	0.07	0.06	0.07	0.07
Gait velocity [m/s]	Mean	1.45	1.37	1.55	1.45	1.46	1.41	1.53	1.43
	SD	0.13	0.14	0.13	0.12	0.17	0.15	0.17	0.19
MTC [mm]	Mean	18.21	12.96	23.72	19.03	17.76	12.42	23.22	19.69
	SD	7.55	3.44	6.83	4.40	5.32	5.43	6.83	5.50

Table 2
Effects of footwear condition, environment and age (as well as all possible interaction effects) on local dynamic gait stability (LDS), stride length variability, stride time variability and minimum toe clearance (MTC) variability. Each gait measure was predicted with separate hierarchical linear models (2 levels, random intercepts). SE: standard error, est: estimate.

fixed factor	LDS (0–50 %)		stride length variability		stride time variability		MTC variability	
	b SE	p	b SE	p	b SE	p	b SE	p
Intercept	1.121 0.023	.000	.0267 .0014	.000	.0196 .0012	.000	.0042 .0002	.000
footwear condition **(reference: shod)**	0.015 0.023	.520	−.0002 .0014	.907	−.0007 .0013	.585	−.0005 .0003	.048
environment **(reference: indoor)**	−0.031 0.023	.182	.0023 .0014	.099	.0008 .0013	.555	.0025 .0003	.000
age (reference: young adults)	0.123 0.031	.000	.0003 .0018	.865	.0009 .0016	.585	.0002 .0003	.494
environment * footwear	0.023 0.033	.487	−.0004 .0019	.818	.0000 .0018	.988	−.0005 .0004	.166
environment * **age**	−0.007 0.031	.818	.0012 .0018	.502	−.0003 .0017	.865	.0000 .0004	.891
footwear * **age**	−0.003 0.031	.927	−.0024 .0018	.183	−.0050 .0017	.004	−.0004 .0004	.235
environment * footwear * **age**	0.014 0.045	.746	.0062 .0026	.019	.0044 .0025	.078	.0000 .0005	.943
random effects	est SE	p	est SE		est SE	p	est SE	p
residual	.009 .001	.000	0.0000 0.0000	.000	0.0000 0.0000	.000	0.000 0.000	.000
intercept	.009 .002	.000	0.0000 0.0000	.000	0.0000 0.0000	.000	0.000 0.000	.000

λ values) during the barefoot and outdoor conditions. Furthermore, there was a footwear x age interaction ($p = 0.001$) for LDS (0–3 %). The decrease in LDS (0–3 %) during the barefoot conditions (vs. shod condition) was lower in older adults compared to younger adults.

Stride length was statistically different between outdoor vs. indoor ($p < 0.001$), footwear ($p < 0.001$) and age ($p = 0.021$) and stride time for outdoor vs. indoor ($p < 0.001$), footwear ($p < 0.001$) and age ($p < 0.001$) (Fig. 4). Stride length was higher in shod trials, outdoor conditions and in younger adults, while stride time was higher in shod and indoor conditions, as well as in younger adults (Table 3).

Gait velocity and minimal toe clearance were affected by outdoor vs. indoor ($p < 0.001$) and footwear conditions ($p < 0.001$) (Fig. 4). Both parameters, gait velocity and MTC, were higher in shod and outdoor conditions (Table 3).

4. Discussion

Our results suggest that barefoot walking differed in some gait variability measures as well as in standard gait parameters when compared to shod walking. MTC variability (in both age groups) and stride time variability (in older adults) was higher during the shod walking condition. For standard gait parameters, barefoot walking led to

Table 3

Effects of shoe condition, environment and age (as well as all possible interaction effects) on local dynamic gait stability (LDS), stride length, stride time, gait velocity and minimum toe clearance (MTC). Each gait measure was predicted with separate hierarchical linear models (2 levels, random intercepts). SE: standard error, est: estimate.

	LDS (0−3 %)		stride length		stride time		gait Velocity		MTC	
fixed effects	b SE	p	b SE	p	b SE	p	b SE	p	b SE	p
intercept	24.40 0.40	.000	1.55 0.02	.000	1.08 0.01	.000	1.45 0.03	.000	.018 .001	.000
footwear (reference: shod)	5.47 0.44	.000	−0.13 0.01	.000	−0.03 0.01	.000	−0.08 0.01	.000	−.005 .001	.000
environment (reference: indoor)	1.558 0.446	.001	0.07 0.01	.000	−0.02 0.01	.000	0.10 0.01	.000	.005 .001	.000
age (reference: young adults)	−0.81 0.53	.127	−0.07 0.03	.021	−0.06 0.02	.000	0.01 0.04	.769	−.000 .001	.747
environment * footwear	0.62 0.63	.325	−0.01 0.01	.630	0.01 0.01	.146	−0.02 0.02	.318	.001 .001	.652
environment * age	0.48 0.60	.423	−0.02 0.01	.091	0.01 0.01	.136	−0.03 0.02	.080	.000 .001	.831
footwear * age	−1.96 0.59	.001	0.01 0.01	.246	−0.00 0.01	.719	0.01 0.02	.461	−.000 .001	.747
environment * footwear * age	1.01 0.85	.235	−0.03 0.02	.135	0.00 0.01	.702	−0.03 0.02	.210	.001 .002	.513
random effects	est SE	p	est SE	p	est SE	p	est SE	p	est SE	p
residual	3.12 0.31	.000	.0014 .0001	.000	.000 .000	.000	.003 .000	.000	0.000 0.000	.000
intercept	1.96 0.47	.000	.0156 .0027	.000	.004 .001	.000	.022 .004	.000	0.000 0.000	.000

a decreased stride length, stride time, gait velocity and minimal toe clearance. Additionally, the local dynamic walking stability (LDS 0−3 %) was decreased during barefoot walking. Furthermore, the environment affected MTC variability as well as all standard gait measures (stride length, stride time, MTC, gait velocity) and LDS (0−3 %). Therefore, indoor gait parameters do not reflect outdoor walking patterns and experimental induced effects might even differ not only in their effect size but also in the direction. We saw this for stride length variability in older adults.

Higher MTC variability was detected when walking shod (and outdoors). MTC variability is relevant for assessing the risk of falling, and a higher variability is associated with an increased risk [26]. Thus, walking barefoot might be an effective strategy to reduce the risk of falling. Since there was an inconvenience in a few participants when asked to walk barefoot outdoors (n = 4), minimal footwear might be a good trade-off to be used in cold and uncommon environments. Minimal footwear protecting the foot and only minimally interfering with foot and gait mechanics [27,28] have been shown to be even more effective in reducing MTC variability for older adults [12]. Furthermore, minimal shoes are in accordance with recommendations for optimal footwear for an older age cohort [29]. Nonetheless, when not habituated to minimal or barefoot locomotion, it needs to be kept in mind that balance control can also be diminished at least in acute and unfamiliar situations [13]. The effect of the higher MTC variability could also be coupled to the higher MTC during the shod (and outdoor) condition. The higher MTC might be a mechanism to reduce the chance of tripping in situations with a higher MTC variability (e.g. shod or outdoor) due to increasing the foot-ground distance. In line with the results for MTC variability, the stride time variability was reduced during barefoot walking, but only in older adults.

LDS (0−50 %) were not affected by barefoot walking, but we found higher λ values (lower LDS) in older adults compared to younger adults. Therefore, small perturbations are better compensated in younger adults on a time scale of (roughly 50 % of the stride time). The worsened ability to compensate for small perturbation in older adults increases the risk of falling risk [8]. The age effect was also found by Petersen et al. [12], who compared walking barefoot vs. walking with minimalist footwear in younger and older adults. Taken together, since gait variability measures were associated with fall risk [7,8], walking barefoot might decrease the risk of falling while outdoor walking might increase it.

Regarding gait velocity, participants walked faster in shod conditions as well as indoors. This is of clinical and practical relevance. Walking speed has been discussed to be a very relevant functional decline over the life span affecting the quality of life and fear of falling [30]. This is in line with other studies that showed (but not for older adults), that footwear use is associated with higher walking velocity [2,31]. In the presence of perturbations (e.g. outdoor walking) or when not familiar with barefoot walking, a reduced gait velocity might be a sign of a more cautious gait pattern. Whether or not a habituation to barefoot walking would result in an increased walking velocity for the group of older adults cannot be determined at the moment. Therefore, further research is suggested to investigate habituation effects of barefoot walking on the functional capacity of walking velocity. The findings of this study regarding shorter stride length and stride time in barefoot walking are in accordance with the literature [2]. This has been discussed to be a pendulum lengthening effect due to the added weight by the footwear or due to a more cautious gait pattern in the unhabituated barefoot condition [2,32] that results in a lower gait velocity. However, no conclusive data exist whether habituated barefoot walkers use an increased stride length compared to habitually shod walkers [6].

While local dynamic stability (LDS 0−50 %) was not affected by the environment nor by the footwear condition, the shorter-time LDS (0−3 %) depicts a more locally stable walking pattern in the shod condition compared to barefoot walking. Small perturbations are better compensated in time on a shorter time scale (roughly 3% of the stride time) while wearing shoes. Probably, the biomechanical features of the shoe compensate for very small perturbation at least in part instantaneously during the stance phase. The use of shorter-time LDS was proposed by Schroll [25] but is rarely used. In contrast to the LDS (0−50 %), this measure is affected by both experimental conditions but not by age. Therefore, it contains other information than compared to the standard LDS (0−50 %) LDS measure. Since different time scales are used, this seems to be intuitive. Taken together, the shorter-time LDS seems to be more sensitive compared to the standard LDS measure and also seems to be affected by different factors [25]. Therefore, this shorter-time LDS seems to be promising, but those differences should be explored in other studies.

4.1. Limitations (Sources of bias) and generalizability

One of the strengths of this study is that concurrently barefoot vs. shod gait was investigated in laboratory indoor and more real-life outdoor situations and compares young and older adults. Therefore, the external validity of this study can be assumed to be high. However, we would like to acknowledge that this study only compared a specific type of footwear (heavily cushioned) to walking barefoot, which limits the generalisation of findings with regard to different types of footwear. Furthermore, only the acute effect of the new footwear conditions was investigated, and no conclusions can be drawn for longer-term or habituation effects.

4.2. Recommendations for further research

This study investigated a healthy population in relatively controlled experimental conditions. To simulate more real world conditions, obstacles and medium perturbations might be needed. New developments in out of laboratory equipment might enable such investigation in the near future. Furthermore, future studies should investigate how cushioned footwear versus minimalist footwear might have different effects on gait stability and variability. Future studies also need to determine the longer-term effects of barefoot or minimal footwear locomotion on parameters relevant for assessing the risk of falling. Moreover, the shorter-time LDS (0−3 %) seems to be a promising measure. However, its value to rate the sensorimotor status should be evaluated in further studies. Lastly, the findings of this explorative study may serve to formulate precise hypotheses in future studies.

5. Conclusion

Gait stability and variability parameters as well as basic gait parameters in older and younger adults were acutely affected by footwear vs. barefoot and indoor vs. outdoor walking. While the direction of the positive and negative effects towards these conditions appear to vary between outcomes, our results suggest that the walking gait stability and variability in each age group is highly adaptive to changes in the environment and experimental conditions. From the prevention and treatment perspective, this emphasises the need to use diverse walking conditions to improve general walking skills. From a diagnostic perspective, our results show that walking data measured under certain conditions cannot easily be transferred to other conditions.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Acknowledgements

We thank the participants of this study.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] R. Pinhasi, B. Gasparian, G. Areshian, D. Zardaryan, A. Smith, G. Bar-Oz, et al., First direct evidence of chalcolithic footwear from the near eastern highlands, PLoS One 5 (6) (2010) e10984. https://www.ncbi.nlm.nih.gov/pubmed/20543959.

[2] S. Franklin, M.J. Grey, N. Heneghan, L. Bowen, F.X. Li, Barefoot vs common footwear: a systematic review of the kinematic, kinetic and muscle activity differences during walking, Gait Posture 42 (3) (2015) 230–239. https://www.ncbi.nlm.nih.gov/pubmed/26220400.

[3] Y.J. Tsai, S.I. Lin, Older adults adopted more cautious gait patterns when walking in socks than barefoot, Gait Posture 37 (1) (2013) 88–92. https://www.ncbi.nlm.nih.gov/pubmed/22867560.

[4] N.B. Holowka, B. Wynands, T.J. Drechsel, A.K. Yegian, V.A. Tobolsky, P. Okutoyi, et al., Foot callus thickness does not trade off protection for tactile sensitivity during walking, Nature 571 (7764) (2019) 261–264. https://www.ncbi.nlm.nih.gov/pubmed/31243365.

[5] K. Hollander, J.E. de Villiers, S. Sehner, K. Wegscheider, K.M. Braumann, R. Venter, et al., Growing-up (habitually) barefoot influences the development of foot and arch morphology in children and adolescents, Sci. Rep. 7 (1) (2017) 8079. https://www.ncbi.nlm.nih.gov/pubmed/28808276.

[6] K. Hollander, C. Heidt, V.D.Z. BC, K.M. Braumann, A. Zech, Long-term effects of habitual barefoot running and walking: a systematic review, Med. Sci. Sports Exerc. 49 (4) (2017) 752–762. https://www.ncbi.nlm.nih.gov/pubmed/27801744.

[7] D. Hamacher, N.B. Singh, J.H. Van Dieen, M.O. Heller, W.R. Taylor, Kinematic measures for assessing gait stability in elderly individuals: a systematic review, J. R. Soc. Interface 8 (65) (2011) 1682–1698. https://www.ncbi.nlm.nih.gov/pubmed/21880615.

[8] S.M. Bruijn, O.G. Meijer, P.J. Beek, J.H. van Dieen, Assessing the stability of human locomotion: a review of current measures, J. R. Soc. Interface 10 (83) (2013), 20120999, https://www.ncbi.nlm.nih.gov/pubmed/23516062.

[9] D. Hamacher, D. Liebl, C. Hodl, V. Hessler, C.K. Kniewasser, T. Thonnessen, et al., Gait stability and its influencing factors in older adults, PLoS One 9 (2018) 1955. https://www.ncbi.nlm.nih.gov/pubmed/30733686.

[10] K. Hollander, D. Hamacher, A. Zech, Running barefoot leads to lower running stability compared to shod running - results from a randomised controlled study, Sci. Rep. 11 (1) (2021).

[11] A. Ekizos, A. Santuz, A. Arampatzis, Transition from shod to barefoot alters dynamic stability during running, Gait Posture 56 (2017) 31–36. https://www.ncbi.nlm.nih.gov/pubmed/28482203.

[12] E. Petersen, A. Zech, D. Hamacher, Walking barefoot vs. with minimalist footwear - influence on gait in younger and older adults, BMC Geriatr. 20 (1) (2020) 88. https://www.ncbi.nlm.nih.gov/pubmed/32131748.

[13] K.C. Broscheid, A. Zech, Influence of barefoot, minimalist, and standard footwear conditions on gait and balance in healthy older adults, J. Am. Geriatr. Soc. 64 (2) (2016) 435–437. https://www.ncbi.nlm.nih.gov/pubmed/26889847.

[14] T. Cudejko, J. Gardiner, A. Akpan, K. D'Aout, Minimal shoes improve stability and mobility in persons with a history of falls, Sci. Rep. 10 (1) (2020) 21755. https://www.ncbi.nlm.nih.gov/pubmed/33303964.

[15] T. Cudejko, J. Gardiner, A. Akpan, K. D'Août, Minimal footwear improves stability and physical function in middle-aged and older people compared to conventional shoes, Clin. Biomech. 71 (2020) 139–145.

[16] M. Machulik, D. Hamacher, K. Lindlein, A. Zech, K. Hollander, Validation of an inertial measurement unit based magnetictiming gate system during running and sprinting, Deutsche Zeitschrift für Sportmedizin 71 (3) (2020) 69–75.

[17] Y.S. Cho, S.H. Jang, J.S. Cho, M.J. Kim, H.D. Lee, S.Y. Lee, et al., Evaluation of validity and reliability of inertial measurement unit-based gait analysis systems, Ann. Rehabil. Med. 42 (6) (2018) 872–883. https://www.ncbi.nlm.nih.gov/pubmed/30613081.

[18] E. von Elm, D.G. Altman, M. Egger, S.J. Pocock, P.C. Gotzsche, J. P. Vandenbroucke, et al., The strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies, PLoS Med. 4 (10) (2007) e296. https://www.ncbi.nlm.nih.gov/pubmed/17941714.

[19] D. Hamacher, D. Hamacher, M. Krowicki, L. Schega, Between-day test–retest reliability of gait variability in older individuals improves with a familiarisation trial, Aging Clin. Exp. Res. 29 (2) (2017) 327–329.

[20] D. Hamacher, D. Hamacher, W.R. Taylor, N.B. Singh, L. Schega, Towards clinical application: repetitive sensor position re-calibration for improved reliability of gait parameters, Gait Posture 39 (4) (2014) 1146–1148.

[21] D. Hamacher, D. Hamacher, N.B. Singh, W.R. Taylor, L. Schega, Towards the assessment of local dynamic stability of level-grounded walking in an older population, Med. Eng. Phys. 37 (12) (2015) 1152–1155.

[22] A.M. Fraser, H.L. Swinney, Independent coordinates for strange attractors from mutual information, Phys. Rev. A 33 (2) (1986) 1134.

[23] M.B. Kennel, R. Brown, H.D. Abarbanel, Determining embedding dimension for phase-space reconstruction using a geometrical construction, Phys. Rev. A 45 (6) (1992) 3403.

[24] M.T. Rosenstein, J.J. Collins, C.J. De Luca, A practical method for calculating largest Lyapunov exponents from small data sets, Physica D: Nonlinear Phenomena 65 (1-2) (1993) 117–134.

[25] A. Schroll, Der maximale Lyapunov Exponent - Methodische Beiträge zur Theorie und Anwendung in der Sportwissenschaft, doctoral dissertation, Department of Sport Sciences, Humboldt-Universität, Berlin, 2020.

[26] R.S. Barrett, P.M. Mills, R.K. Begg, A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking, Gait Posture 32 (4) (2010) 429–435. https://www.ncbi.nlm.nih.gov/pubmed/20692163.

[27] J.F. Esculier, B. Dubois, C.E. Dionne, J. Leblond, J.S. Roy, A consensus definition and rating scale for minimalist shoes, J. Foot Ankle Res. 8 (2015) 42. https://www.ncbi.nlm.nih.gov/pubmed/26300981.

[28] K. Hollander, A. Argubi-Wollesen, R. Reer, A. Zech, Comparison of minimalist footwear strategies for simulating barefoot running: a randomised crossover study, PLoS One 10 (5) (2015) e0125880, https://www.ncbi.nlm.nih.gov/pubmed/26011042.

[29] J.C. Menant, J.R. Steele, H.B. Menz, B.J. Munro, S.R. Lord, Optimising footwear for older people at risk of falls, J. Rehabil. Res. Dev. 45 (8) (2008) 1167–1181. https://www.ncbi.nlm.nih.gov/pubmed/19235118.

[30] M. Cruz-Jimenez, Normal changes in gait and mobility problems in the elderly, Phys. Med. Rehabil. Clin. N. Am. 28 (4) (2017) 713–725. https://www.ncbi.nlm.nih.gov/pubmed/29031338.

[31] B. Wirth, F. Hauser, R. Mueller, Back and neck muscle activity in healthy adults during barefoot walking and walking in conventional and flexible shoes, Footwear Sci. 3 (3) (2011) 159–167.

[32] D. Oeffinger, B. Brauch, S. Cranfill, C. Hisle, C. Wynn, R. Hicks, et al., Comparison of gait with and without shoes in children, Gait Posture 9 (2) (1999) 95–100. <Go to ISI>://WOS:000080609900002.