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The Impact of Fatigue in Foot-Stabilizing Muscles on Foot Pronation during Gait and a Comparison of Static and Dynamic Navicular Drop Assessments

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Abstract: Background: Individuals may exhibit altered foot pronation during gait when fatigue sets in. Therefore, a more evidence-based understanding of these fatigue-induced changes may be helpful for future gait analysis and return-to-play tests since fatigue can provide new insights that might explain a person's complaints. Methods: A total of 25 healthy individuals (12♂, 13♀; 24.3 ± 2.7 years; 174.9 ± 9.09 cm; 70 ± 14.2 kg; BMI: 22.7 ± 2.8) participated in this controlled non-randomized study of unilateral fatigue of the right foot's stabilizing muscles with regard to the pronation of the foot, measured by navicular drop (ND) in static (statND; standing) and dynamic (dynND; walking) states. The left foot served as the control. Surface electromyography was used to verify fatigue. Results: While the statND did not change, the dynND increased significantly by 1.44 ± 2.1 mm (=22.3%) after the foot-stabilizing muscles experienced fatigue. No correlation was found between the statND and dynND. Conclusions: Muscular fatigue can affect foot pronation. The dynND appears to be more representative of the loads in everyday life, whereby most studies use the statND.

Keywords: foot posture; navicular drop; navicular height; gait analysis; return to play; gait analysis; longitudinal arch; prevention

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1. Introduction

With its intricate arrangement of bones, ligaments, and muscles, the human foot serves as a remarkable biomechanical structure fundamental to human mobility. Among its movements, foot pronation, encompassing eversion, abduction, and dorsiflexion, plays a pivotal role in maintaining balance, absorbing shock, and transferring energy during various activities [1,2]. Therefore, understanding the influence of fatigue on foot pronation and its potential effects on arch structure is of great interest in biomechanics [3].

Pronation describes the medial lowering movement of the midfoot in the Chopart joints. This is usually associated with a pes planus and is the counterpart of supination. The inconsistent terminology should also be noted at this point [4]. Eversion and pronation are not synonyms. Eversion explicitly refers to the rearfoot with its calcaneus, even if coupling is common, as is the case with pes planovalgus [5]. Lowering of the longitudinal arch structure thus corresponds to pronation, which can be measured by a static navicular drop (statND) and a dynamic navicular drop (dynND), representing two methods often used to objectively rate pronation while standing and during gait [6–8]. DynND describes the degree of pronation via the lowering of the navicular bone when the foot is maximally loaded throughout the gait cycle, usually occurring throughout the gait phases "loading response" or "mid stance". The procedure is very similar to the statND, except the height of the navicular bone is compared under a relaxed sitting position and under a load in a single-leg standing position, which is a modified version of the method first described by Brody [9].

Fatigue is a progressive decline in physical and mental performance [10]. Especially during sustained or repetitive activities, fatigue can be caused by various mechanisms, ranging from a lack of energy-providing molecules and the accumulation of metabolites within muscle fibers to inadequate motor command in the motor cortex [11]. Different factors may lead to reduced inter- and intramuscular coordination, illustrating the complex character of fatigue [12,13]. The special consideration of neuromuscular fatigue in movement analysis represents a significant paradigm shift [14]. Traditionally, gait analysis has predominantly focused on assessing static or baseline biomechanics and is carried out as a part of preventive diagnostics [15] in an absolute majority of cases when a patient or athlete is in a recovered state. However, it is increasingly clear that this approach may not capture the full spectrum of human movement, as it is known that fatigue-induced alterations can lead to significant changes in gait dynamics [16–18] and foot functions [3,19] in sports science and clinical practice [14,20]. Athletes engaging in endurance events or repetitive training sessions may experience fatigue-induced deviations in foot pronation, which could increase the risk of sport-induced inflammation (e.g., achillodynia and shin splints) and hinder performance [15,21,22]. Similarly, in clinical settings, individuals with certain foot conditions or pathologies may exhibit altered foot mechanics only when neuromuscular fatigue sets in [23,24], necessitating a more comprehensive understanding of these fatigue-induced changes.

A muscle's performance can be limited by neuromuscular fatigue. Considering the function of the m. tibialis anterior and posterior for appropriate pronation, it is conceivable that incorrect or delayed activation could increase the pronation behavior of the midfoot. Headlee, Leonard, Hart, Ingersoll and Hertel [3] had similar thoughts and used a similar approach to examine healthy participants who performed 75 repetitions of isotonic dorsal flexions of the foot with a resistance of 4.55 kg. They found that the navicular drop increased by an average of 1.8 mm. Gardin, et al. [25] also support the widely believed thesis that the navicular drop is an indicator of pronation-related injuries, which may be increased by fatigue. The authors fatigued the tibialis muscles of their 36 healthy participants and compared a static navicular drop between a sitting position and a standing position without evidence of an increased drop due to fatigue. Lee, Kim and Cho [19] examined the influence of foot muscle fatigue on balance and plantar foot pressure distribution. Although there were no significant changes in terms of balance, the medial foot pressure load increased, which can be interpreted as an indicator of increased pronation.

By examining existing research, elucidating the underlying biomechanical mechanisms, and highlighting potential clinical and sports-related implications, this study aims to emphasize the importance of fatigue as a critical variable in movement analysis and return-to-play tests.

The following hypotheses are examined in the present study:

Hypothesis 1 (H1). *If the foot-stabilizing muscles suffer neuromuscular fatigue, the static navicular drop (statND) in a one-legged standing position will increase.*

Hypothesis 2 (H2). *If the foot-stabilizing muscles suffer neuromuscular fatigue, the dynamic navicular drop (dynND) during gait will increase.*

Hypothesis 3 (H3). *There is a measurable relation between the statND and dynND values.*

The lack of further evidence to clearly support the thesis and achieve a clear consensus, missing sensitization to determine the potential importance of fatigue in diagnostics, and the combination of the statND and dynND to determine the possible effects of fatigue distinguish this study from the few existing studies. Ultimately, this research may contribute to the development of tailored interventions and assessment strategies, ensuring that fatigue-induced alterations in foot pronation and arch structure are recognized, understood, and managed effectively, benefiting both athletes and individuals with clinical conditions.

2. Materials and Methods

2.1. Subjects

The sample size was calculated a priori using G*Power (Version 3.1.9.6 for Macintosh, University of Kiel, Germany) for a repeated ANOVA (within–between interaction, f = 0.5, and α = 0.05). A minimum group size of 20 participants was calculated (power 0.96). This study was carried out in accordance with the current guidelines of the Declaration of Helsinki and was approved by the responsible ethics commission (No. 55). All participants signed informed consent forms and provided permission to publish the results. The authors have no conflicts of interest to declare.

All 25 participants (12♂, 13♀; 24.3 ± 2.7 years; 174.9 ± 9.09 cm; 70 ± 14.2 kg; and BMI: 22.7 ± 2.8) were sports students and staff (between 18 and 35 years of age). The exclusion criteria were subjects > 35 years, illness (e.g., fever, cough, or runny nose), acute complaints or injuries, previous injuries potentially limiting the foot's range of motion (forefoot, midfoot, or rearfoot), or the ankle joint (e.g., fractures), and foot deformities (pes cavus, pes planus, or pes planovalgus). For this purpose, the Navicular Index was determined for all test subjects, which averaged 0.27 ± 0.03 on the left side and 0.27 ± 0.03 on the right side (<0.17 = pes planus, 0.22–0.31 = standard, and >0.35 = pes cavus) [26].

2.2. Test Procedure

The test procedure is intended to provide a general understanding of the process. A detailed description of the methodology with the corresponding background is presented below.

The participants arrived in a rested state without intensive physical activity 48 h before the measurements were taken. All measurements were conducted by the same experienced researcher. All test subjects received standardized instructions on the study procedure. First, the statND was manually measured by comparing the navicular height in a sitting position with that in a single-leg standing position. Next, the subjects were marked for the three-dimensional motion tracking of the dynND during walking, and surface electromyography (sEMG) was used to analyze neuromuscular fatigue (see Section 2.3.2). The gait analysis was carried out over a walking distance of 800 cm, whereby only the respective gait cycles (three per side and condition) within a marked corridor of 540 cm were evaluated. This was followed by a short foot mobilization exercise with a 25× full range of motion (ROM) foot rotation to the right and left sides for both feet. Subsequently, isometric maximal voluntary contraction (IMVC) measurements (external rotation and internal rotation) were taken with sEMG. Once all measurements for the pretest were taken, the fatigue treatment with the sEMG control was applied to the right foot only. Afterward, the IMVC measurements (external rotation and internal rotation) with sEMG were repeated. Finally, the three-dimensional motion tracking for the dynND was carried out during walking. The chronology of the measurements (statND and dynND) was reversed in the posttest, as the dynND was the most important for the authors and should, therefore, be placed closest to the treatment.

2.3. Fatigue

2.3.1. Fatigue Protocol

All exercises were carried out on the right foot in a standing or seated position (Table 1). A detailed description of the protocol can be seen in Table 1. In the seated position, the right leg was placed on a spacer to be fatigued through exercises. The spacer was positioned between the lower part of the m. gastrocnemius and the heel to ensure that the right ankle had a full ROM during all exercises and that the reflective markers (optical motion tracking) and electrodes (sEMG) were not moved or damaged by floor contact. Before each exercise, standardized exercise instructions were given, and a test trial was conducted with a resistance band (Power Band SQMIZE, type: PB22; resistance: 24 kg; Seevetal/Hittfeld, Germany). Nevertheless, continuous movement control and correction were carried out by the instructor during the exercises. If the exercise could no longer be performed in accordance with the instructions, even after corrective instructions were given during the last repetitions, the instructor canceled the set. The aim of all exercises was a good quality of movement with maximum ROM and a predefined velocity of 1-0-1 s (concentric–isometric–eccentric). All exercises except the first and fifth were carried out by the all-out principle (maximum effort, full commitment). The time between exercises and between measurements was kept as short as possible to minimize recovery effects. Exercises one and five were executed on an Airex mat (Airex, Sins, Switzerland). The Borg rating of the perceived exertion scale (RPE scale) was used at the end of the treatment [27].

Table 1. The standardized exercises of the neuromuscular fatigue protocol and their characteristics.

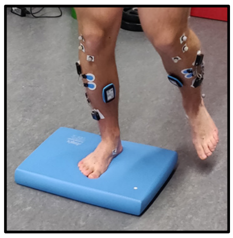
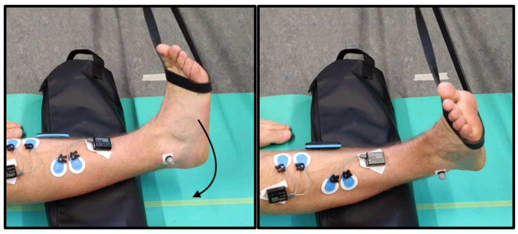
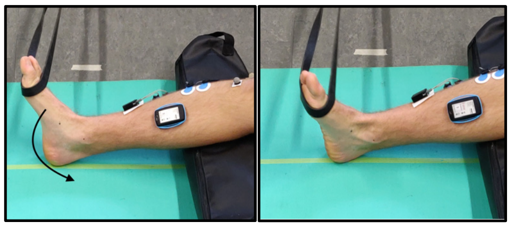
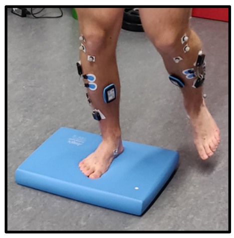
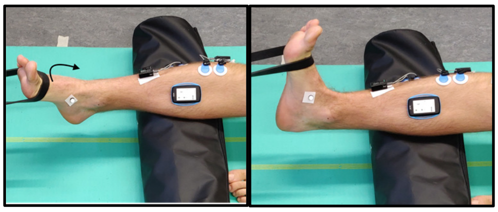
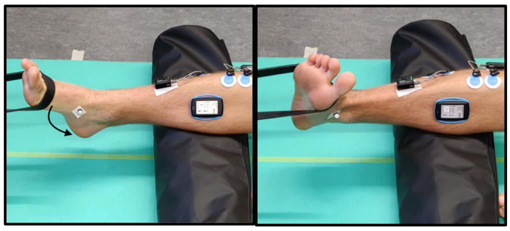
Exercise	Characteristics	Imaging
1. Standing on unstable ground on a single leg	- 1×60 s - aim: maximal foot stabilization - to increase the level of difficulty, a tennis ball was thrown back and forth between the participant and the instructor - targeted muscles: all foot-stabilizing muscles were in the one-legged stance	
2. Plantar flexion	- 1-0-1 s [1], all-out, full ROM [2] - calf raises: the forefoot was placed on a stepper, and the participant was allowed to rest their fingers on a windowsill to support their balance - targeted muscles: m. gastrocnemius, m. tibialis posterior, m. tibialis anterior	
3. Pronation	- 1-0-1 s, all-out, full ROM - the seated participant was aligned sideways (90°, distance: 73 cm) with a resistance band attached to the left - from the starting position, the foot was flexed, abducted, and maximally pronated - targeted muscles: m. fibularis longus, m. fibularis brevis	
4. Supination	- 1-0-1 s, all-out, full ROM - the seated participant was aligned sideways (90°, distance: 73 cm) with a resistance band attached to the right - from the starting position, the foot was flexed, abducted, and maximally pronated - targeted muscles: m. tibialis posterior, m. tibialis anterior	
5. Standing on unstable ground on a single leg	- 1×60 s - aim: maximal foot stabilization - to increase the level of difficulty, a tennis ball was thrown back and forth between the participant and the instructor - targeted muscles: all foot-stabilizing muscles were in the one-legged stance	

Table 1. *Cont.*

Exercise	Characteristics	Imaging
6. External rotation	- 1-0-1 s, all-out, full ROM - frontal alignment (180°, distance: 73 cm) of the seated participant with a resistance band attached at the front - from the starting position, the foot was flexed, abducted, and maximally pronated - sEMG [3]: the entire exercise was recorded using sEMG to compare the values (MDF [4] and MNF [5]) from the beginning and end of the exercise - targeted muscles: m. fibularis longus, m. fibularis brevis	
7. Internal rotation	- 1-0-1 s, all-out, full ROM - frontal alignment (180°, distance: 73 cm) of the seated participant with a resistance band attached at the front - from the starting position, the foot was flexed, adducted, and maximally supinated - sEMG: the entire exercise was recorded using sEMG to compare values (MDF and MNF) from the beginning and end of the exercise - targeted muscles: m. tibialis posterior, m. tibialis anterior	

[1] 1-0-1 = concentric–isometric–eccentric in seconds (s); [2] ROM = range of motion; [3] sEMG = surface electromyography; [4] MDF = median frequency; [5] MNF = mean frequency.

2.3.2. Surface Electromyography (sEMG)

sEMG was carried out using a telemetric Noraxon Desktop DTS (Noraxon, Scottdale, PA, USA; sampling frequency: 1500 Hz; lowpass filter: 500 Hz) to determine the fatigue of the foot-stabilizing muscles. To record muscle activity, adhesive electrodes (Ag/AgCl; Ambu Blue Sensor P: Ambub A/S, Ballerup, Denmark; diameter: 34 mm) were attached. The skin preparation procedure, electrode placement, and recording technology complied with the SENIAM standard [28]. To carry out the pre–post comparison to verify muscular fatigue, the median frequency (MDF) and mean frequency (MNF) during IMVC and during exercises six and seven (see 2.2; Table 1) were analyzed using Fast Fourier Transformation (FFT) with the MR3 software (Version 12.56, Noraxon, Scottdale, PA, USA). For all signals, the root mean square and average rectified values were computed (bandwidth: 10–500 Hz). The activity of the m. fibularis longus (FL) was measured as a representative of the pronators of the foot and that of the m. tibialis anterior (TA) for the supinators of the foot. The FL can be palpated and derived using sEMG at the lateral compartment of the calf, and the TA was chosen since it is not possible to carry out sEMG for the m. tibialis posterior, which is considered to play a more important role in stabilizing the longitudinal arch structure during the stance phase [29].

The muscular activity for the pre–post comparison of IMVC was performed using both feet throughout external (for FL) and internal rotation (for TA). This way, the left foot served as a control group, and the right foot served as the intervention group (fatigue).

1. External rotation: a combination of maximal pronation of the midfoot and dorsiflexion in the ankle joint for the m. fibularis longus.
2. Internal rotation: a combination of maximal supination of the midfoot and dorsiflexion in the ankle joint for the m. tibialis anterior.

The participants positioned themselves frontally to the resistance band (the distance to the attachment point of the resistance band (113 cm) ensured standardized tension). Each movement (external rotation and internal rotation) was performed three times and held for five seconds with the instruction to flex the corresponding muscles to achieve maximum foot movement. Since the IMVC is usually not reached right at the beginning, an exact three-second time window was evaluated with FFT to obtain the MNF and MDF for all runs as soon as the muscle reached maximum activity. The test with the highest frequencies based on the MDF and MNF was selected for the pre–post comparison. Left-sided sEMG (MDF and MNF) throughout treatment exercises six and seven allowed a comparison of the initial (15 s) and final (15 s) external rotation (ER) and internal rotation (IR).

Due to a technical error on one day, the sample for this part of the sEMG analysis was reduced by five test subjects to $n = 20$ (Table 2).

2.4. Pronation

2.4.1. Static Navicular Drop (statND)

First, the navicular bone was palpated and then color-marked at its base. The height of the navicular bone was then measured manually with a ruler while the individual was in a seated position, with the shank in a vertical position, as performed by Barton, Bonanno, Levinger and Menz [8]. The navicular height equals the vertical difference between the floor and the navicular bone. The next value was measured from a standing position to apply a body weight load to the foot. Similar to the gait analysis, where the foot is in a one-legged support phase for approximately 40% of the analysis [1], the contralateral foot is lifted. This introduces a static but full load to the foot. From this position, the height of the navicular bone was measured again. The difference between the navicular height (NH) in the seated position and that in the one-legged position is the statND (Figure 1).

$$NH_{sitting} - NH_{single\text{-}leg\ stance} = statND$$

The statND represents the sagittal plane displacement of the navicular bone. The procedure described in this study is a modified version of Brody's procedure [9].

2.4.2. Dynamic Navicular Drop (dynND)

The dynND is an analyzing method used in gait analysis to determine the degree of pronation. DynND refers to the distance by which the navicular bone drops towards the ground under load throughout the stance phase. During gait analysis, the point of the maximum drop is usually found between the loading response and mid stance [1]. The dynND was measured using three-dimensional motion capture with a Qualisys Track Manager (Version 2.15, Göteborg, Sweden; 200 Hz). Therefore, the IOR lower body maker set [30] was used and modified by two additional super-spherical reflective markers (Noraxon, Scottdale, PA, USA; size: 8 mm diameter), which were attached to the skin on the navicular bone (right and left feet) with double-sided adhesive tape. The height of the marker at the beginning of the loading response, when the foot was in a fixed and flat position, and the lowest point of the marker, which usually occurs until the end of the mid stance, were used to calculate the dynND. Further markers were applied according to the IOR lower body model [30], but they were only used to identify gait phases. In this case, the gait phases between the start of the loading response, which begins with the first contact of the metatarsal heads, and the end of the mid stance, when the heels begin to detach from the ground (heel-off), were of particular interest. The height of the dynND was recorded using the Mokka Motion Kinematic & Kinetic Analyzer software (version 0.6.2) [31].

To measure the dynND, the test subjects walked ten times on an 800 cm walkway. The measurement took place in a middle section of 536 cm in length. The walking speed and step frequency were measured for all stride sequences to ensure that there were no differences between the pretest (4.40 ± 0.40 km/h) and posttest (4.33 ± 0.42 km/h) that could influence the results of the dynND. The speed of each gait cycle was measured by analyzing the heel marker of the right foot of each gait cycle from its initial contact to the next initial contact of the right foot. The speed could then be calculated based on the distance traveled in relation to the time required. If there was a deviation of more than 0.4 km/h, the corresponding step sequences were excluded. The difference between the pretest and posttest was 0.1 ± 0.3 km/h on average. Three-step sequences were always randomly selected for each test subject, and each side, and a representative mean value was calculated. ND outliers with more than 1.5 of the interquartile range were eliminated; these occurred in 24 out of 500 cases.

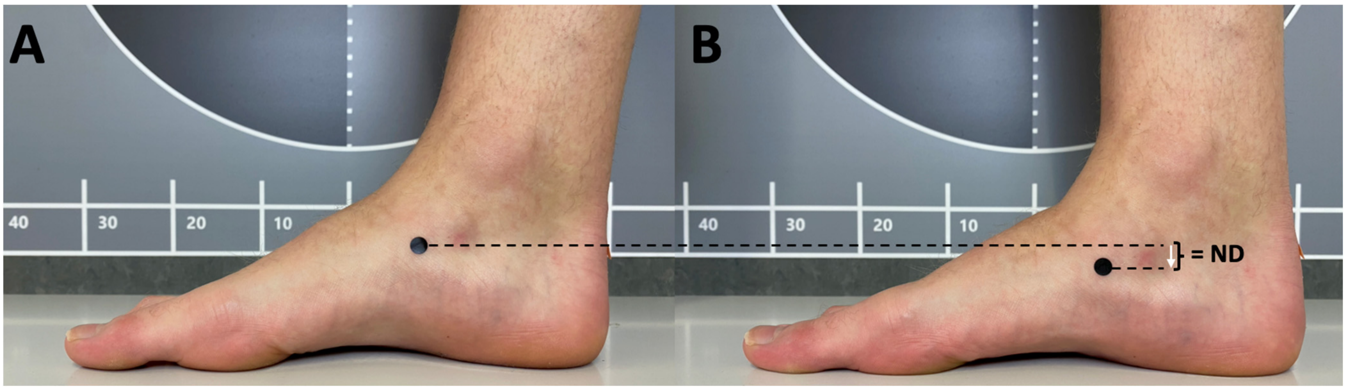


Figure 1. An illustration of the navicular drop (ND) in general, which describes the lowering of the navicular bone in a standing position (statND) or over the course of the stance phase during gait (dynND). The smallest navicular-to-ground distance usually appears during the gait phase loading response or mid stance. (**A**) shows the navicular position at the initial position (e.g., loading response). (**B**) shows the navicular position at its lowest position under a load (e.g., mid stance). The difference between (**A**) and (**B**) results in the ND (e.g., dynND).

2.5. Statistics

Statistics were calculated using IBM SPSS (29.0 for Macintosh, Chicago, IL, USA). The results are stated as the mean values ± standard deviations.

To ensure fatigue on the right side throughout the treatment, *t*-tests were applied for dependent and paired samples. sEMG (MDF and MNF) during IMVC was compared between the pre (3 × 3 s) and post (3 × 3 s) treatment periods for both feet. Left-sided sEMG (MDF, MNF) throughout treatment exercises six and seven allowed a comparison of the initial (15 s) and final (15 s) external rotation (ER) and internal rotation (IR).

All test requirements for the *t*-test were checked and confirmed. The significance level was set at $p < 0.025$ after the Bonferroni correction since the MDF and MNF were always measured in one trial. Cohen's *d* is provided as an effect size for significant results (0.2 = small effect; 0.5 = medium effect; and 0.8 = large effect).

To analyze the pre–post effects of fatigue on the statND (Hypothesis 1) and dynND (Hypothesis 2) side differences (non-fatigued (left) vs. fatigued (right)), an ANOVA with repeated measures was applied. The dependent variables were the manually measured statND and the three-dimensional dynND. Additionally, to analyze the relation between the two assessment methods, statND and dynND (Hypothesis 3), a mixed linear regression model was created. The dependent variables were the manually measured statND and the three-dimensional dynND. For this part of the statistical analysis, only one main effect (methods) was considered to answer Hypothesis 3. "Side" and "time" do not provide any additional value in testing this hypothesis. All test requirements for the ANOVA and for the mixed linear regression model were checked and confirmed. For the mixed linear regression model, the sample size increased (n = 200) as the values from the right foot (n = 25) and left foot (n = 25), and the pretest and posttest values were combined per method (statND and dynND). The significance level was set at $p < 0.05$.

3. Results

3.1. Proof of Fatigue

While no significant difference for the m. fibularis longus occurred on the left side, the MDF and MNF for the m. tibialis anterior increased significantly in the posttest. The right side (fatigue) showed significant decreases in the MDF and MNF for both muscles (Table 2).

Additionally, throughout the external rotation (exercise 6; see Table 1) and internal rotation (exercise 7; see Table 1) exercises of the right foot, the MDF and MNF (initial 15 s and final 15 s) were analyzed. During the external rotation exercise, the activity of the m. fibularis longus, the initial sequence, and the final sequence differed significantly for the MDF and the MNF. During the internal rotation exercise, the activity of the m. tibialis anterior, the initial sequence, and the final sequence differed significantly for the MDF and the MNF (Table 2).

Table 2. Proof of fatigue treatment for the foot-stabilizing muscles, the m. fibularis longus (FL) and m. tibialis anterior (TA). sEMG during isometric maximal voluntary contraction (IMVC) was compared between the pre (3 × 3 s) and post (3 × 3 s) treatment periods. Left-sided sEMG throughout treatment exercises six and seven allowed for a comparison of the initial (15 s) and final (15 s) external rotation (ER) and internal rotation (IR). All values are stated as the average ± standard deviation.

Parameter	**Left (Control)**			**Right (Fatigue)**		
***n* = 20**	**Pre**	**Post**		**Pre**	**Post**	
FL IMVC MDF [hz, *n* = 20]	86.39 ± 22.18	86.04 ± 22.44	$p = 0.451$	85.65 ± 23.38	72.03 ± 19.81	$\mathbf{p = 0.003}$ $d = 0.69$
FL IMVC MNF [hz, *n* = 20]	102.09 ± 22.21	102.33 ± 22.52	$p = 0.468$	102.02 ± 24.55	88.02 ± 21.26	$\mathbf{p = 0.002}$ $d = 0.73$
TA IMVC MDF [hz, *n* = 20]	115.58 ± 21.92	124.81 ± 27.69	$\mathbf{p = 0.021}$ $d = -0.57$	109.02 ± 24.32	94.91 ± 22.69	$\mathbf{p = 0.010}$ $d = 0.56$
TA IMVC MNF [hz, *n* = 20]	130.05 ± 17.00	137.19 ± 22.66	$\mathbf{p = 0.012}$ $d = -0.62$	124.50 ± 22.42	107.67 ± 21.71	$\mathbf{p < 0.001}$ $d = 0.81$
FL ER MDF [hz, *n* = 20]	---	---		80.40 ± 16.46	65.22 ± 15.29	$\mathbf{p < 0.001}$ $d = 1.02$
FL ER MNF [hz, *n* = 20]	---	---		98.92 ± 20.05	83.14 ± 22.18	$\mathbf{p < 0.001}$ $d = 0.97$
TA IR MDF [hz, *n* = 20]	---	---		88.21 ± 20.67	67.72 ± 18.91	$\mathbf{p < 0.001}$ $d = 1.26$
TA IR MNF [hz, *n* = 20]	---	---		101.56 ± 21.07	79.71 ± 19.90	$\mathbf{p < 0.001}$ $d = 1.37$

FL = m. fibularis longus; TA = m. tibialis anterior; MDF = median frequency; MNF = mean frequency; --- = left-side sEMG was not carried out throughout this exercise.

Due to the test setup and procedure, a comparison with the left foot served as the control. On average, the participants rated the treatment with a score of 18.0 ± 2.0 on Borg's RPE, which corresponds to "very hard" exertion [27]. The sEMG values confirm the validity of the fatiguing treatment (see Table 2).

3.2. Pronation Measured with the Static Navicular Drop (statND; Hypothesis 1)

The static ND differed on average by 0.00 ± 1.26 mm (pre: 5.56 ± 2.36 mm; post: 6.81 ± 1.75 mm) for the left foot and by 0.2 ± 1.85 mm (pre: 6.16 ± 2.17 mm; post: 6.81 ± 1.75 mm) on the fatigued right side (Table 3). The results show no significant difference for the within-subject factors "time of measurement" (pre vs. post) ($F(1,24) = 0.267$, $p = 0.610$), "side" (right vs. left foot) ($F(1,24) = 2.324$, $p = 0.140$), and "time*side" ($F(1,24) = 0.160$, $p = 0.693$).

3.3. Pronation Measured with the Dynamic Navicular Drop (dynND; Hypothesis 2)

For the pre–post comparison of the dynamic ND, the gait speed was determined in the pretest (4.40 ± 0.44 km/h) and posttest (4.33 ± 0.42 km/h), with no significant difference found ($p = 0.351$). The dynamic ND changed on average by 0.00 ± 1.93 mm (pre: 6.16 ± 2.17 mm; post: 6.36 ± 2.34 mm) for the left control side and increased on average by 1.44 ± 2.11 mm (pre: 6.16 ± 2.17 mm; post: 6.36 ± 2.34 mm) for the right fatigued side. The results show a significant difference for the within-subject factors "time of measurement" (pre vs. post) ($F(1,24) = 6.419$, $p = 0.018$, $\eta^2 = 0.211$), "side" (right vs. left foot) (F(1,24) = 22.646, $p < 0.001$, $\eta^2 = 0.485$), and "time*side" (F(1,24) = 6.190, $p = 0.020$, $\eta^2 = 0.205$).

3.4. Relation between Dynamic (dynND) and Static Navicular Drop (statND) (Hypothesis 3)

The mixed linear regression model shows a significant difference between the dynND and statND (F(8,199) = 1.936, p =< 0.001, d = 0.2). Figure 2 shows the Bland–Altman plot, in which the difference between two measurements is plotted against the mean values of the two measurements.

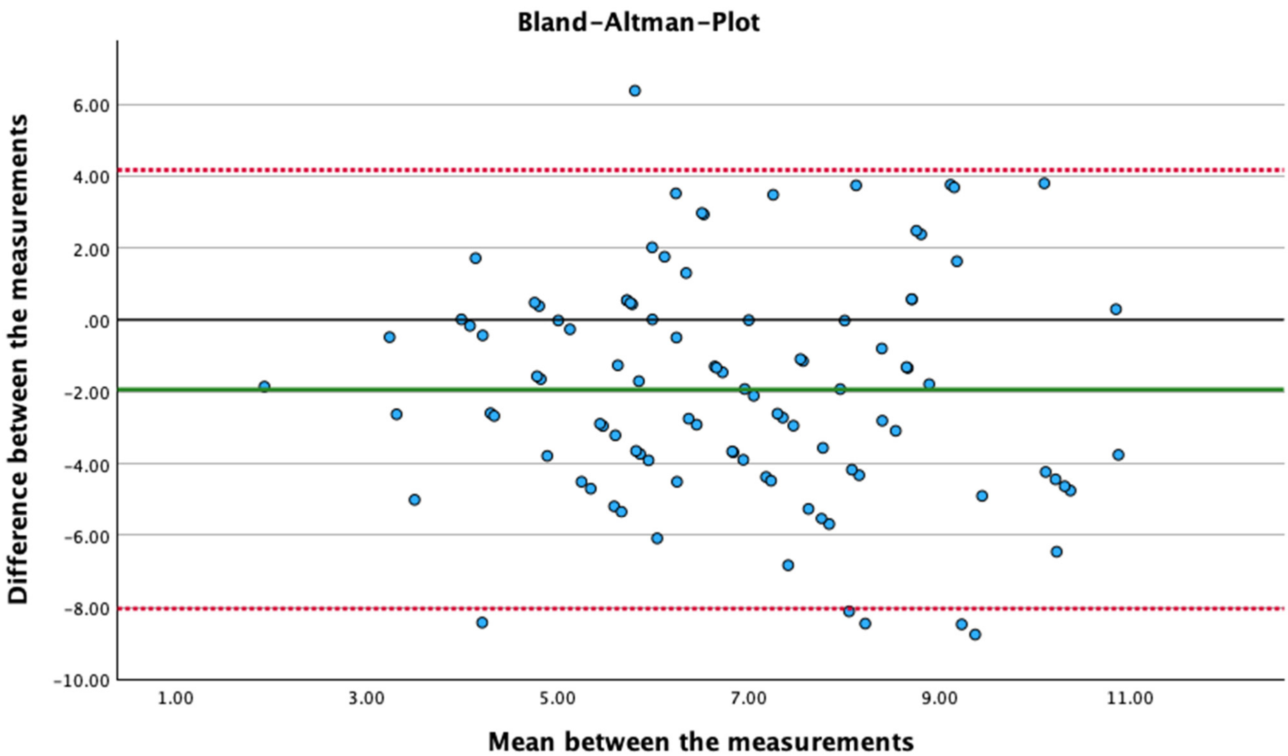


Figure 2. Bland–Altman plot between dynamic (dynND) and static (statND) navicular drop. The green line represents the mean difference. The red lines represent the ± 1.96 standard deviations from the mean difference.

4. Discussion

The results show that the treatment led to measurable fatigue. Pronation (dynND) during gait increased significantly as a result, which is in line with Hypothesis 2. Contrary to Hypothesis 1, pronation (statND) while standing did not change after fatigue. Similarly, the test for Hypothesis 3 showed that the two assessment methods (statND bs. dynND) are not as related as we originally thought. A further discussion of the results and methods is presented in the below sections.

4.1. Dynamic Navicular Drop (dynND) and Fatigue (Hypothesis 2)

The present study investigated the influence of fatigue of the ankle-stabilizing muscles on the pronation of the midfoot. The m. fibularis longus and brevis are important pronators of the foot and protect the foot against supination trauma, one of the most common injuries in sports [32]. The m. tibialis anterior and posterior are the antagonists and, therefore, the supinators of the foot. They support the rearfoot rocker during gait (initial contact and loading response) and the shock absorption (loading response and mid stance) of the foot. The cushioning effect is mainly achieved by the pronation of the midfoot, in which the fibularis muscles work eccentrically. If the pronation is too strong (pes planus) [25,33] or too fast [34,35], this might lead to overuse of the anatomical structures.

Midfoot pronation, measured via the dynND, increased by 1.44 mm ($p < 0.001$) on the fatigued side, while that of the control side did not change. The dynND increased by an average of 22.28% on the fatigued side. In 5 out of 25 cases, it even increased by >50%. The effect sizes underline the relevance of the changes. Depending on the authors, a dynND of 5.0–8.0 mm can be considered to be normal (Table 3). Up to this level, it can be assumed that pronation is adequate and functional in terms of the metatarsal shock absorption mechanism. Figure 2 shows that the ND will change depending on the sample and methods used. If we compare these values with the pretest values in this study, then the ND is basically within the normative range for the left foot (6.81 mm), whereas the ND of the right foot is generally a little higher (8.16 mm), although the participants had no signs of deformities, as the navicular index was assessed (see Section 2.1). In the authors' opinion, this could be due to a systematic bias in the measurement or a systematic asymmetry (right vs. left). A minority of sources make a distinction between the right and left sides in their data. However, a change can be observed between the pretest and posttest, which even occurred in the healthy (symptom-free) and athletic subjects without foot deformities. The increasing ND under the influence of fatigue could help to identify deviations that would not be observable without a fatigued state.

Table 3. An overview of the dynamic navicular drop values (dynND) of comparable studies.

Author	N	Average ND	Subjects and Methods
Cornwall and McPoil [36]	106	5.9 mm	- 57♀, 49♂ - 6D electromagnetic tracking system
Dicharry, et al. [37]	72	8.2 mm	- 38♀, 34♂ - 3D motion tracking
Kim and Park [38]	24	5.1 mm	- 17♀, 7♂ - 3D motion tracking
Nielsen, Rathleff, Simonsen and Langberg [7]	280	5.3 mm	- 136♀, 144♂ - 2D video analysis
Nielsen, et al. [39]	280	6.0 mm	- 136♀, 144♂ - 2D video analysis
Nielsen, Rathleff, Simonsen and Langberg [7]	79	5.4 mm	- 42♀, 37♂ - 2D video analysis

It is important to mention that three-dimensional marker-based motion tracking, even if it is considered the gold standard, has a certain probability of measurement error concerning accuracy. The mean trueness and uncertainty should be below 0.33 mm for the system used [40]. Nevertheless, the authors interpret the systematics and proportionality of changes as potentially relevant for practice. In gait and movement analyses, a marginal change can lead to a complaint. The results of the present study match those of Headlee, Leonard, Hart, Ingersoll and Hertel [3], in which the ND (in this study, the statND) increased by an average of 1.8 mm following the fatigue of the plantar intrinsic foot muscles. Fiolkowski, et al. [41] anesthetized the intrinsic foot muscles in ten test subjects with the aid of an injection, which increased the ND (in this study, the statND) by 3 mm. Willems, et al. [42] and Weist, et al. [43] observed a medial shift in the foot pressure distribution in the heel area in a fatigued state. Whether this observation was due to the eversion of the heel or pronation was not precisely differentiated, but those two movements are often mechanically coupled. In contrast to the results of this study, Zadpoor and Nikooyan [44] and Okamura, et al. [45] also found local fatigue of the intrinsic foot muscles but observed a reduction in the heel eversion angle and a reduction in the statND, which they attributed to a kind of compensatory mechanism.

Given the limited number of comparable approaches, some studies show that fatigue (local and global) can influence foot kinematics and kinetics [46]. Even if there is much to suggest that midfoot pronation would be increased, further studies should be carried out to investigate the dynND, as the majority of studies used the statND. Nevertheless, they all show that fatigue has an influence on the ND—regardless of the direction—and it should therefore be taken into account in gait and movement analyses [14].

4.2. Static Navicular Drop (statND) and Fatigue (Hypothesis 1)

The midfoot pronation measured via the statND increased non-significantly by an average of 0.2 mm. In view of the statND data, it must be stated that fatigue did not lead to a demonstrable change, as was the case with the dynND. The statND is an efficient method for objectifying pronation, which seems to be the most used method so far, but this method is significantly more error-prone and not as close to everyday life in direct comparison to three-dimensional optical motion tracking during gait (dynND). Although the examiner was trained, the palpation and marking of the base of the navicular bone with a pencil entails potential measurement inaccuracies. Even more vulnerable in regard to the pre–post comparison is the manual reading of the navicular height using a ruler. Furthermore, it can be assumed that the lack of dynamics and, consequently, comparatively low ground reaction forces or gravitational forces (standing vs. walking) could explain the difference between the statND and dynND. Headlee, Leonard, Hart, Ingersoll and Hertel [3] were able to measure the difference between the statND before and after fatigue using a similar methodology. A possible explanation could be that the measurement of the statND in the present study was placed after that of the dynND. This resulted in a time delay of approximately two minutes, which could have been enough to stabilize the fatigued state of the right foot. In addition, the statND of Headlee, Leonard, Hart, Ingersoll and Hertel [3] is already significantly higher in the pretest, with an average of 10.0 mm, than that in this study, with an average of 5.6 mm. For this reason, it is conceivable that the sample generally had a poorer foot status, as this ND would already be deviating from normative values according to most authors [38,41,47,48].

4.3. Comparing Static (statND) and Dynamic (dynND) Navicular Drop Assessments (Hypothesis 3)

The results of the present study show that there is a significant difference between the two measurement methods. From the authors' point of view, there are two main reasons for this. Firstly, the neuromuscular profile for the dynND is significantly higher than that for the statND [49]. Compared to a dynamic measurement and greater gravitational forces, the foot has comparatively greater stability when standing. Weaknesses, such as those caused by fatigue, can probably be better compensated for while standing. Secondly, the two parameters presumably differ considerably in terms of reliability. While the dynND was measured in this study using a three-dimensional optical tracking system with technical support according to the best current possibilities, the statND was measured manually. Measurement inaccuracies, therefore, presumably have a significant influence on this part of the study. Based on the results, it would be advisable to measure pronation using the ND in dynamic mode using two- or three-dimensional videos. Nevertheless, the practicability of the statND with sufficient reliability cannot be denied [50]; only the procedure for measuring the statND should be standardized. Some researchers compare the ND between bipedal sitting and standing [51]; others choose one-legged stance variants [52] or a comparison when the subtalar joint is positioned neutrally and loaded without corrections [53]. Nevertheless, our results confirm those of Rathleff, Nielsen and Kersting [47], who were also unable to demonstrate a predictive correlation between the statND and dynND. Similar results were observed by Deng, Joseph and Wong [51], who had a similar setup with 51 subjects, except they obtained the statND using a sit-to-stand comparison. This is to be understood less as a final thesis but primarily as an outlook for the necessity of further investigations of the two measurements. So far, it seems like static measures of the ND do not predict the ND during gait analysis [37,51,54].

With both methods, however, it must be taken into account that normative values are only a rough guide with widely discussed advantages (orientation, especially for clinical conditions) and disadvantages (individuality). The extent of the ND must be set in relation to other abnormalities and symptoms, as the ND is already strongly influenced by foot size and BMI [7]. An increase in those parameters usually resolves in an increase in the ND.

4.4. Limitations

There are some limitations of this study that must be taken into account when interpreting the results. The fatigue treatment does not represent everyday stress. The content of the study was designed to be as standardized and economical as possible with the aim of achieving local muscle fatigue. It should also be noted that the m. tibialis posterior is considered to be of the greatest importance in stabilizing the pronation of the midfoot [29]. However, this muscle cannot be measured via sEMG. For this reason, the authors used the partially synergistically working m. tibialis anterior. The fatigue treatment (see Table 1) focuses more on the functions of the m. tibialis anterior (dorsiflexion, supination, and inversion) than on those of the m. tibialis posterior (plantar flexion, supination, and inversion). Consequently, a greater emphasis should have been placed on exercises combined with a form of plantar flexion and supination. This could have led to a further increase in the ND.

Future studies that also use three-dimensional motion capture should additionally determine the rearfoot angle (eversion) at the point of maximum pronation. This will allow for an even more differentiated interpretation of the foot posture and its misalignments or weaknesses. Another potential next step could be to investigate whether and to what extent the velocity of the internal tibial rotation increases as a result of fatigue. Internal tibial rotation is mechanically linked to metatarsal pronation and can be the cause of complaints, even if the overall range (in this study, the navicular drop) remains unchanged [55].

5. Conclusions

While our results show that the statND is only affected by fatigue to a minor and non-significant extent, the dynND shows a significant increase in the navicular drop by an average of 1.44 mm. This may not seem much, but for sport-specific cases, it could explain the causes of certain complaints in the gait and movement analyses, which we would not be able to observe with the absence of fatigue.

No relation between the statND and dynND could be established in the present study, which is why further investigations are required. Future studies should focus on presenting a clear explanation of the navicular drop (e.g., the statND vs. dynND). More studies should try using the dynND since it seems to be closer to everyday life when looking at the gait cycle and its phase of single-legged support.

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