Changes in Navicular Drop during a Workday among Health Personnel and the Association with Musculoskeletal Discomfort and Pain

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Abstract

Objective

The aim was to understand the relationship between foot fatigue and the development of musculoskeletal discomfort/pain throughout a workday among Danish healthcare personnel. This study used stretch sensor technology with a reliable and valid measure of dynamic navicular drop (DND) to gain insights into foot fatigue. Any self-experienced pain or discomfort was represented by a Numeric Rating Scale Score (NRS) >0.

Methods

This prospective cohort study recruited 24 nurses/nurse assistants. The participants were allocated to three groups post-trial according to their NRS throughout the workday. The participants' DND was measured repeatedly four times throughout the workday with concurrently reported NRS. Group P (n= 9) represented participants with NRS >0 at baseline, Group NP (n=10) represented participants with NRS <0 and Group DVP (n=5) represented participants with NRS <0 at baseline but with NRS >0 at least once throughout the workday.

Results

The primary analysis showed a significant Time*Group interaction effect (p = 0.009). The analysis of the estimates of fixed effects revealed a significant difference in the interaction effect between group DVP and NP from Time point 2-3 (estimate: 3.28 (95% CI 1.344 to 5.209; p=0.001), a significant difference in interaction effect between group P and NP from Time point 2-3 (estimate: 2.276 (95% CI 0.538 to 3.969; p=0.009), and a significant difference in interaction effect between group P and NP from Time point 3-4 (estimate: 2.631 (95% CI 0.854 to 4.408; p=0.004).

Conclusion

This study shows that stretch sensor technology is applicable, allowing repeated measures of the DND. The results revealed that the DND changes differently throughout a workday for health personnel with no pain/discomfort. Therefore, the authors introduced a paradigm shift in the understanding of the dynamic biomechanics of the foot. This has the potential to gain a more nuanced understanding of foot biomechanics and target interventions to reduce work absenteeism.

Background

In 2017, sickness absence in the public sector in Denmark amounted to 12.8 and 11.8 sick days a year per full-time employee in the municipality and region respectively (1,2). The public sector's sickness absence rate was 73.5% higher than the private sector in 2017 and on average had 4.3 more sick days yearly than the general working population (1). More recent statistics are available, but these data cover the period from 2020 to 2022 and are very influenced by Covid-19 (1,2).

Sickness absence is managed by acquiring substitutes and paying overtime, which is a major expense compared to a full-time employee (1). It is estimated that a reduction in sick leave days by just one day annually could save approximately 790 million DKK in economic costs (1). This corresponds to approximately 270 full-time nurse positions in the Danish regions, which indicates incentive and potential for a reduction in sickness absence (1).

Nurses and nurse assistants in the region have an average of 14.2 and 12.8 yearly sick days, respectively, and they constitute the largest regional work functions in Denmark (1,2). Sickness absence can have consequences for the individual employee and the department at the hospital. The remaining clinical staff must work faster, leading to decreased service quality and an increase in the use of substitutes (1). This further pressures the budgets and creates instability in all aspects of patient bio-psycho-social treatment (1).

Sickness absence is thus a major problem, compounded by the significant global challenges in recruiting and retaining healthcare employees (3). The understanding of sickness absence and challenges faced by nurses and nurse assistants is therefore crucial for alleviating the healthcare sector challenges in Denmark.

Musculoskeletal pain is among the most frequent causes of sickness absence globally (4–11). In Denmark, musculoskeletal pain is a significant cause of sickness absence (12–15) and early retirement in the healthcare sector (16). Musculoskeletal pain is a risk factor for long-term sick leave (12,14,15,17,18) and in a Danish study, 8.6% of those on long-term sick leave were diagnosed with a musculoskeletal disorder (10).

Nurses and nurse assistants have an increased risk of developing musculoskeletal problems (7,19–25). Their work consists of standing and light physical activity (22), which increases the risk of sickness absence compared to jobs that are more sedentary (23).

Work-related musculoskeletal pain occurs based on a complex interaction between factors that accumulate over time (26). The load-tolerance model, or the cumulative trauma model, describes that an injury can occur as a result of a cumulative effect of repeated external load due to repeated exposures or prolonged work activities (26). The external load is transmitted through biomechanical processes in the body, which exert an internal load on the body’s tissue (26). Both internal and external factors contribute to the accumulation of stress on the body and how it is experienced by employees (27-29). If the accumulated effect exceeds the subjective load-tolerance it will appear as a continuum between discomfort, pain, and functional impairment (26). Musculoskeletal discomfort in the workplace is a predictor for the development of musculoskeletal pain (23,24,27), and therefore relative discomfort often precedes pain, except in cases of acute trauma (26,27).

The work composition of standing and light-physical activity means that large parts of the working day as a nurse and nurse assistant involve external load through the feet. The normal function of the lower extremities depends on the biomechanics of the ankle and foot (31). The foot plays a crucial role in distributing external loads as it's the most distal link in the lower kinetic chain (28). Improper distribution of external load and exceeding the load tolerance can cause increased stress on body tissues (31). For an employee who exceeds this mechanism through walking, this can result in a wide range of musculoskeletal problems (28–35), demonstrating an interdependence between the foot and the proximal joints.

Research has demonstrated that fatigue in the foot and lower leg plays a crucial role in foot function (36–42). However, much of the existing literature concentrates on the impact of foot fatigue on lower leg biomechanics during running and jumping (36,37). Yet, a few studies have shown that fatigue of the structures of the foot can result in a more centered center of pressure (38), a higher impact of the vertical reaction force with the ground (39), an increase in the navicular drop (40), changes in the foot kinematics (41), and moderate changes in force production (42). For this reason, it can be hypothesized that foot fatigue may impact foot biomechanics and function, potentially contributing to the development of work-related musculoskeletal pain/discomfort.

The navicular drop is a commonly used method to evaluate foot function (46-49). The navicular drop measurement is considered the most valid indicator of medial longitudinal arch function and mobility in the current literature (43–49). The relative accumulated load through the feet during a workday possibly affects the function and biomechanics of the foot. Therefore, the dynamic navicular drop (DND) is hypothesized to be a measurement of this effect. A higher DND might increase the likelihood of musculoskeletal pain (50), but the threshold for the excessive navicular drop is unknown. The current most reliable cut-off value may have been found by Nielsen et al who measured the DND in 280 participants. They found that 95% of the subjects had a DND between 1.7 and 8.7 mm (51).

A systematic review from 2014 concluded the need for a more clinically accessible method to measure the DND accurately (52). Since then, new methods to measure the DND have been developed (53,54). Kappel et. al developed a stretch sensor in 2012 that was further refined and patented by Navigraff in 2019 (53). The stretch sensor is valid and reliable (53,55) and demonstrates the possibility of an easy and more accessible measurement tool for assessing the dynamic function of the foot in clinical practice (Appendix 9).

The DND might therefore be the key to further understanding the relationship between foot fatigue and the development of musculoskeletal pain/discomfort at any given body region. Therefore, this study aimed to understand the relationship between foot fatigue and the development of musculoskeletal discomfort/pain over the course of a workday, using stretch sensor technology to measure the DND among Danish healthcare personnel. We hypothesized that participants with pain/discomfort at baseline would differ significantly throughout the day compared to participants with no pain at baseline.

Methods

This prospective cohort study observed 24 nurses and nurse assistants (23 women and 1 male). The participants (aged 25-53) were recruited from the Department of Endocrinology, Aalborg University Hospital, and the Department of Cardiovascular and Hormonal Diseases, Regional Hospital Hjoerring, Denmark (Appendix 1 and 2).

The study was approved by Aalborg University and conducted in accordance with the Helsinki Declaration (56). All participants were given written and verbal information about the study and signed an informed consent form before participating (Appendix 3 and 4).

Eligibility for participation

Participants were eligible for participation if they had graduated nursing school or the education for nurse-assistants, they didn’t have any acute injury or chronic diseases preventing them from working a full workday, no previous arthrodesis related to the lower back and extremity, they hadn't taken any strong pain-relieving medicine within 24 hours of participating and no pregnancy in the second trimester or further.

Sample size

Since the stretch sensor is still a relatively new technology, the company is still developing and improving the product. Therefore, the authors were able to borrow 8 stretch sensors consisting of prototypes and untested new products. This framework set a limitation on the number of participants it was plausible for the authors to recruit. Concerning the authors' limited timeframe, limited resources, and the exploratory nature of the study, the authors estimated a maximum feasible sample size of 25 participants for the study.

Measurement of DND using stretch sensor technology

The stretch sensor is made of an elastic capacitive material called PolyPower (53). The stretch sensor is strainable in one direction and can capture dynamic measurements between two end-points on the medial side of the foot (53). As per Kappel et. al, the optimal attachment of the module is approximately 20 mm above the medial malleolus and the corresponding attachment of the stretch sensor is approximately 20 mm below and in front of the navicular tuberosity (53). The stretch sensor was attached to the participant's feet as illustrated in Figure 1.

Figure 1: Placement of the stretch sensor on the foot and ankle

The stretch sensor can collect data during 30 seconds of walking or running. The stretch sensor is connected to an application developed by Navigraff, which displays a visual graph of the foot's movement and provides an accurate measurement of the DND in mm. The application requires an internet connection to be functional (Appendix 5).

Location

The clinical trials were conducted at the Department of Endocrinology at Aalborg University Hospital and the Department of Cardiovascular and Hormonal Diseases at the Regional Hospital in Hjoerring, Denmark. The experimental setup was based in the head nurse's office in the respective departments, where the equipment was installed. The trial was carried out as described per the Standard Operating Procedure (Appendix 5).

Outcome measures

The primary outcome was the DND in mm as an expression of foot fatigue measured over time. To assess the impact of foot fatigue on pain/discomfort, the participants were divided into three groups using the Numeric Rating Scale (NRS) (Appendix 6). Group pain (P) consisted of those who experienced musculoskeletal pain/discomfort at baseline and throughout the workday (NRS > 0).

Group no pain (NP) consisted of those who experienced no musculoskeletal pain/discomfort at baseline and throughout the workday (NRS = 0). Finally, the group developed pain (DVP) was comprised of those who had no musculoskeletal pain/discomfort at baseline (NRS = 0), but developed pain/discomfort at least once throughout the workday (NRS > 0).

Outcomes were assessed during four distinct time points throughout the workday. The first time point (Time point 1) was at baseline in the morning at around 7 am. The second time point (Time point 2) was just before or after the health personnel's first break, which usually occurs around 10 am. The third time point (Time point 3) was just before or after the lunch break, which typically happens around 12 pm. Lastly, the fourth time point (Time point 4) was in the afternoon at around 2 pm. These time points were chosen in consideration of the health personnel's busy work schedules.

Statistical analysis

The data was collected as repeated measures on each unique participant. To compare foot fatigue and pain/discomfort over time, a Linear Mixed Effects Model (LMM) was used due to its robustness and flexibility. LMM is an extension of linear regression and describes the correlation between a dependent response variable and other independent variables measured simultaneously (57–59). The distribution of participants into three groups created a nested level for analysis, adding another hierarchical level that consisted of a group level and a subject level (57–59). The group level represented the allocation of participants and the subject level represented the structure of each participant's longitudinal repeated outcome measures. These groupings and levels created a clustering effect in the data where the individual variation in the subject could affect the variation of foot fatigue measured over time. Furthermore, similarities of characteristics in the unique groups could affect the dependent variable.

LMM allowed for the incorporation of both random and fixed effects into the model (57–59). The random effect was represented by the subject ID and the subject's variation, while the fixed effects were represented by the development in time and the three groups. The interaction between time and group (Time*Group) was also treated as a fixed effect variable. The fixed and random effects enable the model to adjust for systematic changes over time and the individual variation between subjects and groups. A post-hoc pairwise comparison was used to explore differences in the estimated marginal means of DND between the groups at different time points. Least Significant Difference was used to adjust for multiple comparisons.

Nielsen et al determined normal values for the navicular drop during walking and found that the navicular drop had a within-subject variability of 1.7 mm (±1 SD) (51). Therefore, this cut-off value was used as a minimally important difference in the data analysis and interpretation. Exceeding this value indicates a DND above or below the normal expected variability.

Results

No dropouts throughout the trial were registered and no exclusion of participants due to poor data quality was made. The data collection was concluded in March 2024. Baseline characteristics are displayed in Table 1. No patients reported adverse events. Analysis and data visuals were done in SPSS, 29.0.0.0.

The study sample

This prospective cohort study measured DND throughout a workday for 24 nurses and nurse assistants (Table 1). Of the sample, 95.83% were women with a median age of 31. The total mean (standard deviation) navicular drop at baseline was 3.60 (1.61) mm. The distribution of participants into the three groups was; group P (n=9), group NP (n=10), and group DVP (n=5). The median age for the groups was 35, 30, and 27, respectively. The mean navicular drop in the groups at baseline was 3.84 (1.61) mm, 2.75 (1.41) mm, and 4.53 (1.08) mm, respectively. The median NRS in the groups at baseline were 1, 0, and 0, respectively (Table 1). Descriptive statistics for the groups and the overall interaction effect are presented in Table 2.

Table 1: Demographics at baseline

	Participants	P	NP	DVP
n	24	9	10	5
Sex (% women)	95.83 %	100%	100%	80%
Age years, median (interquartile range)	31(26-42)	35 (26-49)	30 (22-45)	27 (26-42)
Navicular drop in mm, mean (SD)	3.60 (1.61)	3.84 (1.78)	2.75 (1.41)	4.53 (1.08)
NRS, mean	0.46	1.22	0	0

DND (mm), Dynamic Navicular drop in millimeter; DVP, Group for 'Developed Pain'; P, Group for 'Pain'; NP, Group for 'No Pain'.

Table 2: Descriptive statistics

Groups	Time point 1 mean (SD)	Time point 2 mean (SD)	Time point 3 mean (SD)	Time point 4 mean (SD)	Total mean (SD)	Time x Group (*p*)
DND (mm)						
P	3.84(1.78)	3.76(1.41)	3.39(1.39)	2.62(1.17)	3.45(1.48)	
NP	2.75(1.41)	3.40(1.31)	4.57(1.58)	4.28(1.22)	3.69(1.51)	
DVP	4.53(1.08)	3.99(2.15)	3.07(2.59)	4.25(2.68)	3.96(2.11)	
Total for groups	3.60(1.61)	3.70(1.52)	3.72(1.82)	3.63(1.81)	3.66(1.66)	0.009*

*Denotes statistical significance (p<0.05).
DND (mm), Dynamic Navicular drop in millimeter; DVP, Group for 'Developed Pain'; P, Group for 'Pain'; NP, Group for 'No Pain'.

Figure 2 shows the raw measurements of DND for each participant throughout the day. The chart presents the individual missing values but does not account for group allocation. The data varies greatly at the first measurement (Time point 1), ranging from under 1 mm to over 7 mm. The participants showed a mix of ascending and descending development of DND throughout the day, reflected in a similar variation at the end of the day (Time point 4). Only one data point exceeded the overall variation between 1-7 mm, measuring just above 9 mm. Overall, the line chart shows high data variability at baseline, and the variations are similar throughout the day. To highlight the change over time, a line graph reflecting each participant's successive differences in the DND was created (Figure 3).

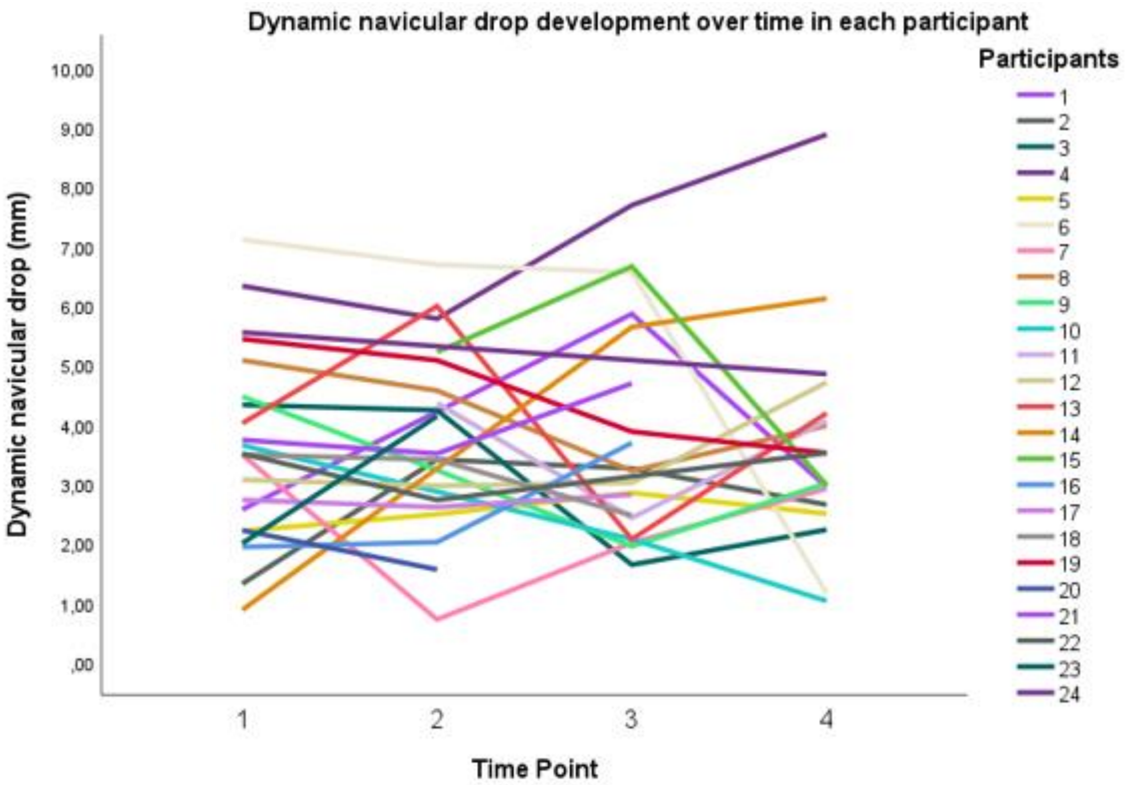

Figure 2: Navicular drop development over time for each subject

The successive differences are displayed in Figure 3, highlighting the changes in the DND for each participant during a workday. The line graph used the 1.7 mm minimal important difference as the cut-off value for the expected variability in the DND. To determine whether each subject stayed within the expected variability, Time point 1 (Figure 3) was used as a baseline comparison for the successive measurements. The differences in the development of the DND stayed within or slightly beyond the cut-off value, with some differences visually differing from the cut-off value. 4 measurements at time point 1, 7 measurements at time point 2, and 7 measurements at time point 3 exceeded the cut-off value. Visually the line graph presents a homogeneric development of differences, where roughly 68% of the sample's differences stayed within the cut-off value across the time points. This indicates similarities in the data between this study and the reference study of Nielsen et. al. Furthermore, this indicated that some individuals had changes in the DND outside the expected variability. To explore the characteristics of the individuals that deviated from the expected variability, the data was also analyzed in groups related to pain characteristics (Figure 4).

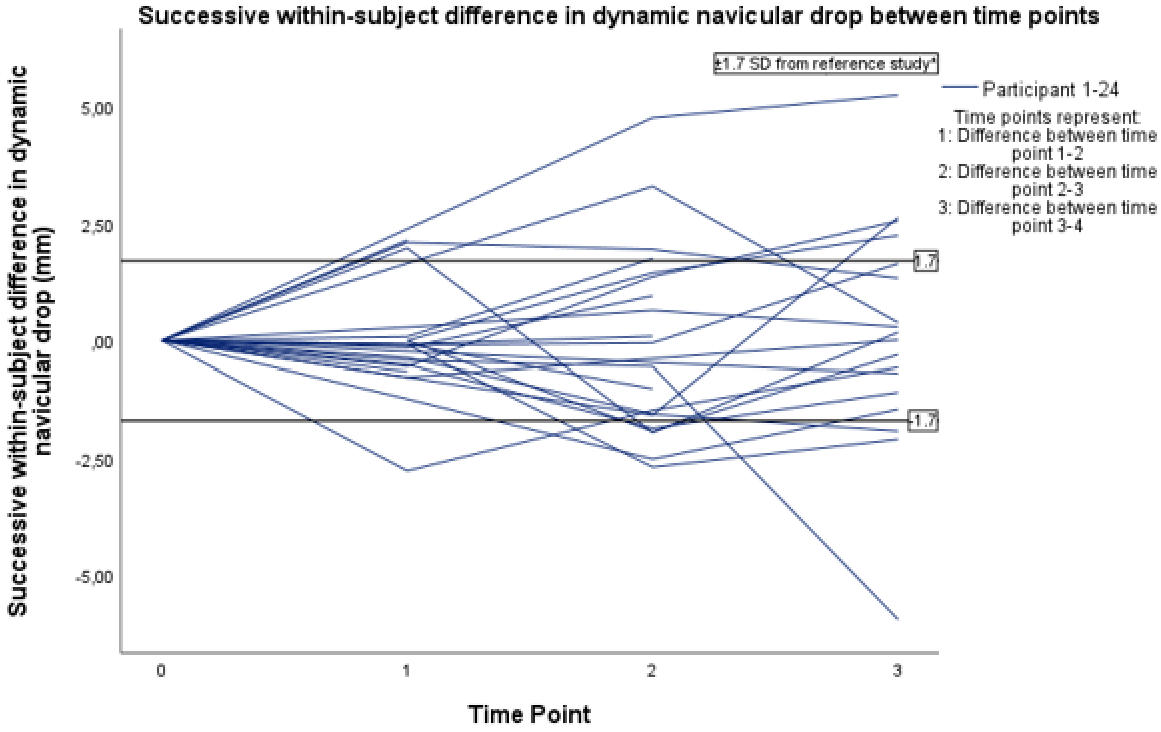

Figure 3: Difference in DND (mm) between the repeated measures in each participant *Nielsen et al. Determination of normal values for navicular drop during walking: a new model correcting for foot length and gender (51).

Figure 4 represents the average development of DND throughout the day for each of the three groups. The group mean at Time point 1 (Figure 4) used the reference SD as the cut-off value. This created three sets of cut-off values (±1.7 mm) to follow the group development of mean DND. Figure 4 shows that the development of mean DND differs from each group throughout the day with a tendency to a descending DND in group P and DVP across Time point 1-3. This tendency changes significantly from Time point 3-4, where the DND in the DVP group increases, and group P continues its decrease and exceeds the cut-off value. The NP group showed a different tendency than the other groups with an increase from Time point 1-3, exceeding the cut-off value, and a slight decrease from Time point 3-4. These results indicate an influence of pain/discomfort on the development of DND during a workday.

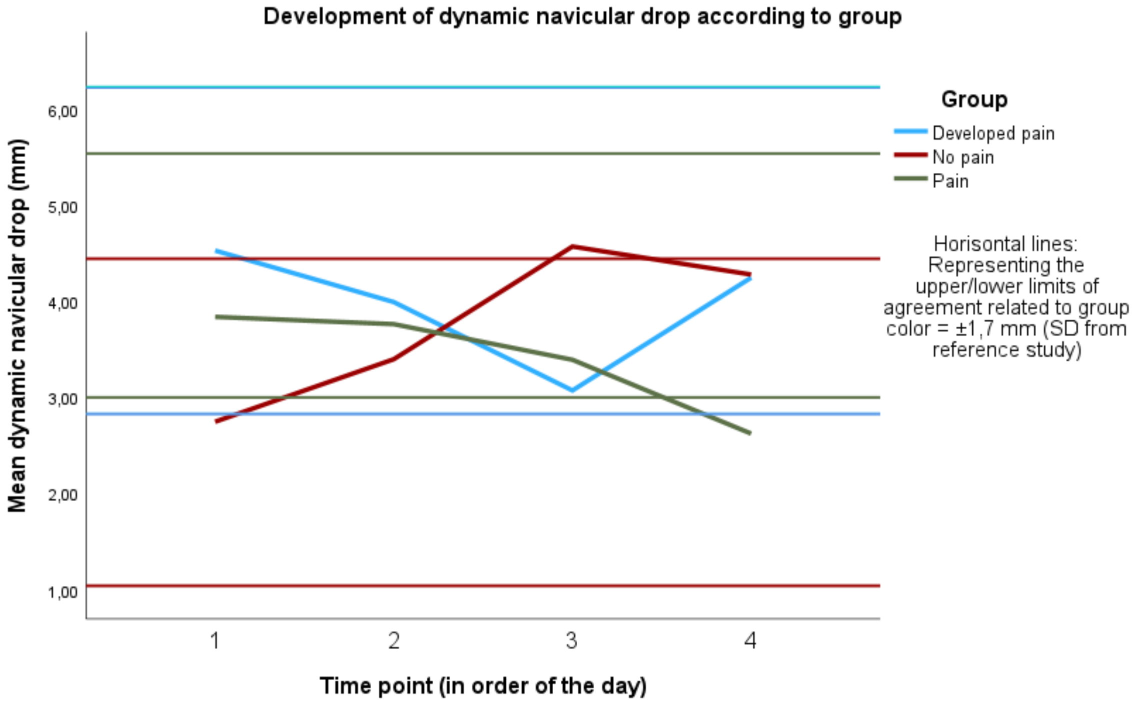

Figure 4: Navicular drop development in the groups over time with cut-off value from reference study (51).

Primary outcome (Time*Group interaction effect)

The LMM analysis revealed a significant Time*Group interaction effect (p = 0.009) (Table 2), indicating an interacting relationship between time progression and group allocation on the DND. The analysis of the estimates of fixed effects revealed a statistically significant difference in the interaction effect between group DVP and NP from Time point 2-3 (estimate: 3.28 (95% CI 1.344 to 5.209; p=0.001), a significant difference in interaction effect between group P and NP from Time point 2-3 (estimate: 2.276 (95% CI 0.538 to 3.969; p=0.009), and a significant difference in interaction effect between group P and NP from Time point 3-4 (estimate: 2.631 (95% CI 0.854 to 4.408; p=0.004) (Table 3). No significant difference in interaction effect was found between group DVP and P at any Time point (estimate: 0.460 (95% CI -1.371 to 2.292); p=0.617, estimate: 1.000 (95% CI -0.856 to 2.857); p=0.285, estimate: -1.076 (95% CI -2.964 to 0.812); p=0.121), no significant difference in interaction effect between group DVP and P at time point 1-2 and 3-4 (estimate: 1.337 (95% CI -0.592 to 3.267); p=0.617, estimate: 1.555 (95% CI -0.422 to 3.532); p=0.121), and no significant difference in interaction effect between group P and NP from Time point 1-2 (estimate: 0.877 (95% CI -0.785 to 2.539); p=0.296) (Table 3).

Table 3: Estimates of Fixed Effects			
Time point	**P vs DVP**	**NP vs DVP**	**NP vs P**
Estimates (95% CI)			
DND (mm)			
1			
2	0.46 (-1.37 to 2.29)	1.34 (-0.59 to 3.27)	0.88 (-0.79 to 2.54)
3	1.00 (-0.86 to 2.86)	3.28* (1.34 to 5.21)	2.28* (0.58 to 3.97)
4	-1.08 (-2.96 to 0.81)	1.55 (-0.42 to 3.53)	2.63* (0.85 to 4.41)

*Denotes statistical significance (p<0.05).
DND (mm), Dynamic Navicular drop in millimeter; DVP, Group for 'Developed Pain'; P, Group for 'Pain'; NP, Group for 'No Pain'.

Pairwise comparison of mean DND
The post-hoc pairwise comparisons were conducted to explore differences between the groups at each time point (Table 4). The overall results of the comparison revealed a significant difference in DND between group DP and NP at time point 1 (adjusted mean difference: 1.747 (95% CI 0.042 to 3.452); p=0.045) and a significant difference in DND between group DVP and P at Time point 4 (adjusted mean difference: 1.766 (95% CI 0.020 to 3.512); p=0.048). No significant difference in DND was found between DVP and P at time points 1, 2, and 3, no significant difference between group DVP and P at time points 2, 3, and 4, and no significant difference between group P and NP at any time point. The adjusted mean difference exceeded the cut-off value at all significant different measures but did not exceed the cut-off value at any time in the non-significant measures.

While the overall results did not reveal a consistent statistically significant pattern of differences between the groups, notable trends were observed in the adjusted mean differences across different time points. The mean differences between group P and DVP tended to be smaller compared to the differences of the comparisons for group NP (Table 4). In support of this, the absolute total means (Table 4) showed a larger difference in the comparisons for group NP, compared to the difference between the pain groups. Similar trends were observed, yet not continuously across different time points, indicating a somewhat consistent pattern of group NP being different from the other groups, despite the lack of statistical significance.

Table 4: Pairwise comparisons between groups						
Time point	**DVP**	**P**	**NP**	**P vs DVP**	**NP vs DVP**	**NP vs P**
Mean (SD)				**Adjusted mean difference (95% CI)**		
DND (mm)						
1	4.53 (1.08)	3.84 (1.78)	2.75 (1.41)	0.69 (-1.00 to 2.38)	1.75* (0.04 to 3.45)	1.06 (-0.39 to 2.50)
2	3.99 (2.15)	3.76 (1.41)	3.40 (1.31)	0.23 (-1.46 to 1.92)	0.41 (1.33 to 2.15)	0.18 (-1.31 to 1.67)
3	3.07 (2.59)	3.39 (1.39)	4.57 (1.58)	-0.31 (-2.02 to 1.40)	-1.53 (-3.27 to 0.21)	-1.22 (-2.74 to 0.30)
4	4.25 (2.68)	2.62 (1.17)	4.28 (1.22)	1.77* (0.02 to 1.60)	0.19 (-1.60 to 1.98)	-1.57 (-3.18 to 0.03)
Total absolute means				3.00	3.88	4.03

*Denotes statistical significance (p<0.05).
DND (mm), DND in millimeter; DVP, Group for 'Developed Pain'; P, Group for 'Pain'; NP, Group for 'No Pain'.

Discussion

The results showed an overall significant Time*Group interaction effect. Group NP had a significant interaction effect more than once, compared to the other groups. Having no pain/discomfort increased the DND significantly at some time points compared to the pain/discomfort groups. Participants without pain/discomfort would vary significantly from participants experiencing pain/discomfort at given time points during a workday.

The results for the post-hoc pairwise comparisons revealed trends in the mean differences between groups, despite the general lack of statistical significance in the comparisons. The difference in the total absolute means supported a larger difference between group NP and the other groups and a lower difference between the two pain groups. This correlated with the significant interaction effect for group NP, indicating a larger change in the DND for group NP.

The results suggest that the progression of time interacts differently with the DND for participants with pain/discomfort, developed pain/discomfort, and no pain/discomfort. All significant interaction effects and adjusted mean differences succeeded the cut-off value.

A paradigm shift

This was the first trial to investigate the change in the DND during a workday for health personnel and its relationship with pain/discomfort. Headlee et al found a significant correlation between fatigue of the intrinsic foot muscles and an increase in navicular drop in healthy participants (40). This supports the significant interaction effect of group NP in the current study and suggests a hypothesis that foot fatigue changes the DND differently for healthy participants, contrary to participants with pain/discomfort. This highlights the importance of considering both time progression and individual pain characteristics when assessing the foot. It suggests that the DND can be a useful measurement to investigate foot dynamics in individuals with and without pain. Tracking the DND over time could potentially detect early indications of pain issues, because these issues seem to have a different effect on the DND.

In relation to the rigidity and flexibility of the midfoot, navicular drop has often been used as a static measure for this classification (55). Classification of the symptomatic adult flatfoot has changed throughout the years and varied in stages and descriptions (60). Common for these classifications was the focus on the rigidity or flexibility of the midfoot (60). Traditionally the clinician uses observation, palpation, passive movement, and special tests to assess the rigidity and flexibility of the midfoot (61). The authors of this study propose a nuanced paradigm shift in the assessment and consensus of the biomechanics of the midfoot. The traditional focus on the static assessment of the midfoot seems to be missing a major element, as the dynamic measure of the midfoot could bring new insights into the biomechanical changes over time. Navigraff's stretch sensors made it possible to assess the midfoot and measure the DND, and hereby add a dynamic aspect to the paradigm of rigidity and flexibility of the midfoot. The significant interaction effects for the NP group could indicate a nuance of midfoot flexibility for this group and a nuance of rigidity for the pain/discomfort groups. The DND in individuals with pain/discomfort shows a more rigid development throughout a workday for health personnel. It remains unknown whether this rigidity, which is reflected by the changes over time, could be an indication of a causative relationship between over-time rigidity and the development of pain/discomfort.

Practical implications

To solve the challenges of sick leave in the healthcare sector, this study has taken the first step towards understanding the relationship between the biomechanical changes of the midfoot throughout a workday for health personnel and its relationship with pain/discomfort. This offers insights into

potential preventive measures and interventions to manage pain/discomfort and reduce absenteeism. This study has shown it is possible to overcome the technical challenges of gaining these valuable insights by using stretch sensor technology. Future technological advancement in the stretch sensors software to continuously measure throughout an entire workday could provide a more detailed and comprehensive insight into the biomechanical nature of the foot in this population. This would give a more nuanced presentation of the current study's results and help us understand the biomechanical, psychological, and environmental aspects of foot fatigue and pain/discomfort. Continuous monitoring could reveal how workload and specific tasks affect foot mechanics and pain/discomfort over time. This could inform preventive measures and ergonomic improvements aimed at reducing the risk of pain/discomfort. Continuous measurements in the workplace could highlight bio-psycho-social factors that are not captured through unique measurements and assessments in the clinic. This could help understand the individual variations in DND and pain, leading to personalized interventions to better support health personnel in specific environments and roles.
The paradigm shift presented by this study introduces clinical practice to a suggestion of midfoot assessment, where the foot is measured dynamically with repeated measurements to capture the over-time changes and complex biomechanical nature of the foot.

Considerations for future research

Going further, research could explore this paradigm shift by investigating if individuals who don't experience pain/discomfort but have foot biomechanics that show signs of over-time rigidity, will develop pain/discomfort later in life. That could lead to further knowledge about the over-time rigidity, and clinical implications of the possible early detection of pain/discomfort using the dynamic navicular over time. Future research could dwell into the specific time points where the interaction effect between time and group was significant in this study. It's interesting to observe and understand what happens between these time points biomechanically, environmentally, and psychologically in health personnel. With this knowledge, it could be possible to investigate if changes done to these factors could have an impact on the biomechanical changes in the midfoot and the development of pain/discomfort.

Limitations

The explorative longitudinal nature of the study made it difficult to implement strategies for data exclusion due to poor data quality. Barton et al. excluded participants due to poor data quality from different conditions such as the accumulation of sweat during testing and the loosening of the stretch sensor attachments (62). The poor data quality was determined by a very large drop or increase in the DND, e.g. 20 or 30 mm, but no data in this study reached these levels. Further, this study was the first to investigate the effect of foot fatigue on pain/discomfort using repeated measures. Excluding measurements with a smaller increment of a sudden drop or increase in the DND was therefore not applicable because the development of the DND during a workday was untested. Barton recommended re-applying and calibrating the stretch sensors after each use. However, this was not implementable in this study due to time constraints and respect for the health personnel's busy schedules.
This study was constrained by the availability of only 8 stretch sensors, consisting of a mix of prototypes and newly untested products. This limited the number of recruitable participants and may have created variability in the measurements due to unknown and untested differences in the sensor types. Prototypes and untested products may have been more prone to technical issues or errors compared to the specific setup validated by Christensen et al (55). This could have increased measurement errors in this study and reduced the reliability and validity of the data collected. Yet, the specific stretch sensor technology didn't vary across the different models, despite the way the product

is molded and assembled. Therefore, the findings may not be fully generalized to settings using only the same sensor model. Overall, the data is measured using a specific stretch sensor type that is validated. The course of action follows directions from the company itself and guidelines from Christensen et. al and Barton et. al (55,62).

Specific eligibility criteria in the recruitment process of participants may have introduced selection bias to this study. The primary focus of the study was to investigate the relationship between foot fatigue and the development of musculoskeletal discomfort throughout a workday for healthcare personnel. Therefore, it was essential to exclude pre-existing health conditions to assess the impact of the workday without any influence of underlying health factors. Yet, excluding individuals with acute injuries, chronic diseases or pregnancy may have limited the generalizability of the findings to the wider population of healthcare workers. Because this study was conducted by novel students, ensuring the safety and well-being of participants was paramount. The exclusion of certain individuals helped mitigate the risk of adverse or serious adverse events. Further, had this study included participants with these characteristics, it could have impacted their workability in such a way that they would have introduced confounding due to abnormal pain or inability to work a full shift. The exclusion therefore also enhanced the reliability and validity of the study findings.

Conclusion

This study introduced a paradigm shift in the understanding of the dynamic biomechanics of the foot. The DND changes differently throughout the day for individuals experiencing no pain/discomfort compared to individuals with pain/discomfort. Stretch sensor technology is applicable, offering the possibility to repeatedly measure the DND in different environments. Continuous measurement of the DND has the potential to gain insights into a more nuanced understanding of foot biomechanics and inform targeted interventions to improve health and reduce work absenteeism. Future research could investigate the development of pain/discomfort in individuals experiencing no pain/discomfort with indication of over-time dynamic rigidity.

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