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The influence of gait and speed on the dynamic navicular drop – A cross sectional study on healthy subjects

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Abstract

Introduction. Variations of gait speed influence kinematic variables that may have an effect on dynamic foot deformation. The influence of gait speed on the navicular drop has not yet been investigated.

Methods. The navicular drop was evaluated in static and dynamic conditions using a 3D-motion capture system. The dynamic navicular drop was evaluated on a treadmill while walking and running at three different speeds. A repeated measures ANOVA and post-hoc tests were conducted to evaluate the differences in dynamic navicular drop, corresponding unloaded navicular height at foot strike and loaded navicular height during stance.

Results. Higher walking speed led to a significant decrease in navicular height at foot strike and a subsequent decrease of dynamic navicular drop ($p = 0.006$). Across increasing running speeds, minimum navicular height was significantly decreased which in consequence led to an increased dynamic navicular drop ($p = 0.015$). For walking and running at the same speed, there was a large effect of gait style with an increase of dynamic navicular drop by 3.5 mm ($p < 0.001$) during running.

Discussion. The change of gait from walking to running at the same speed had a large effect on dynamic navicular drop. The values of navicular height at foot strike and minimum navicular height during stance should be taken into account for the interpretation of dynamic navicular drop measures. Static and dynamic navicular drop measures differ substantially.

Keywords: navicular height, navicular drop, gait speed, barefoot kinematics, 3-D motion capture

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1. Introduction

Numerous approaches have been used to gain more understanding of dynamic foot kinematics. Foot posture characteristics like hyperpronation [1] during running and walking have been linked to injuries [2] and overuse syndromes [3]. During stance, load causes a deformation of the foot by flattening the medial longitudinal foot arch (MLA) and by pronation of the foot that is eccentrically controlled by the M. tibialis posterior, M. tibialis anterior, M. peroneus longus, M. flex hallucis longus, M. triceps surae and the intrinsic foot muscles [4]. The talo-navicular joint exhibits the largest range of motion (ROM) and is therefore seen as an adequate reference for the deformation of the MLA [5]. The term navicular drop (ND) is commonly defined as the difference in height of the navicular bone between loaded and unloaded conditions [6] and is thought to be an adequate measure of foot pronation [1] and flattening of the MLA. A greater navicular drop is associated with overuse injuries like medial tibial stress syndrome [7], and patella-femoral pain syndrome [8]. Non-neutral foot postures have been associated with a higher risk of injuries to the lower extremities [9]. It can be assumed, that the variability of foot deformation during gait is related to multiple intrinsic and extrinsic factors that modulate influencing forces. Factors such as speed, gait style and strike pattern influence vertical ground reaction forces (GRF): There is a linear increase of GRF in walking and running speeds up to 14.4 $\mathrm{km\,h^{-1}}$, where vertical GRF remains relatively constant at 2.5 times body weight [10]. However, there is insufficient research regarding the influence of varying walking and running speed on the dynamic navicular drop (*dNDrop*). Different approaches to quantify MLA deformation impede the comparability and lead to fractionally contradictory results: Whereas the navicular drop was found to be a poor predictor for the dynamic navicular drop [11], the longitudinal arch angle (LAA) during quiet standing was found to be highly predictive for LAA at mid-stance during walking [12, 13]. Dicharry et al. developed a practicable 5-marker model using 3-dimensional motion capture to investigate the navicular drop in dynamic gait conditions [14]. The authors recently developed a minimal markerset with four markers to measure the navicular drop under dynamic conditions [15] and found that the dynamic navicular drop is reliably measurable in intrasession gait assessments (repeatability 1.2 mm; SEM 0.5 mm; ICC21 0.97) [16]. The goal of this study was therefore to examine the influence of different gait velocities and gait style on the dynamic navicular drop using the minimal markerset. This study was designed to explore (1) the influence of gait speed on the dynamic navicular drop in walking and running and (2) to compare the influence of the kind of gait (walking, running) on the dynamic navicular drop at the same speed.

2. Methods

2.1. Subjects

This explorative study was carried out in a cross-sectional design on healthy individuals. Eligibility criteria were: age 18-65 years, no current symptoms to the musculoskeletal system, treadmill experience >3 hours and running activity >3 h/week. Exclusion criteria were: current pain (lower limbs or back), history of lower extremity injury <6 months, surgery in the lower limbs <24 months, and no experience in treadmill running. Prior to the study, written informed consent was obtained. Ethics approval was given by the ethics committee of the canton of Bern (KEK-No. 052/15).

2.2. Preparation and instrumentation

Four markers (diameter 14 mm regular feet and 9 mm for particularly small feet) were attached to each foot after skin-disinfection with double-faced adhesive tape and additional circumfluent tape to prevent drop off during running. The markers were placed by a single investigator in consecutive order at the: lateral caput of 5th metatarsal bone (1), medial caput of 1st metatarsal bone (2), middle of dorsal calcaneus (3) and tuberosity of the navicular bone (4). Kinematic data was obtained with 3D motion capture system (Vicon Motion Systems Ltd, 10 Vicon Bonita cameras, measurement volume (4 x 1.5 x 1.5) m^3). Walking and running was performed on a treadmill (Kettler Marathon TX, Ense-Parsit, GER) instrumented with two force transducers (KMB52K10KN, Megatron, Putzbrunn, GER) under the rear sockets to retrieve signals for the discrimination of corresponding foot strike and toe off events to extract the gait cycles. Speed levels of walking were defined as: G3kmh = $0.83\,\mathrm{m\,s^{-1}}$ ($3\,\mathrm{km\,h^{-1}}$), Gselfkmh = self-selected walking speed, G6kmh = $1.67\,\mathrm{m\,s^{-1}}$ ($6\,\mathrm{km\,h^{-1}}$) and speed levels of running J6kmh = $1.67\,\mathrm{m\,s^{-1}}$ ($6\,\mathrm{km\,h^{-1}}$), J9kmh = $2.5\,\mathrm{m\,s^{-1}}$ ($9\,\mathrm{km\,h^{-1}}$), J12kmh = $3.3\,\mathrm{m\,s^{-1}}$ ($12\,\mathrm{km\,h^{-1}}$). The order of speed levels was randomized and adjusted to two minutes each with data recording for the last 60 seconds. Walking and running at the same speed of $6\,\mathrm{km\,h^{-1}}$ was performed to isolate effects of changing the kind of gait from effects of changing the gait speed.

2.3. Procedure

All subjects executed a sit-to-stand navicular drop test before (M1) and after (M2) the treadmill measurements to evaluate potential changes due to repetitive impacts during the test protocol. Sitting position was adjusted to 90 degree flexion at the hip, knee and ankle joints respectively. The feet were placed on the ground and adjusted to hip width and vertical shin axis. The subjects were instructed to perform five sit-to-stand repetitions. Prior to the treadmill measurements, subjects completed a four-minute acclimatisation trial by running at a speed of $2.2\,\mathrm{m\,s^{-1}}$ ($8\,\mathrm{km\,h^{-1}}$) to accustom tissue stiffness. All six walking and running speeds were performed barefoot with attached markers.

2.4. Data analysis

Data was processed and analysed with custom Matlab software (Version R2017a, The MathWorks Inc., Natick, USA). A gait cycle detection algorithm was developed to extract and time-normalize the navicular height (NH) to the gait cycles. Samples of 30 steps per foot were averaged for both feet to receive robust average measures. Strike patterns were defined according to foot strike angles (FSA) between ground and the foot's longitudinal axis: (1) fore foot strike (FFS = FSA $<-3°$), (2) mid foot strike (MFS = $-3° <$FSA $<3°$) and (3) rear foot strike (RFS = FSA $>3°$).

2.5. Calculation of the static and dynamic navicular drop

The navicular drop was calculated as the difference in navicular height between loaded and unloaded conditions. The navicular height was the distance of the navicular bone marker from the reference plane spanned by the other three markers. The reference plane was calibrated based on a static trial in order to measure the navicular height perpendicular to the foot's plantar surface. The navicular height from the static trial in standing pose served also as zero position to express the navicular height from the dynamic measurements. Unloaded and loaded conditions for the static navicular drop (ND_{ST}) were sit and stand, respectively (Eq. 1). The dynamic navicular drop ($dNDrop$) was the difference between the minimum navicular height during stance (NH_{Min}) and the navicular height at foot strike (NH_{FS}) (Eq. 2).

$$ND_{\mathrm{ST}} = NH_{\mathrm{Sit}} - NH_{\mathrm{Stand}} \tag{1}$$

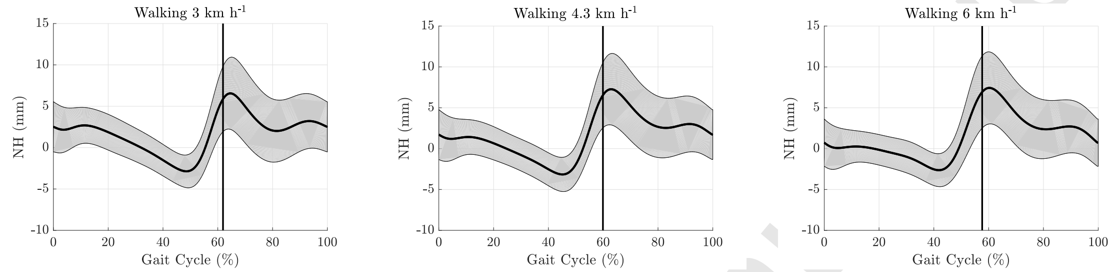
$$dNDrop = NH_{\mathrm{FS}} - NH_{\mathrm{Min}} \tag{2}$$

2.6. Statistical analysis

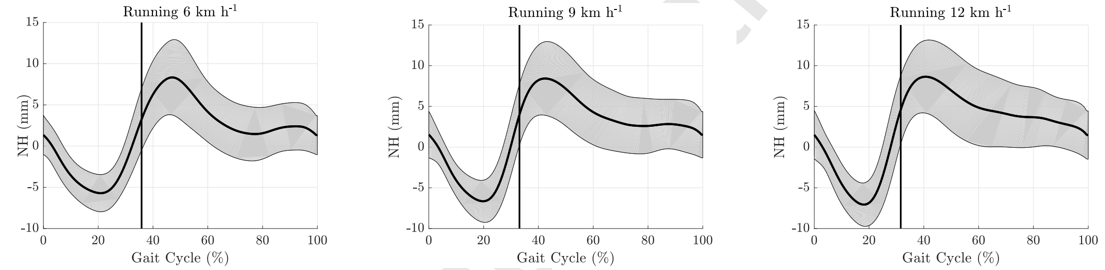
Assumptions of normality for all dependent variables were tested using Kolmogorov-Smirnov test. Analysis of variance (ANOVA) with repeated measurements was used to statistically examine ND_{ST}, $dNDrop$, NH_{FS} and NH_{Min} (dependent variables) on within subject effects of gait speed levels (independent variable). The Tukey-Kramer post-hoc procedure was used for subsequent pairwise comparisons. Statistical level of significance was set at 0.05.

3. Results

A total of 22 individuals were recruited and measured from which two must have been excluded from data analysis due to erroneous force signals and hence the inability to the detect gait events. Data from 13 males (age 32 ± 7 years; body weight 76.5 ± 8.6 kg; body height 182 ± 5 cm) and 7 females (age 29 ± 6 years; body weight 61.1 ± 10.5 kg; body height 168 ± 6 cm) was analyzed and the mean self-selected walking speed over all participants was $4.3 \pm 0.5\ \mathrm{m\,s^{-1}}$. Investigations of the static navicular drop showed no significant differences between M1 and M2 ($p = 0.999$). The static navicular drop was significantly smaller than the dynamic navicular drop during walking (-2.3 mm) and running (-5.8 mm) at 6 $\mathrm{km\,h^{-1}}$ ($p<0.001$, Fig. 3, Tab. 2). There was a significant effect of gait speed on the dynamic navicular drop for walking ($p = 0.006$) and running conditions ($p = 0.015$). Post-hoc testing indicated a significant decrease in the dynamic navicular drop between speed levels G3kmh and G6kmh (-2.0 mm, $p = 0.008$, Fig. 3, Tab. 2). In contrast, post hoc tests for running conditions indicated a significant increase of the dynamic navicular drop between J6kmh and J12kmh (1.7 mm, $p = 0.046$,Fig. 3, Tab. 2). There was a significant effect of gait style ($p < 0.001$) that showed an increase of the dynamic navicular drop by 3.5 mm for running compared to walking at the same speed of 6 $\mathrm{km\,h^{-1}}$ (Tab. 2). ANOVA of repeated measures carried out to investigate the effects of gait speed on navicular height at foot strike revealed a significant effect of walking speed ($p = 0.024$) but not for running ($p = 0.938$). Post-hoc testing revealed a significant decrease of navicular height at foot strike between G3kmh and G6kmh of 1.8 mm ($p = 0.044$) but no effect of running speed (Tab. 2). ANOVA investigating the effect of gait speed on minimum navicular height resulted in a significant effect for running speed ($p = 0.023$) with post-hoc tests indicating a significantly lower minimum navicular height between J6kmh and J12kmh ($p = 0.03$) (Tab. 2). No change in minimum navicular height was found for walking ($p = 0.561$).



(a) G3kmh (b) Gselfkmh (c) G6kmh



(d) J6kmh (e) J9kmh (f) J12kmh

Figure 1: Gait cycle (GC) time-series of navicular height from walking (a-c) and running (d-f) conditions, respectively averaged among all subjects. Solid black lines: mean; shaded grey areas: mean ± one standard deviation. Walking and running curves show the characteristic minima that served for extracting the dynamic navicular drop around 50 and 20%GC (80 and 50% stance, see Tab. 1), respectively. Gait cycle time-series from single subjects can be found in the **supplementary material**.

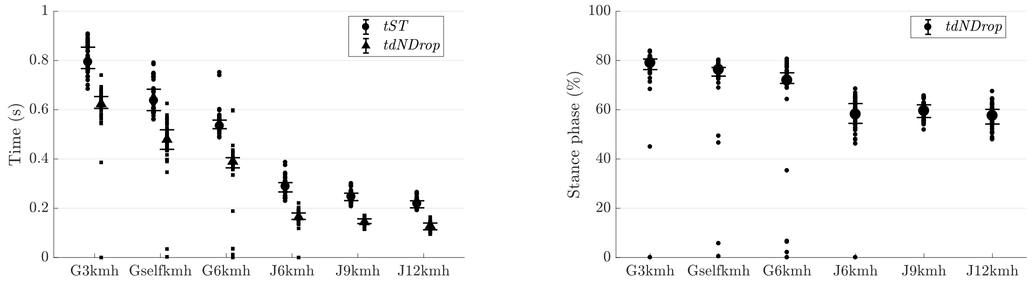


Figure 2: Dot-whisker representation of the timing variables with underlying data points (small dots). Large dots: medians. Whiskers: 0.25 and 0.75 quantiles, respectively. For descriptive statistics see Tab. 1.

	Speed (km h^{-1})	tST (s)	$tdNDrop$ (s)	$tdNDrop_{\mathrm{Rel}}$ (%SP)	$dNDrop$ (mm)	NH_{FS} (mm)	NH_{Min} (mm)
G3kmh	3	0.80 ± 0.06	0.62 [0.61,0.65]	79 [76,81]	-5.6 ± 3.1	2.5 ± 3.0	-3.1 ± 2.0
Gselfkmh	4.3 ± 0.5	0.65 ± 0.06	0.48 [0.44,0.52]	76 [74,77]	-5.1 ± 3.0	1.7 ± 3.1	-3.4 ± 2.1
G6kmh	6	0.53 [0.52,0.56]	0.39 [0.36,0.41]	72 [71,75]	-3.6 ± 2.4	0.7 ± 2.9	-2.9 ± 2.1
J6kmh	6	0.29 ± 0.03	0.16 ± 0.03	57 ± 10	-7.2 ± 2.3	1.3 ± 2.4	-5.8 ± 2.3
J9kmh	9	0.25 ± 0.02	0.15 ± 0.01	59 ± 3	-8.3 ± 2.6	1.5 ± 2.8	-6.8 ± 2.6
J12kmh	12	0.22 ± 0.02	0.13 ± 0.02	57 ± 5	-8.8 ± 3.0	1.5 ± 3.0	-7.3 ± 2.7
M1	-	-	-		-1.4 ± 1.4	-	-
M2	-	-	-		-1.7 ± 1.9	-	-

Table 1: Descriptive statistics of the dynamic navicular drop ($dNDrop$), the navicular height at foot strike (NH_{FS}) and the minimum navicular height during stance NH_{Min}). The time points associated with the dynamic navicular drop are given absolute ($tdNDrop$) and relative ($tdNDrop_{\mathrm{Rel}}$) to the stance phase time (tST). Variables which presented a normal distribution are given as (mean ± sd), otherwise the 0.25 and 0.75 quantiles are given together with the median (median [q25,q75]). For a graphical representation see Fig. 3 and 2.

	$dNDrop/ND_{\mathrm{ST}}$ Δ [95% CI]	**p-value**	NH_{FS} Δ [95% CI]	**p-value**	NH_{Min} Δ [95% CI]	**p-value**
Walking						
G3kmh vs. Gselfkmh	-0.5 [-2.2,1.2]	0.985	0.8 [-1.0,2.6]	0.787	0.3 [-1.1,1.7]	0.99
Gselfkmh vs. G6kmh	-1.5 [-3.1,0.2]	0.132	1.0 [-0.8,2.8]	0.601	-0.5 [-1.9,1.0]	0.934
G3kmh vs. G6kmh	**-2.0 [-3.6,-0.3]**	**0.008**	**1.8 [0.0,3.6]**	**0.044**	-0.2 [-1.6,1.2]	0.999
Gait Style						
G6kmh vs. J6kmh	**3.5 [1.9,5.2]**	**<0.001**	-0.6 [-2.4,1.2]	0.926	**2.9 [1.5,4.3]**	**<0.001**
Running						
J6kmh vs. J9kmh	1.1 [-0.5,2.8]	0.435	-0.2 [-2.0,1.6]	>0.999	0.9 [-0.5,2.4]	0.415
J9kmh vs. J12kmh	0.5 [-1.1,2.2]	0.976	0.0 [-1.7,1.8]	>0.999	0.6 [-0.9,2.0]	0.861
J6kmh vs. J12kmh	**1.7 [0.0,3.3]**	**0.046**	-0.2 [-1.9,1.6]	>0.999	**1.5 [0.1,2.9]**	**0.03**
Static						
M1 vs. M2	0.3 [-1.3,2.0]	0.999	-	-	-	-
M1 vs. G6kmh	**-2.3 [-3.9,-0.6]**	**<0.001**	-	-	-	-
M1 vs. J6kmh	**-5.8 [-7.4,-4.2]**	**<0.001**	-	-	-	-

Table 2: Results from post-hoc pairwise comparison tests. Effects of walking and running speed and gait style on the dynamic navicular drop ($dNDrop$), the navicular height at foot strike (NH_{FS}) and the minimum navicular heigth during the stance phase (NH_{Min}). The static navicular drop (ND_{ST}) was compared to walking and running at 6 km h^{-1} and between before (M1) and after (M2) the dynamic measurements. Estimated between-group differences are reported in mm together with the associated 95% confidence intervals. For a graphical representation see Fig. 3

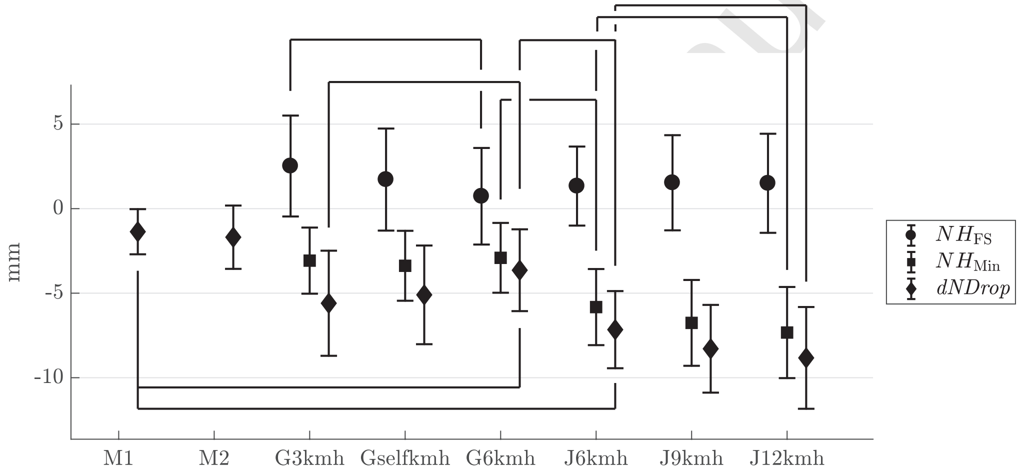


Figure 3: Dot-whisker representation (mean ± sd) for comparing between testing conditions. The static navicular drop (ND_{ST}) is considered for M1 and M2. The navicular height at foot strike (NH_{FS}), the minimum navicular height during stance (NH_{Min}) and the dynamic navicular drop ($dNDrop$) are presented for the dynamic conditions. Brackets indicate significant differences ($p<0.05$).

4. Discussion

This study investigated the influence of gait and speed on the dynamic navicular drop. Changes in navicular drop were evaluated between static and dynamic conditions. The study also looked at the navicular height at heel strike and the minimum navicular height during stance to evaluate their contributions to changes in the dynamic navicular drop.

4.1. Static navicular drop

With mean values of 1.4 mm and 1.7 mm, the static navicular drop was remarkably smaller than what was previously reported for hypomobile (2.9 mm), neutral (4.9 mm) and hypermobile feet (7.1 mm) during sit to stand experiments [14]. This discrepancy is ascribed to differing methodologies how the static navicular drop was assessed. While Dicharry et al. [14] used the common clinical approach with a ruler we used 3D motion capture for the static assessments, which was previously shown to underestimate the navicular drop compared with clinical methods [17].

4.1.1. Fatigue

The duration of an eighteen-minute treadmill program had no significant impact on the static navicular drop and is likely to be insufficient to show effects of fatigue or altered joint stiffness. One study has indicated that fatigue of intensive isometric contractions of the plantar intrinsic muscles against a 4.5 kg mass induced an increase in static navicular drop by 1.8 mm [18]. The results by Cowley et al. also confirmed that the navicular height was substantially decreased by a mean of 5 mm after a half marathon [19]. Muscle fatigue after 60 minutes of treadmill running has been shown to have an effect on higher impact loading rates of vertical GRF [20]. Passive structures such as the plantar aponeurosis and active structures like the tibialis posterior muscle and the plantar intrinsic foot muscles contribute to the dynamic foot stability and resistance to fatigue [18]. The present results confirm, that an eighteen-minute treadmill program was not confounding our examinations on the dynamic navicular drop due to potential muscle fatigue as reported after prolonged running [19].

4.1.2. Relation to dynamic assessment

Concerning the ability of static measures to predict dynamic foot function, one must differentiate between (i) static measures predicting foot posture at discrete time points and (ii) static (range of motion) measures predicting foot deformation under dynamic conditions. On one hand, several studies found that static measures of the medial longitudinal arch are able to predict the arch height at specific instances during stance [12, 21–25]. On the other hand, the literature suggests that static (range of motion) measures are hardly able to predict medial longitudinal arch deformation [14, 22, 26, 27]. The latter case is in accordance with the finding from this study, that the static navicular drop is different from the dynamic navicular drop during walking and running.

4.2. Dynamic navicular drop

4.2.1. Influence of walking speed on the dynamic navicular drop

The dynamic navicular drop was described as a construct of foot kinematics indicating foot pronation and flattening of the MLA during stance. Due to an increase of impact force at increasing gait speed [10] it was postulated a priori, that the dynamic navicular drop would increase with increasing speed. Nevertheless, our results show that an increase in walking speed led to a significant decrease of the dynamic navicular drop. Between walking at 3 $\text{km}\,\text{h}^{-1}$ and at 6 $\text{km}\,\text{h}^{-1}$, the dynamic navicular drop decreased by 35% (-2.0 mm). These findings differ from results previously reported, that indicated an angularly increased flattening of the MLA by an increase of walking speed [28]. Angular measures of the MLA cannot directly be transferred to navicular drop measures. However a positive change of MLA angle is likely to include an increased navicular drop [29]. According to the results of the present investigations, there is also a decrease in the navicular height at foot strike with increasing walking speed. The minimal navicular height during stance phase stayed nearly constant among the different walking speeds whereas the navicular height at foot strike decreased with rising walking speed levels. The mean dynamic navicular drop for walking was comparable to studies that investigated foot kinematics on a treadmill [30]. The dynamic navicular drop during walking occurred around 75% of stance, which is also consistent with findings from others [14]. At fast walking speeds (6 $\text{km}\,\text{h}^{-1}$), our study exhibited a shift of the dynamic navicular drop towards mid-stance (around 60%) where the activity of the tibialis posterior muscle has been shown to be significantly increased at fast walking speeds [31]. A stiffening of the MLA by dynamic stabilisation might be a possible explanation for the occurrence of relatively stable minimum navicular height across walking speeds.

4.2.2. Influence of the running speed on the dynamic navicular drop

As proposed a priori, an increase in running speed resulted in a significant increase of the dynamic navicular drop. In contrast to walking, the navicular height at foot strike stayed almost constant in running, whereas the minimum navicular height decreased, leading to higher dynamic navicular drop values. Our dynamic navicular drop results are comparable to previous research, where the dynamic navicular drop was investigated at self-selected running speeds performed barefoot on a treadmill [14, 30]. The shifting of the time point of the dynamic navicular drop, e.g. the time point of maximum medial longitudinal arch flattening, from around 75% during walking towards around 58% during running is also consistent with previous findings [14, 32]. Another notable finding was the large effect of the kind of gait with explicitly larger dynamic navicular drop in running (3.5 mm) compared to walking at the same speed. The comparability of this effect with the literature is limited, because to the knowledge of the authors no other study conducted a similar investigation with the same speed level during walking and running to isolate the effect of the kind of gait. However, the difference is larger than that previously reported by Dicharry et al. [14], who found only a significant difference in dynamic navicular drop of 1 mm between walking at self-selected speed and submaximal running in the group with hypermobile feet. The dynamic navicular drop represents a measure for medial longitudinal arch deformation and it is therefore obvious to ask whether similar effects concerning the kind of gait were demonstrated by experiments with multi-segment foot models which measured relative rotations between fore-foot and hind-foot. Indeed, Morio et al. [32] and Milner et al. [33] both found an increase in fore-foot to hind-foot dorsiflexion excursion during running compared to walking at self-selected speeds, respectively. Higher GRF at the transition from walking to running seem to be one possible explanation. Variation in strike patterns modulate GRF with lower initial force amplitudes for RFS compared to FFS patterns [34] which possibly has an effect on muscle fatigue and joint stiffness. Across running velocities, the foot strike patterns were distributed as FFS: 27%, MFS: 40%, RFS: 33% in our sample. Considering prolonged running, switching foot strike patterns may be of greater importance to temporarily relief muscular fatigue [35]. However, initial impact forces have not yet been linked to the dynamic navicular drop and the determination of differences between groups of specific foot strike patterns were not explored in this study because of the small sample size.

4.2.3. Relative movement of the navicular bone

Currently, there is no data about navicular motion during swing phase but it seems most likely that the navicular bone reverts to talo-navicular neutral position during swing phase. Our results demonstrate that the navicular height at foot strike had an impact on the dynamic navicular drop during walking. The navicular height at foot strike decreased significantly between G3kmh and G6kmh (-1.8 mm), which also resulted in significant decrease of the dynamic navicular drop (-2.0 mm). Angles of dorsal flexion and muscle activation of the tibialis anterior increase across higher walking velocities [31]. It is most likely, that supination of the forefoot by increased muscle activation of the tibialis anterior might have reduced the orthogonal distance between the navicular marker and the reference plane for navicular height calculation. A neutral alignment of the reference plane is crucial for the construct of static and dynamic navicular drop respectively. The difference in navicular height between unloaded sitting and at foot strike during gait, might be a representative approach to evaluate the dynamic navicular drop. It can therefore be recommended to investigate the dynamic navicular drop not as an isolated measure, but in dependency to the unloaded static navicular height.

4.3. Strengths and limitations

4.3.1. Laboratory conditions

The results of 3D motion capture depend essentially on the setup of the motion laboratory [36]. Preliminary adjustments were tested, incorporating optimised region of interest (ROI), number of cameras and camera settings to determine optimal setting conditions. Laboratory tests were conducted implicating the most preferential setting (10 cameras, adjusted ROI) with a mean trueness and uncertainty of -0.08 mm and 0.33 mm [36]. Small changes between navicular drop assessments have to be interpreted in respect to mean trueness and uncertainty. Our methodological transparency will assist the interpretation of results as well as future investigations. Running barefoot on a treadmill might have altered gait characteristics for subjects accustomed to running over ground with footwear. The magnitude and speed of navicular motion has been reported to be higher on a treadmill compared to running and walking over ground [30]. This potentially limits a direct transfer of the reported magnitudes to the overground gait situation. However, conducting the experiments on a treadmill guaranteed controlled testing conditions and allowed to capture thirty consecutive gait cycles. Because walking and running were both performed under treadmill conditions, it can be assumed that the measurements are intrinsically comparable among the kind of gait and gait speed. Using the same 3D motion capture testing protocol increases the comparability of the reported static and dynamic measures of navicular drop. This study focused on the sagittal movement of the navicular bone. The navicular bone is most likely to exhibit a three dimensional movement. Especially the medial drift, coupled with pronation and inversion of the hind foot might be important for a better understanding of dynamic foot deformation. Further investigations should include an approach in respect of the transversal and frontal plane respectively.

4.3.2. Study sample

The study sample was small and not sex-balanced and therefore sex was not considered as a covariate factor. However, the study sample can thought to be representative, because movement patterns of the navicular bone and dynamic navicular drop magnitudes were similar to what was previously reported in a larger samples [14, 37, 38]. We respected that foot length was previously claimed to influence the dynamic navicular drop [38], but we did not find different results than those presented, compared to normalized values of dynamic navicular drop. We therefore preferred to present the results in millimeter instead of a unit-less dimension. The range of the static navicular drop and the sample size would have been large enough to create subgroups for foot mobility as previously described by Dicharry et al. [14]. Outliers that accordingly indicated hypomobility or hypermobility were not excluded to represent sample variability. Small skin artefacts might have to be taken into consideration when interpreting our results. However, navicular drop has previously been graded as a robust measurement for mid-foot kinematics that is minor susceptible for skin artefacts during movement [37].

5. Conclusion

The influence of the kind of gait and gait speed on the dynamic navicular drop were investigated using 3D motion capture. The component measures of navicular height during unloaded and loaded conditions were differentiated for the interpretation of the construct of corresponding navicular drop measures in both, static and dynamic conditions. An eighteen-minute treadmill program had no influence on static navicular drop measures. Dynamic navicular drop was substantially larger and cannot reflect the magnitude of static navicular drop. Hence, the navicular drop must be measured dynamically to deliver meaningful information about foot function. Compared to walking, running at the same speed led to a significantly larger dynamic navicular drop. There was an increase in dynamic navicular drop in running and a decrease in dynamic navicular drop in walking with increasing gait speeds. The lower navicular height at foot strike with constant minimum navicular height caused a decrease in the dynamic navicular drop across walking speeds. Vice-versa, the increase in the dynamic navicular drop with increasing speed during running could have been explained by changes in the minimum navicular height but not by changes in navicular height at foot strike. Future investigations should consider both, unloaded and loaded navicular heights when investigating the dynamic navicular drop and it would be worth to relate the dynamic navicular drop to foot strike patterns and muscle activity. A better understanding of foot kinematics throughout the whole gait cycle may enable targeted prevention strategies for individuals at increased risk of injury.

6. Brief summary

6.1. What Is Already Known?

- The navicular drop, a surrogate measure of foot pronation, is commonly defined as the difference in height of the navicular bone between loaded and unloaded conditions or between neutral and relaxed subtalar joint configurations.
- Increased navicular drop assessed in static conditions is thought to be related to overuse injuries like medial tibial stress or patella-femoral pain syndromes, but the evidence suggests that the static navicular drop is a poor predictor of the dynamic navicular drop.
- There is insufficient knowledge regarding the influence of dynamic conditions per se and varying walking and running speed on the dynamic navicular drop.

6.2. What This Study Adds

- The dynamic navicular drop during walking and running at 6 $\mathrm{km\,h^{-1}}$ was substantially larger than the static navicular drop determined from sit to stand tests and can therefore not reflect the magnitude of the static navicular drop.
- The change of gait from walking to running at the same speed had a large effect on the dynamic navicular drop and the speed had a decreasing effect during walking and an increasing effect during running.
- The values of navicular height at foot strike and minimum navicular height during stance should be taken into account for the interpretation of the dynamic navicular drop.

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                                   highlights.txt
## Highlights for manuscript "The influence of gait and speed on the dynamic
navicular drop -- A cross sectional study on healthy subjects"
- Implementation of a 4-marker foot model to evaluate navicular drop (ND)
- Magnitudes of static ND are not reflected in dynamic ND measures
- The gait style, running or walking, has a large effect on the ND
- Increasing ND in running and decreasing ND in walking for increasing gait speed
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