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Orthopedic footwear has a positive influence on gait adaptability in individuals with hereditary motor and sensory neuropathy

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ABSTRACT

Background: Individuals with Hereditary Motor and Sensory Neuropathy (HMSN) are commonly provided with orthopedic footwear to improve gait. Although orthopedic footwear has shown to improve walking speed and spatiotemporal parameters, its effect on gait adaptability has not been established.
Research question: What is the effect of orthopedic footwear on gait adaptability in individuals with HMSN?
Methods: Fifteen individuals with HMSN performed a precision stepping task on an instrumented treadmill projecting visual targets, while wearing either custom-made orthopedic or standardized footwear (i.e. minimally supportive, flexible sneakers). Primary measure of gait adaptability was the absolute Euclidean distance [mm] between the target center and the middle of the foot (absolute error). Secondary outcomes included the relative and variable error [mm] in both anterior-posterior (AP) and medial-lateral (ML) directions. Dynamic balance was assessed by the prediction of ML foot placement based on the ML center of mass position and velocity, using linear regression. Dynamic balance was primarily determined by foot placement deviation in terms of root mean square error. Another aspect of dynamic balance was foot placement adherence in terms of the coefficient of determination (R^2). Differences between the footwear conditions were analyzed with a paired t-test or Wilcoxon signed-rank test ($\alpha = 0.05$).
Results: The absolute error, relative error (AP) and variable error (AP and ML) decreased with orthopedic footwear, whereas the relative error in ML-direction slightly increased. As for dynamic balance, no effect on foot placement deviation or adherence was found.
Significance: Gait adaptability improved with orthopedic compared to standardized footwear in people with HMSN, as indicated by improved precision stepping. Dynamic balance, as a possible underlying mechanism, was not affected by orthopedic footwear.

1. Introduction

Hereditary Motor and Sensory Neuropathy (HMSN) disease is an inherited progressive polyneuropathy that affects the sensory and motor nerves of the peripheral nervous system. HMSN is the most common hereditary neuromuscular disorder and can occur in the myelin structure (type 1) or the axons (type 2) of the peripheral nerves [1]. As a result, there is a reduced motor control and a sensory loss in the feet and legs [2]. Over time, the weak neural signals to the muscles will cause muscle atrophy and muscle weakness [2], which can result in foot deformities like pes cavus and claw toes [3]. Sensorimotor disturbances and foot deformities together result in an adjusted walking pattern of foot drop, lateralized roll-off, impaired push off [4,5], and compensatory mechanisms at the level of the knee and hip [5–7]. Furthermore, a low gait speed [8] and increased risk of falling [9], indicating a decreased gait capacity, have been reported.

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Human gait capacity can be described by a tripartite model of 1) stepping, 2) dynamic balance, and 3) gait adaptability [10]. The first aspect (stepping) refers to the cyclical pattern of limb movements during gait. This gait pattern is specified by spatiotemporal parameters and joint kinematics and kinetics. The second aspect (dynamic balance) is defined as the ability to control the Center-of-Mass (CoM) in relation to the base of support during gait. The third aspect (gait adaptability) refers to the ability to adjust the gait pattern and dynamic balance to changing environmental demands.

Orthopedic footwear is often provided to individuals with HMSN who experience gait impairments [11]. In general, orthopedic footwear aims to accommodate foot deformity and enable plantigrade foot loading. Additional orthotic support may be integrated in the orthopedic footwear to compensate for muscle weakness to further enhance stability in the stance phase and foot clearance in the swing phase. Our research group recently investigated the effects of orthopedic footwear on two aspects of gait capacity: stepping (i.e. specific spatiotemporal parameters such as step length and width, and joint kinematics and kinetics) and dynamic balance (i.e. CoM – Center-of-Pressure (CoP) kinematics) [12]. We found that orthopedic footwear enhanced walking speed and step length, and decreased step width, whereas no effects on the dynamic relationship between CoM and CoP during regular walking could be established compared to standardized footwear. Furthermore, the propulsive force and ankle range of motion during the stance phase of gait, two mechanisms essential for gait adaptation, were not affected by orthopedic footwear during regular walking. Yet, gait adaptability during irregular gait requires larger propulsive forces and greater ankle range of motion compared to regular walking. Since orthopedic footwear may limit the maximal propulsive force and full ankle range of motion, it might have a negative impact on gait adaptability.

Hence, in this follow-up study, the aim was to investigate the effects of orthopedic footwear on gait adaptability in individuals with HMSN by assessing the performance on a precision stepping task while walking with either orthopedic or standardized footwear. Dynamic balance control during the precision stepping task was assessed to obtain insight in possible underlying mechanisms of improvement.

2. Methods

2.1. Participants

In total, 15 individuals with HMSN participated in this study. Participants were included if they were 1) between 18 and 80 years old, and 2) used customized orthopedic footwear for a minimum of two months to improve postural stability and/or to prevent falling. Participants were excluded if they were 1) unable to walk independently for 2 min, 2) experienced pain and/or pressure sores related to the orthopedic footwear, 3) had surgery of the lower extremities less than one year ago, or 4) were diagnosed with other neurological or musculoskeletal disorders influencing the walking pattern.

Demographic information like age, sex, height and weight were registered at inclusion. From the medical records, clinical information (HMSN disease type and Medical Research Council (MRC) Scale scores [13] of the ankle dorsi- and plantarflexors) were extracted.

All participants gave written informed consent in accordance with the Declaration of Helsinki. The study was approved by the internal review board of the Sint Maartenskliniek and the regional medical ethics committee of Arnhem-Nijmegen (2018–4306).

2.2. Intervention

All participants brought their custom-made orthopedic footwear to the assessments. This footwear had previously been provided through the outpatient clinic of the Sint Maartenskliniek in close collaboration between the treating physician (orthopedic surgeon or physiatrist) and the orthopedic shoe technician. The orthopedic footwear was molded to the individual foot shape, the insole accommodating the foot deformity while assisting in achieving or maintaining a position of the hindfoot as neutral as possible. Other individual footwear features were prescribed based on clinical characteristics (muscle strength, walking pattern and treatment goal). Common footwear features concerned shaft height, heel adjustment/height and forefoot apex position. Eleven participants wore orthopedic footwear with a shaft height above the ankle joint. Eleven participants had a beveled heel (i.e. posterior edge rounded off), two participants a flared heel (i.e. extended with a lateral flare), while two participants had no heel adjustments. The forefoot apex position was proximal to the metatarsal joints in nine participants and was aligned with the metatarsal joints in six participants.

2.3. Assessment

All participants visited the GRAIL (Gait Real-time Analysis Interactive Lab, Motek Medical BV, the Netherlands) of the Sint Maartenskliniek once. The GRAIL is an instrumented dual belt treadmill, equipped with a 10-camera motion capture system (VICON, Oxford, United Kingdom) and two embedded force plates underneath each treadmill belt. Marker position data was collected at a sample frequency of 100 Hz, whereas force plate data was sampled at 1000 Hz. The system is also equipped with a floor projector to project objects on the treadmill belt.

Before the start of the measurement, functional outcome and pain of the ankle and hindfoot were assessed using the American Orthopedic Foot and Ankle Society (AOFAS) Ankle-Hindfoot Scale score [14]. The classification of foot deformity proposed by Louwerens [15] was used to describe the position and flexibility of the first metatarsal and hindfoot.

Afterwards, reflective markers were placed on anatomical landmarks of the participants according to the Plug-In-Gait lower body model, while all foot markers were placed on the footwear. To indicate the anterior border of the footwear, an additional marker was placed at the tip of the footwear anterior to the metatarsal II marker and in line with the metatarsal II and heel marker on the sagittal axis.

Participants first performed a baseline measurement to familiarize themselves with walking on the GRAIL, and to assess spatiotemporal gait parameters during regular walking with orthopedic footwear. After the baseline measurement, participants completed a precision stepping task of two minutes with either orthopedic or standardized footwear (each participant completed both conditions). The order of the footwear was randomized across all participants.

2.3.1. Baseline measurement

During the baseline measurement, participants walked two minutes in a self-paced mode and two minutes at a preferred fixed speed. In the self-pace mode, the speed of the treadmill was automatically controlled by continuously comparing the position of the pelvis to the midline of the treadmill. Walking forward or backward relative to the midline resulted in acceleration or deceleration, respectively. Participants were instructed to walk at a comfortable walking speed for 2 min. The mean walking speed over the last 1 min and 45 s was considered as the preferred walking speed. Subsequently, participants walked 2 min at this preferred fixed speed to assess step length and step width during regular walking.

2.3.2. Precision stepping task

The precision stepping task lasted two minutes and was performed at the preferred walking speed, determined during the baseline measurement. Rectangular stepping targets (length and width identical to the participant's footwear) were projected on the treadmill. During the task, the stepping targets followed an irregular stepping pattern based on variations in step length and step width as determined during the baseline measurement. The step length varied across − 20%, − 10%, 0%, + 10%, and + 20% of the baseline step length, whereas step width varied across − 10 cm, 0 cm, and + 10 cm of two times the baseline step width (Fig. 1). Participants were instructed to step as accurately as

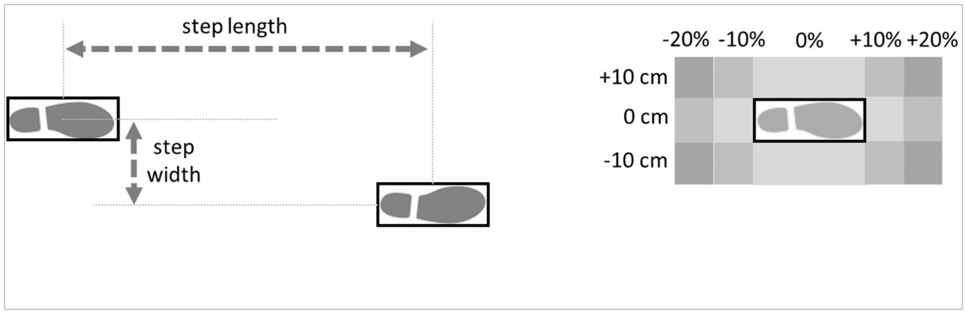

Fig. 1. Precision stepping task, with black rectangles following the regular stepping pattern and with shaded rectangles as variation options in anterior-posterior and medial-lateral direction.

possible within the borders of the stepping targets. Correct foot placement was defined as the middle of the foot within 5 cm of the target center.

All participants practiced stepping on the stepping targets once for approximately two minutes while they followed their own stepping pattern using the baseline step length and doubled baseline step width. During practicing, participants received real-time feedback regarding the foot placement in relation to the target. When the foot was placed correctly (<5 cm), the target lightened up green and a sound was played. In the case of incorrect foot placement, no sound or light was presented. No feedback was given during the actual precision stepping task.

2.4. Data analysis

Marker data were filtered using the Woltring cross-validity quintic spline routine (MSE=20). Subsequently, force plate and filtered marker data were filtered using a zero lag, fourth-order low-pass Butterworth filter with a cut-off frequency of 20 Hz.

Identification of heel strikes and toe-offs was based on the velocity of the foot markers [16]. The instant at which the velocity of the calcaneus marker started moving backwards was defined as a heel strike. Toe off was defined as the instant at which the velocity of the metatarsal II marker started moving forward [16]. Midstance was defined as 50% between heel strike and toe off.

To assess precision stepping performance, the distance between the target center and the middle of the foot at midstance was calculated. The middle of the foot was determined as the mean position of the tip of the footwear and the heel marker. The primary measure of gait adaptability was the absolute error [mm] defined as the absolute Euclidean distance between the target and foot (Fig. 2A). Secondary outcomes included the relative error and the variable error. The relative error [mm] was the distance between the target and foot in both anterior-posterior (AP) and medial-lateral (ML) directions (Fig. 2B and C, respectively). Positive values indicated an overshoot (anterior or lateral to the target), whereas negative values indicated an undershoot (posterior or medial to the target). The variable error [mm] was defined as the within-subject standard deviation of the distance between the target and the foot across steps in both AP and ML directions (Fig. 2D and E, respectively).

Dynamic balance was assessed by analyzing the relation between the CoM kinematics and the foot placement (FP) in ML-direction (i.e. the foot placement strategy) using linear regression. The ML foot placement was predicted based on the ML CoM position and velocity at heel strike [17,18], using the following formula:

$$FP = \beta_{pos} \bullet COM + \beta_{vel} \bullet \dot{COM} + \varepsilon$$

in which β_{pos} and β_{vel} are the regression coefficients of the CoM position and velocity, respectively, and ε the model error. CoM was estimated using the average of the four pelvis markers [19]. The CoM position was defined with respect to the calcaneus marker of the stance leg at

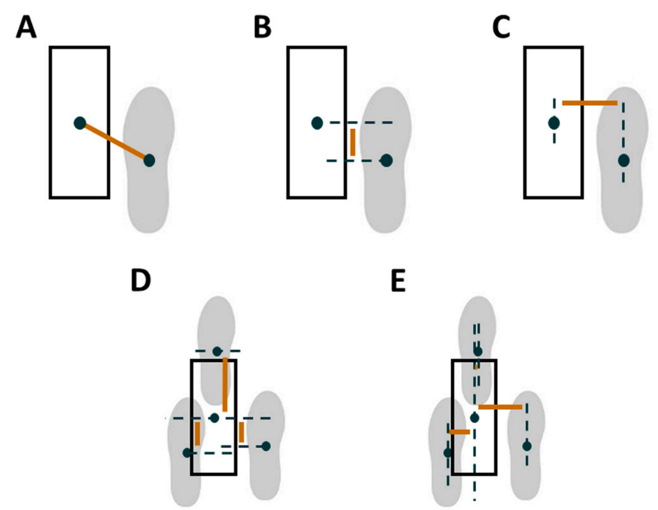

Fig. 2. Outcome measures for the precision stepping task. Black rectangles indicate the stepping targets and grey feet, the placement of the foot. The target center and middle of the foot are indicated with green dots. The orange lines represent the outcome measures: A. absolute error, which is the absolute Euclidean distance between target center and middle of the foot, B. relative error AP, which is the AP-distance between the target center and middle of the foot, C. relative error ML, which is the ML-distance between the target center and middle of the foot, D. variable error AP, which is the SD of the AP-distance across steps, E. variable error ML, which is the SD of the ML-distance across steps. AP: anterior-posterior. ML: medial-lateral, SD: standard deviation.

midstance. The CoM position and velocity were demeaned. Foot placement was defined as the demeaned ML distance between the left and right calcaneus markers at midstance.

We primarily determined the root mean square error (RMSE) of the linear regression to assess the accuracy of the foot placement strategy and referred to this measure as foot placement deviation [mm]. To verify adherence to the foot placement strategy, the coefficient of determination (R^2) of the linear regression was calculated and referred to as foot placement adherence. All data processing and analyses were performed using MATLAB 2018b (The MathWorks Inc, Natick, MA, USA).

2.5. Statistical analysis

Means and standard deviations of the absolute, relative and variable errors were individually calculated for the left and right leg together. Individual foot placement deviation and adherence were first determined for each leg separately, and then averaged for the left and right leg. To analyze the group differences between both footwear conditions a paired t-test ($\alpha = 0.05$) was performed. When the assumption of normality was violated, median and ranges were calculated and a non-parametric Wilcoxon signed-rank test ($\alpha = 0.05$) was performed. Since the secondary outcome measures were exploratory in nature, correction for multiple testing was not applied. All statistical tests were performed using MATLAB 2018b (The MathWorks Inc, Natick, MA, USA).

3. Results

3.1. Participants

Fifteen individuals with HMSN (10 males/5 females) and with an average age of 50 ± 15 years old participated [12]. Their mean height was 179 ± 10 cm and mean weight was 82 ± 18 kg. Nine participants were diagnosed with HMSN disease type 1, five with HMSN disease type 2, and one with HMSN disease type 4 h. The mean AOFAS Ankle-Hindfoot scale of all participants was 78 ± 14 points. The MRC-scale scores of the ankle plantar flexors were below 3 for ten participants, 4 for three participants, and 5 for one participants. The MRC-scale scores of the ankle dorsiflexors were below 3 for eight participants, 3 for four participants, 4 for one participant and 5 for two participants.

3.2. Gait adaptability

The mean preferred walking speed during the precision stepping task was 0.83 ± 0.22 m/s. A significant difference between footwear conditions was found for the primary outcome measure: absolute error ($t(14) = -2.9$, $P = 0.01$) (Table 1). Furthermore, all secondary outcome measures showed significant differences between footwear conditions: relative error in both AP-direction ($Z = 2.4$, $P = 0.02$) and ML-direction ($Z = 2.4$, $P = 0.004$), and the variable error in both AP-direction ($t(14) = -3.2$, $P = 0.01$) and ML-direction ($Z = 2.7$, $P = 0.004$)(Table 1). Remarkably, while the absolute error, relative error (AP) and variable error (AP and ML) decreased with orthopedic footwear, the relative error in the ML-direction slightly increased.

3.3. Dynamic balance

The foot placement deviation and adherence did not show significant differences between footwear conditions (Table 2).

4. Discussion

Orthopedic footwear improved gait adaptability in individuals with HMSN. The absolute error of foot placement decreased, as well as the relative error in AP-direction and the variable errors in AP- and ML-direction. Only the relative error in ML-direction showed a slight increase. At the same time, no effects on dynamic balance in terms of foot placement deviation or adherence were found with orthopedic footwear.

This was the first study that evaluated the effect of orthopedic footwear on gait adaptability in individuals with HMSN compared to standardized footwear. The mean absolute error of 66 mm with standardized (conventional) footwear as observed in the current study is in line with the stepping error found in individuals with diabetic peripheral neuropathy [20] or with Parkinson's disease [21]. With orthopedic footwear, the mean absolute error improved to 54 mm, which was still higher compared to healthy controls of comparable age (38 mm) [20]. In the literature, the difference in absolute stepping error between individuals with balance problems and healthy controls ranges from 17 to 22 mm [20–23]. Against this background, the improvement of about 12 mm in absolute stepping error with orthopedic compared to standardized footwear as observed in the current study would be considered clinically relevant.

Improvement in absolute error was mainly due to a decrease in relative error in the AP-direction. With orthopedic footwear individuals placed their foot on average 12 mm closer to the target in the AP-direction, while in the ML-direction the foot was placed on average 4 mm more medially to the target. The latter observation may be related to the fact that orthopedic footwear is generally wider than standardized footwear. Consequently, the markers placed at metatarsal II and the anterior border of the orthopedic footwear are placed more medially compared to standardized footwear, resulting in a more medial determination of the position of the middle of the foot compared to standardized footwear. Nevertheless, the variable error in both the AP- and ML-direction was smaller with orthopedic footwear, indicating that foot placement relative to the target was more consistent than with standardized footwear. Together, the smaller absolute error in AP-direction and the more consistent foot placement in both AP- and ML-direction demonstrate that individuals with HMSN were able to place their foot more precisely while wearing orthopedic footwear compared to standardized footwear.

In line with our previous study, orthopedic footwear did not affect dynamic balance. The higher foot placement deviation of 30 mm and lower foot placement adherence of around 0.7 compared to healthy controls [17,18,24,25], suggests an impaired foot placement strategy. The impaired foot placement strategy can most likely be attributed to the sensory impairments of HMSN individuals that are specifically present in the ankles and feet. Accordingly, the sensory information to estimate the state of the CoM and placement of the feet in space during walking is reduced or delayed. Since the interaction between the CoM and foot placement was comparable between footwear conditions in the current study and in a previous study, orthopedic footwear did not seem to influence the sensory input from the feet.

Some limitations of this study need to be addressed. Some participant characteristics, such as age, showed a wide range. To compare disease severity across participants, we assessed the MRC-scale for muscle force of the ankle dorsal and plantar flexors. Although all participants showed diminished muscle force (MRC<5) of the ankle dorsal and/or plantar flexors, everyone was able to perform the measurements without assistance. In addition, walking speed differed across participants. However, participants performed the precision stepping task at the same speed in both footwear conditions. During the precision stepping task, foot placement was imposed, but earlier research showed that restricted foot placement did not influence foot placement adherence [24].

Table 1
Precision stepping task outcomes.

Outcome	Orthopedic footwear	Standardized footwear	Mean difference	*p*
Absolute error [mm][a]	54 ± 22	66 ± 25	-12 ± 16	**0.01**
Relative error AP [mm][b]	-28 [− 109 − 1.5]	-33 [− 92 − 17]	11 [− 65 29]	**0.01**
Relative error ML [mm][b]	-18 [− 28 − 4.7]	-15 [− 27 3.2]	3.3 [− 13 20]	**0.004**
Variable error AP [mm][a]	35 ± 7.9	43 ± 14	-7.9 ± 9.5	**0.01**
Variable error ML [mm][b]	26 [15 43]	29 [17 70]	3.0 [− 4.9 44]	**0.004**

Bold: significant difference between footwear conditions ($p < 0.05$).
[a] mean ± standard deviations, statistically tested with a paired t-test
[b] median [min max], statistically tested with a Wilcoxon signed-rank test

Table 2
Dynamic balance outcomes.

Outcome	Orthopedic footwear	Standardized footwear	Mean difference	*p*
Foot placement deviation [mm][b]	29 [24 36]	31 [22 50]	-0.8 [− 25 7.7]	1.0
Foot placement adherence[a]	0.71 ± 0.07	0.68 ± 0.10	0.03 ± 0.09	0.23

Bold: significant difference between footwear conditions ($p < 0.05$).
[a] mean ± standard deviations, statistically tested with a paired t-test
[b] median [min max], statistically tested with a Wilcoxon signed-rank test

Furthermore, during precision stepping, multiple stepping targets were visible on the treadmill, giving individuals the opportunity to proactively plan their next steps, which implies that our precision stepping task is not able to assess reactive gait adaptations. Because reactive gait adaptations are also an important aspect of gait adaptability, the effect of orthopedic footwear on reactive gait adaptability should further be investigated.

In conclusion, gait adaptability in people with HMSN improved with orthopedic compared to standardized footwear, as indicated by better precision stepping. This improvement in anticipatory gait adaptability could not be explained by a congruent change of dynamic balance. Therefore, future research should focus on elucidating the underlying mechanisms of improved gait adaptability with orthopedic footwear in HMSN, with the aim to further optimize footwear features and to investigate whether targeted balance and gait training with orthopedic footwear might have additional clinical value.

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CRediT authorship contribution statement

L.A.F. de Jong: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft preparation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Y.L. Kerkum**: Conceptualization, Methodology, Writing – review and editing, Writing – review & editing, Supervision, Funding acquisition. **V.C. Altmann**: Resources, Writing – review & editing. **A.C.H. Geurts**: Supervision, Writing – review & editing. **N.L.W. Keijsers**: Conceptualization, Methodology, Software, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This study is part of the GaReC project, which is co-funded by OIM Orthopedie and the PPP Allowance made available by Health ~ Holland, Top Sector Life Sciences & Health, to stimulate public-private partnerships. Lysanne de Jong is employed by OIM Orthopedie. Neither OIM Orthopedie, nor Lysanne de Jong have (financial) benefits related to this project. There are no other conflicts of interest associated with this study.

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