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Effectiveness of a web-based foot-ankle exercise program for treating ulcer risk factors in diabetic neuropathy in a randomized controlled trial

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The need for strategies to prevent complications from diabetic neuropathy (DPN) is well recognized. However, foot-ankle exercise programs show weak to moderate evidence, and barriers to their implementation persist, including broad and facilitated access to exercise programs, which guarantee for equity. In this paper, we report for the first time the effectiveness of a web-based foot-ankle exercise program aiming to improve DPN-related outcomes, gait biomechanics and functional outcomes. Sixty-two participants with DPN were randomly allocated into the control group (CG; *n* = 31), which received the usual care, or the intervention group (IG; *n* = 31), which received the usual care plus a 12-week foot-ankle exercise program using a web-based software (the SOPeD software). The primary outcomes, DPN symptoms and severity, were assessed using the Brazilian version of the Michigan Neuropathy Screening Instrument and the Decision Support System for Classification of Diabetic Polyneuropathy, respectively. Secondary outcomes included tactile sensitivity (monofilaments) and vibration perception (tuning fork), functional outcomes, such as foot pain and function (Foot Health Status Questionnaire), foot muscle strength and plantar pressure during gait (emed plate), and foot-ankle kinematics and kinetics during gait. Outcomes were assessed at baseline, 12 and 24 weeks by an assessor blinded to group allocation. DPN symptoms and severity remained unchanged after the web-based foot-ankle program. However, IG showed improvements compared to CG, with greater functional reach at 12 weeks, better foot function, reduced foot pain and greater plantarflexion degree during push-off at 24 weeks. Regarding plantar loading during gait, the forefoot pressure reduced in the IG at 12 weeks compared to baseline, but at 24 weeks, forefoot load increased in the IG compared to CG. The 12-week web-based foot-ankle exercise program was feasible, acceptable, demonstrating safety with minimal adverse events, such as delayed onset muscle soreness and foot muscle cramping. While DPN-related outcomes were unaffected by the 12-week SOPeD program, modest improvements in foot pain and function, functional reach, and changes in plantar pressure and plantarflexion degree during gait were noted, mostly at 24 weeks.

Trial registration: ClinicalTrials.gov, NCT04011267. Registered on 8 July 2019.

Keywords Diabetic neuropathies, Exercise therapy, Foot-related exercises, eHealth, Rehabilitation technology, Biomechanics

Diabetic peripheral neuropathy (DPN) is a highly prevalent comorbidity[1,2] and negatively impacts quality of life[3]. It leads to loss of protective sensation, peripheral arterial disease[4–6], and diminished foot-ankle function and mobility[7–9]. These effects disrupt proper foot rollover and plantar pressure distribution during gait[9–11] increasing

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the risk of foot ulcers, infections, and amputations[12]. These risk factors, dependent on diabetes progression and DPN severity, highlight the urgent need for evidence-based preventive measures in healthcare systems.

General preventive and management strategies recommended by the International Working Group on the Diabetic Foot (IWGDF), such as proper glycemic control, adopting a healthy lifestyle, regular foot monitoring, using adequate footwear, and performing specific foot-ankle exercises, can potentially reduce the risk and progression of DPN[13]. However, raising awareness for and adherence to these preventive strategies has been particularly challenging[14] in people with chronic diseases such as diabetes. This difficulty is attributed to factors such as the complexity of disease management, limited patient education, psychological barriers, and socioeconomic constraints, which collectively hinder the successful implementation of preventive measures[14]. In addition to depression and anxiety[15], lack of motivation to exercise, low income, and long distance to treatment facilities are frequent barriers that hinder treatment adherence[16]. In this sense, the use of Mobile Health (m-Health) and telehealth apps can be promising and cost-effective tools to address adherence and compliance problems[17], due to their convenience, ubiquity, and accessibility[18]. Although m-health and telehealth apps do not completely replace face-to-face interventions, the use of these apps has the potential to improve patient motivation and empowerment by stimulating individuals to actively engage in their own health management, which can lead to better health outcomes, broader access to healthcare treatments[19–21], and may reduce health care costs due to diabetes[22,23].

Foot-ankle exercise programs are a proven strategy to improve modifiable risk factors for ulcers in individuals with diabetes, including improving plantar pressure redistribution, increasing foot-ankle strength, improving joint mobility, and optimizing gait biomechanics[24]. Additionally, recent evidence from a systematic review[13] suggested that a 8–12 week foot-ankle exercise program may improve DPN signs and symptoms in individuals with diabetes at risk for foot ulceration. However, a web-based treatment strategy has not yet been tested in this population. Therefore, we conducted[13] a superiority randomized controlled, single-blinded, two parallel arm trial, the FOotCAre trial I (FOCA-I), to investigate the effectiveness of a 12-week customized web-based foot-ankle therapeutic exercises program based on the *Sistema de Orientação ao Pé Diabético* software (SOPeD; translation: *Diabetic Foot Guidance System*; www.soped.com.br[25]) on DPN symptoms and severity in people with DPN (categories 1 and 2 according to the IWGDF risk classification). The secondary aims were to investigate the effectiveness of this intervention at 12 and 24 weeks on foot-ankle biomechanics and plantar pressure during gait, tactile and vibration sensitivities, foot health and functionality, foot strength, and functional balance.

Methods

Study design

The FOCA-I trial was designed and reported in accordance with the CONSORT guidelines[26], received approval on May 10, 2019 from the Ethics Committee of the School of Medicine, University of São Paulo (CAAE:90331718.4.0000.0065), and was registered at ClinicalTrials.gov on July 8, 2019 (NCT04011267). *All procedures adhered to the Declaration of Helsinki, and informed consent was obtained from each participant.* The trial was carried out at the Physical Therapy Department of the School of Medicine of the University of São Paulo and the methodology and protocol have been extensively explained elsewhere[27]. Briefly, 62 eligible patients categorized as IWGDF risk category 1 (low risk, with loss of protective sensation (LOPS) or peripheral artery disease (PAD)) or category 2 (moderate risk, with LOPS and PAD, LOPS and foot deformity, or PAD and foot deformity) were randomized 1:1 (using a computer-generated randomization sequence in blocks of four to eight[28]) to receive either the protocol intervention or usual care. The intervention lasted for 12 weeks and was closely monitored during this period. However, the total study duration was 24 weeks, which included an additional 12 weeks of follow-up. Only the physiotherapist responsible for prescribing the intervention was aware of group allocation, and participant names were encoded, sealed in an opaque envelope, and concealed from the study statistician and from two other researchers responsible for all assessments.

Participants and recruitment

The participants were recruited from August 1, 2019 to February 1, 2022 through digital social media advertising, from the database of the Endocrinology Outpatient Clinic of the Hospital das Clínicas (School of Medicine, University of São Paulo), and via a population campaign organized by the Brazilian Diabetes Care Association. We recruited a total of 62 adults of both sexes between the ages of 18 and 65 who had a clinical diagnosis of type 1 or 2 diabetes; confirmed DPN using fuzzy software (www.usp.br/labimph/fuzzy; score ≥ 2); and who could walk independently for at least 10 m (Fig. 1). Individuals with the following characteristics were not included: amputation of any part of the foot; an active ulcer; a history of surgical procedures or indications for surgery involving the foot, ankle, knee, or hip; a diagnosis of any severe neurological disease unrelated to diabetes; presence of dementia or inability to provide consistent information; receiving any physiotherapy or using offloading devices during the study period; use of walking aids; major vascular complications and/or severe retinopathy, as indicated in medical records. In addition, all eligible participants had to have digital literacy.

Each eligible participant received a thorough explanation from the main researcher about all the stages of the study, including the assessment and follow-up process, possible risks, and lack of compensation or benefits. After agreeing to participate, participants signed an informed consent form approved by the Ethics committee.

Treatment arms

The control (CG) and intervention groups (IG) participants received self-care education and a self-management consultation from the main researcher, as well as a personalized brochure containing summarized self-care instructions. These instructions included regular inspection of the feet, proper nail and skin care, wearing appropriate footwear, managing blood glucose levels, and promptly addressing any foot injuries or abnormalities

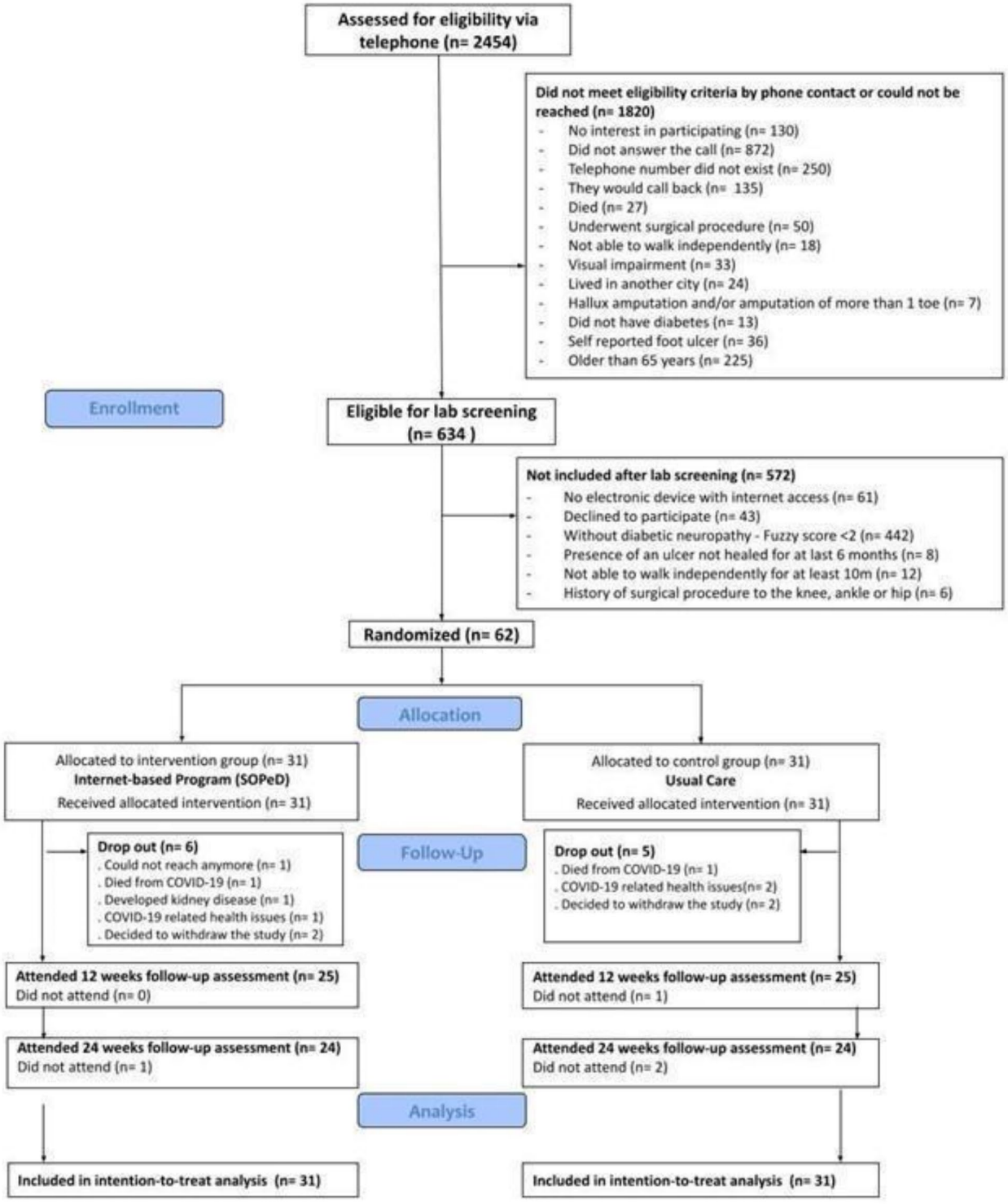

Fig. 1. Flowchart of the participant recruitment, assessment, and follow-up process of the FOCA-I trial.

to prevent complications, as recommended by the IWGDF guidelines[24]. Participants of both groups continued their medical and pharmacological treatments provided by the health care team.

The IG participants followed a web-based foot-ankle exercise program based on the SOPeD software three sessions per week for 12 weeks (total of 36 sessions). Each session lasted approximately 20 to 30 min and consisted of eight exercises that could be done at the participant's convenient time and place. The SOPeD contains a total of 39 different exercises (considering their sub-level progressions, a total of 104 variations) for the intrinsic and extrinsic foot muscles and foot-ankle joints, including warm-up, arch stretching, strengthening,

and functional exercises, such as balance and gait training (see supplementary material). We maintained control over session frequency by closely monitoring adherence to the software, ensuring consistency in core principles of the intervention, while allowing necessary flexibility in intensity. As for the intensity and progression, we developed an algorithm in the SOPeD based on each user's perceived effort designed to closely mimic an individualized, in-person session, taking into account each individual's limitations and specificities. Users could either advance to a more challenging level, maintain their current level, or revert to a previous stage according to their effort scores: a score of 0.0 to 2.0 allowed progression to the next level the following day; a score of 2.1 to 7.0 required maintaining the current level for 2 days before advancing; and a score of 7.1 to 10 mean reverting to the previous level. Exercises may have sublevels for increased load, repetitions, or duration and can range from one to five levels of difficulty. Progression is specific to each exercise, so in a session of eight exercises, a user might progress in only a few exercises while staying at the same level in others. Our approach is based on evidence, which supports that the training intensity and progression should be established through individualization and by considering the participant's training experience[29]. This individualized approach aligns with current best practices in managing diabetic neuropathy and promotes better long-term adherence and outcomes for patients. Detailed information about the software's components and structure can be found elsewhere[27,30].The protocol targets the following muscle groups: medial-plantar (abductor hallucis, flexor hallucis brevis, adductor hallucis), lateral-plantar (abductor digiti minimi, flexor digiti minimi brevis, opponens digiti minimi), middle-plantar (flexor digitorum brevis, quadratus plantae, lumbrical muscles, plantar and dorsal interosseous muscles), and dorsal-foot (extensor digitorum brevis, extensor hallucis brevis).

In the first face-to-face session, the physiotherapist provided individualized care to the IG participants, during which the participants were registered in the SOPeD database and received a kit containing materials for performing the exercises. As for the remaining 35 sessions, the participants performed the exercises without face-to-face supervision, but the main physiotherapist contacted the participants by phone every week to check on their progress and address any potential issue, and also contacted participants in the control group with the same frequency to verify adherence to usual care instructions and address any concerns they might have had. Participants were advised to discontinue the exercises and inform the main physiotherapist if they experienced cramps, intense pain, excessive fatigue, or any other discomfort. After 12 weeks, the IG were encouraged to continue with the exercises program at the SOPeD until the end of the study (24 weeks), and their use of the software were remotely monitored by the administrator area in the software.

Assessments

The primary outcomes were DPN symptoms and severity. DPN symptoms were assessed using the Brazilian version of the Michigan Neuropathy Screening Instrument[31]. Scores range from 0 to 13, with a higher score indicating worse symptoms. DPN severity was determined using the Decision Support System for Classification of Diabetic Polyneuropathy (www.usp.br/labimph/fuzzy)[32]. The fuzzy model system used to classify the severity of DPN was validated through several steps, presented a very strong correlation with the experts' opinion (Pearson's coefficient $r = 0.943$), a high accuracy level when classifying real patients that underwent the model's analysis (ROC curve area = 0.91), ensuring its reliability and accuracy in clinical assessments[32]. The inputs included vibration perception, tactile sensitivity, and DPN symptoms assessment. The combinations of these inputs were used to determine the fuzzy output sets for DPN severity, which allocated subjects to specific severity levels and calculated their membership degrees. The fuzzy expert system classifies each input variable into fuzzy sets (fuzzification process). The resulting output sets are then transformed into numerical values, referred to as the "DPN degree score", which can range from 0 to 10. Higher scores indicate more severe DPN.

The secondary outcomes were DPN-related outcomes, functional outcomes, and gait biomechanics. The DPN-related outcomes were tactile sensitivity of four plantar areas as assessed by a 10-g monofilament[33] and vibration perception of the first metatarsophalangeal joint as assessed by a 128-Hz tuning fork[34]. Functional outcomes were foot pain, function, health and shoes as assessed by the Brazilian version of the Foot Health Status Questionnaire (FHSQ)[35]. The FHSQ evaluates several critical aspects of foot health and functionality. It assesses foot pain, functional limitations, shoe fit, and general foot health. Foot pain is measured by considering the frequency, intensity, and impact of pain on daily activities. The FHSQ includes questions related to the intensity and frequency of foot pain, which typically captures pain resulting from musculoskeletal conditions or general foot pain. Functional limitations are captured by the questionnaire's ability to identify difficulties in performing foot-related tasks, such as walking or standing. The shoe fit section addresses comfort, fit, and suitability for various activities. General foot health is determined by integrating these factors, including any signs of abnormalities or conditions affecting foot well-being. Each component is scored on a Likert scale, providing a numerical value from 0 to 100, with higher scores indicating better condition[35]. Toes and hallux isometric muscle strength as assessed by a pressure plate (emed-q 100; Novel GmbH, Munich, Germany)[36], and functional balance as assessed via the functional reach test[37]. Gait biomechanics variables included foot-ankle kinematics and kinetics, calculated by Motion Capture Nexus 2.6 software (Oxford Metrics); and plantar pressure during gait.

The biomechanics of walking were measured employing a standard gait analysis system composed by eight infrared cameras (at a 100-Hz, Vicon VERO; Oxford Metrics, Oxford, UK) and a force plate (at 1000-Hz frequency, AMTI OR-6-1000; AMTI, Watertown, MA, USA). A total of 42 passive reflective markers were placed on both lower limbs following the setup protocols of Plug-In Gait and the Oxford Foot Model[38]. Participants were instructed to walk at a self-selected comfortable speed along a 10-m track. Five valid gait cycles (strides) were recorded during walking, and the average of the right and left sides was used for statistical analysis[39]. Ankle power was calculated as the product between joint moment and angular velocity in the sagittal plane.

Peak pressure, pressure-time integral, and contact area were recorded before the gait analysis using the emed-q pressure platform at a frequency of 100 Hz. Participants walked barefoot over the platform at a self-

selected comfortable speed for six trials. A geometric mask in the Novel software was used to assess five plantar regions of interest: hindfoot, midfoot, forefoot, hallux and toes. The average of the six trials for each side (right/left) was used for statistical analysis[39].

The gait speed for both foot-ankle kinematics/kinetics and plantar pressure distribution measurements was controlled to ensure consistency across all assessments (baseline, 12-week, and 24-week), with a maximum allowable deviation of 5% between measurements.

Sample size calculation and statistical analysis

Sample size calculation was performed using GPower v.3.1, with Cohen's f = 0.20, a moderate effect size based on Sartor et al. (2014)[40], to ensure a sufficiently large sample size to detect clinically meaningful effects. The secondary outcome, plantar pressure, was chosen due to its clinical relevance for this population. Using an F-test repeated measures design with a power of 0.80, alpha of 0.05, and effect size (Cohen's f = 0.20), we determined that a sample size of 52 individuals was required. Including a 20% anticipated dropout rate, the final sample size was set at 62 patients.

Generalized estimating equations using a gamma distribution were employed to estimate between-group differences and 95% confidence intervals in the SPSS software v.31 (IBMCorp. Armonk, NY). Q-Q plots were generated to assess the normality of each model. Post-hoc tests for pairwise comparisons were performed with Bonferroni correction. SPSS automates the calculation of adjusted p-values for the Bonferroni post-hoc test by considering the total number of comparisons. This ensures that the correction for multiple comparisons is applied correctly, helping to control the risk of Type I error and interpret the results accurately.

Results

Participants' characteristics were similar at baseline (Table 1). The dropout rate, referring to participants who failed to attend the 12- and 24-week follow-up assessments, was 19% ($n = 6$) in the IG and 16% ($n = 5$) in the CG (18% of total sample). Moreover, one participant in the IG did not attend the 24-week assessment, and one participant in the CG did not attend the 12-week assessment. Additionally, two participants in the CG did not attend the 24-week assessment. The reasons for the dropout rate are described in Fig. 1. Two IG participants experienced mild adverse effects during intervention, such as delayed onset muscle soreness and foot muscle cramping; however, neither of them withdrew from the trial due to these effects.

The compliance rate[41] (% of IG that completed the exercise program 3 times/week for 12 weeks) obtained from the SOPeD user bank, which included all sessions completed, was 53% and the adherence rate (% of IG that completed the exercises program at 12 weeks) was 84%.

After 12 and 24 weeks, there were no interaction effects for DPN symptoms and severity, foot function, pain and health, shoes and functional reach; however, there were group and time effects for these outcomes (Table 2). The within-group analysis demonstrated a reduction in DPN symptoms within both the IG (posthoc: $p = 0.004$) and CG (posthoc: $p = 0.036$) after 24 weeks compared to baseline (time effect: $p = 0.001$). The between-group analysis showed a reduction in foot pain in the IG at 24 weeks compared to the CG (group effect: $p = 0.047$; posthoc: $p = 0.014$) and a reduction in foot pain in the IG at 12 weeks (posthoc: $p = 0.001$) and 24 weeks (posthoc: $p = 0.001$) compared to baseline (time effect: $p < 0.001$). The within-group analysis demonstrated an improvement in foot function in the IG at 24 weeks compared to baseline (time effect: $p = 0.037$; posthoc: $p = 0.009$). There was an increase in foot function in the IG compared to the CG at 24 weeks (group effect: $p = 0.043$; posthoc: $p = 0.013$). The between-group analysis also revealed an increase in the functional reach test in the IG compared to the CG at 12 weeks (group effect: $p = 0.046$; posthoc: $p = 0.049$).

The speed of the assessments for both plantar pressure distribution and kinematics had an average of 1.00 m/s and a standard deviation 0.13 m/s. There was an interaction effect in the pressure-time integral at 24 weeks (interaction effect: $p = 0.008$; posthoc: $p = 0.018$), with an increase at the forefoot in the IG compared to the CG (Table 3). In addition, there were significant group and time effects for other plantar pressure outcomes. The within-group analysis demonstrated a reduction in the forefoot peak pressure in the IG after 12 weeks compared to baseline (time effect: $p = 0.027$; posthoc: $p = 0.044$). However, at 24 weeks, there was an increase in the forefoot peak pressure in the IG compared to baseline (time effect: $p = 0.027$; posthoc: $p = 0.026$) and compared to the CG (group effect: $p = 0.049$; posthoc: $p = 0.022$). It is important to highlight that the reduction in the peak pressure from baseline to 12-week was 283 kPa, the increase from baseline to 24-week was 128 kPa, and the mean difference at 24-week between the IG and CG was 157 kPa. Thus, the reduction obtained after the exercise program was completed was greater than the subsequent increase at 24-week. The between-group analysis showed a reduction in the midfoot pressure-time integral in the IG compared to the CG after 12 weeks (group effect: $p = 0.047$; posthoc: $p = 0.038$).

The within-group analysis demonstrated an increase in the ankle range of motion (ROM) in the IG at 24 weeks compared to 12 weeks (time effect: $p = 0.001$; posthoc: $p = 0.018$) (Fig. 2; Table 4). There was also a significant increase in the ankle ROM in the CG at 12 weeks compared to 24 weeks (time effect: $p = 0.001$; posthoc: $p = 0.023$) and at 24 weeks compared baseline (posthoc: $p = 0.043$). The IG showed a significantly increased ankle plantarflexion motion at push-off compared to the CG at 24 weeks (group effect: $p = 0.038$; posthoc: $p = 0.001$). There was also a significant reduction in the minimum arch height in the IG at 12 weeks compared to baseline (time effect: $p = 0.047$; posthoc: $p = 0.029$.

Discussion

We conducted a randomized controlled trial (FOCA-I), to investigate the effectiveness of a 12-week customized web-based foot-ankle therapeutic exercises program on DPN and the program resulted in small-scale functional, clinical and biomechanical effects at 12 and 24 weeks. In the IG, the primary outcomes (DPN symptoms and

	Intervention Group ($n=31$) Mean ± SD	Control Group ($n=31$) Mean ± SD
Age (years)	52.1 ± 9.3	57.0 ± 9.6
Body mass (kg)	78.8 ± 13.4	85.7 ± 16.3
Height (cm)	167.0 ± 0.1	165.0 ± 0.1
Body mass index (kg/m^2)	28.2 ± 4.1	31.7 ± 6.9
Sex (Female = n (%))	20 (64.5%)	18 (58.0%)
Type 2 Diabetes (n (%))	26 (83.8%)	30 (96.7%)
Time of diabetes onset (years)	15.3 ± 9.4	10.3 ± 6.7
Tactile sensitivity (number of areas with loss of protective sensation) [a]	0 [0–1]	0 [0–0]
Vibration perception (n (%))		
Absent	8 (25.8%)	6 (19.3%)
Reduced	4 (12.9%)	5 (16.1%)
Present	19 (61.2%)	20 (64.5%)
Recruitment Location (n (%))		
University tertiary hospital - Hospital das Clínicas	13 (41.9%)	15 (48.4%)
Local and regional population campaign	15 (48.4%)	11 (35.4%)
Brazilian Diabetes Care Association	3 (9.7%)	5 (16.2%)
Education (n (%))		
Elementary education incomplete	2 (6.45%)	2 (6.4%)
Elementary education complete	4 (6.45%)	4 (12.9%)
High school incomplete	3 (3.22%)	3 (9.67%)
High school complete	10 (32.25%)	10 (32.25%)
Higher education incomplete	5 (12.9%)	5 (16.12%)
Higher education complete	7 (38.7%)	7 (22.58%)
Socioeconomic status (n (%))		
Less than 1 Brazilian minimum salary/ month	1 (3.22%)	4 (12.9%)
1 to 3 Brazilian minimum salary/ month	14 (45.1%)	19 (61.2%)
3 to 5 Brazilian minimum salary/month	5 (16.1%)	5 (16.1%)
Up to 5 Brazilian minimum salary/month	11 (35.4%)	3 (9.7%)
DPN symptoms (MNSI score)	6.7 ± 1.9	6.3 ± 1.5
DPN severity (Fuzzy score)	3.9 ± 2.1	3.7 ± 2.0
QALY (EQ-5D score)	0.6 ± 0.1	0.6 ± 0.1
FHSQ (score)		
Foot pain	46.7 ± 23.0	43.1 ± 25.5
Foot function	70.2 ± 26.5	63.0 ± 29.5
Shoes	55.9 ± 38.7	46.7 ± 41.1
Foot Health	25.5 ± 22.6	24.3 ± 21.8

Table 1. Demographics, anthropometrics, and clinical characteristics of the control and intervention groups participants at baseline ($n=62$). Data are presented as mean (SD) or as n or %; and median (interquartile range IQR). Abbreviation: *MNSI* Michigan neuropathy screening instrument; *FHSQ* Foot health status questionnaire; *DPN* Diabetic peripheral neuropathy; *QALY* Quality adjusted life years. [a] Poisson distribution and ordinal logistic models were employed to analyze the variable tactile sensitivity.

severity) did not change after 12 weeks of the foot-ankle program, but the secondary outcome functional balance improved at 12 weeks, foot pain decreased and foot function improved at 24-week compared to CG. Regarding plantar loadings during gait, the 12-week program resulted in a reduction in the forefoot peak pressure compared to baseline. However, at 24 weeks, the plantar loads at the forefoot increased in the IG compared to the CG. There was also an increase in the plantarflexion angle at push-off in the IG compared to the CG at the 24-week follow-up, and there was a reduction in the minimum arch height in the IG at 12 weeks compared to baseline. Some of the effects, such as the DPN symptoms, were also observed in the GC, suggesting a placebo effect probably resulting from therapist–patient interactions[42], or due to better clinical management of the disease.

There was a very good adherence rate to the proposed intervention (84% of IG), despite the recognized high non-adherence to self-managed home-based physical rehabilitation programs[43]. However, there was a relatively low compliance rate (53% of the IG completed 3 sessions/week for 12 weeks), which might have impacted the effectiveness of the intervention. Nevertheless, we surprisingly noticed a trend toward continued treatment beyond the initial intervention period, with approximately 50% of the participants continuing to use the SOPeD after the proposed 12 weeks. This sustained usage of the web-based tool may explain some of the continued

	Intervention Group ($n=31$)			Control Group ($n=31$)			Between-Group Difference (CI 95%)		GEE Analysis (p-values)		
Variables	Baseline estimated	12-week estimated	24-week estimated	Baseline estimated	12-week Estimated	24-week estimated	12-week (intervention X control group)	24-week (intervention X control group)	Group	Time	Group x time (interaction effect)
DPN symptoms (MNSI score, mean ± SE)	6.71 ± 0.34[a]	5.62 ± 0.54	4.90 ± 0.53[a]	6.29 ± 0.27[b]	5.59 ± 0.43	5.29 ± 0.33[b]	0.03 (-1.33, 1. 39)	-0.39 (-1.63, 0.85)	0.977	<**0.001**	0.554
DPN severity (Fuzzy score, mean ± SE)	3.93 ± 0.37	3.22 ± 0.52	2.96 ± 0.56	3.66 ± 0.35	3.31 ± 0.37	3.49 ± 0.41	-0.09 (-1.34, 1.16)	-0.53 (-1.90, 0.83)	0.796	0.111	0.461
Tactile sensitivity (number of areas [median, IQR])	0 [0–1]	0 [0–0]	0 [0–0]	0 [0–0]	0 [0–0]	0 [0–0]	-	-	0.071	0.125	0.397
Vibration perception absent left (number of participants)	9 (29.0%)	3 (9.6%)	2 (6.4%)	5 (16.1%)	4 (12.9%)	3 (9.6%)	-	-	-	-	-
Vibration perception reduced left (number of participants)	3 (9.6%)	6 (19.3%)	2 (6.4%)	2 (6.4%)	4 (12.9%)	3 (9.6%)	-	-	-	-	-
Vibration perception absent right (number of participants)	6 (19.3%)	6 (19.3%)	1 (3.2%)	6 (19.3%)	5 (16.1%)	5 (16.1%)	-	-	-	-	-
Vibration perception reduced right (number of participants)	4 (12.9%)	3 (9.6%)	2 (6.4%)	5 (16.1%)	2 (6.4%)	1 (3.2%)	-	-	-	-	-
FHSQ Foot pain (score, mean ± SE)	46.69 ± 4.06[d, e]	68.09 ± 5.31[d]	71.25 ± 5.58[2,e]	46.09 ± 4.30	54.94 ± 5.46	51.06 ± 6.04[2]	13.15 (-1.78, 28.09)	20.18 (4.04, 36.33)[2]	**0.047**	**0.001**	0.078
FHSQ Foot function (score, mean ± SE)	70.16 ± 4.69[c]	73.13 ± 5.87	84.86 ± 4.46[3,c]	63.02 ± 5.21	74.05 ± 5.45	66.40 ± 5.94[3]	2.08 (-13.63, 17.79)	18.46 (3.88, 33.04)[3]	**0.043**	**0.037**	0.093
FHSQ Shoes (score, mean ± SE)	69.33 ± 5.90	57.89 ± 7.16	66.15 ± 7.45	65.90 ± 6.90	62.49 ± 6.13	51.58 ± 5.76	-4.60(-23.09, 13.88)	14.56 (-3.90, 33.04)	0.506	0.229	0.176
FHSQ Foot health (score, mean ± SE)	34.45 ± 3.96	44.97 ± 5.12	48.38 ± 5.75	32.82 ± 3.85	42.20 ± 4.80	40.31 ± 5.19	0.77 (-13.00, 14.55)	8.07 (-7.11, 23.25)	0.483	0.042	0.648
EQ-5D (score, mean ± SE)	0.59 ± 0.03	0.65 ± 0.03	0.63 ± 0.03	0.60 ± 0.03	0.63 ± 0.03	0.57 ± 0.03	0.01 (-0.06, 0.10)	0.05 (-0.04, 0.15)	0.560	0.121	0.272
Hallux strength (%BW, mean ± SE)	11.35 ± 0.66	11.19 ± 0.98	11.35 ± 0.81	13.79 ± 1.15	13.47 ± 1.09	11.16 ± 0.67	-2.28 (-5.17, 0.60)	0.19 (-1.86, 2.26)	0.146	0.149	0.113
Toes strength (%BW, mean ± SE)	8.28 ± 0.71	8.26 ± 0.75	9.48 ± 0.99	8.95 ± 0.73	8.99 ± 0.74	7.84 ± 1.01	-0.73 (-2.80, 1.33)	1.64 (-1.15, 4.43)	0.936	0.999	0.068
Functional Reach Test (cm, mean ± SE)	27.00 ± 1.15	29.71 ± 1.34[1]	28.75 ± 1.23	24.58 ± 1.31	26.36 ± 1.04[1]	27.44 ± 1.07	3.35 (0.02, 6.68)[1]	1.31 (-1.91, 4.52)	**0.046**	0.066	0.490

Table 2. Estimated mean ± standard error (SE) or IQR when applicable, p-values from generalized estimating equation (GEE), and between-group mean differences at 12 and 24 weeks (95% confidence interval) for the DPN-related and functional outcomes in the Intervention Group and Control Group. *MNSI* Michigan neuropathy screening instrument; *FHSQ* Foot health status questionnaire; *BW* Body weight. [1]Group effect $p=0.046$, between-group difference at 12-week (post hoc $p=0.049$). [2]Group effect $p=0.047$, between-group difference at 24-week (post hoc $p=0.014$). [3]Group effect $p=0.043$, between-group difference at 24-week (post hoc $p=0.013$). [a]Time effect $p<0.001$, difference between baseline and 24-week in the intervention group (post hoc $p=0.004$). [b]Time effect $p<0.001$, difference between baseline and 24-week in the control group (post hoc $p=0.036$). [c]Time effect $p<0.037$, difference between baseline and 24-week in the intervention group (post hoc $p=0.009$). [d]Time effect $p<0.001$, difference between baseline and 12-week in the intervention group (post hoc $p=0.001$). [e]Time effect $p<0.001$, difference between 12-week and 24-week in the control group (post hoc $p=0.001$).

		Intervention Group ($n=31$)			Control Group ($n=31$)			Between-Group Difference (CI 95%)		GEE Analysis (p-values)		
Region of Interest	**Variables**	**Baseline Estimated mean (SE)**	**12-week Estimated mean (SE)**	**24-week Estimated mean (SE)**	**Baseline Estimated mean (SE)**	**12-week Estimated mean (SE)**	**24-week Estimated mean (SE)**	**12-week (Intervention X Control Group)**	**24-week (Intervention X Control Group)**	**Group**	**Time**	**Group x Time (interaction effect)**
Hindfoot	Contact Area [cm^2]	34.1 ± 0.6	34.9 ± 0.7	35.4 ± 0.9	35.1 ± 0.6	35.6 ± 0.8	35.8 ± 0.7	-0.7 (-2.9, 1.4)	-0.4 (-2.7, 1.8)	0.414	0.091	0.769
	Peak Pressure[kPa]	355.3 ± 14.87	365.1 ± 20.6	386.4 ± 35.2	343.3 ± 11.7	349.3 ± 14.3	350.8 ± 14.7	15.8 (-33.4, 65.0)	35.6 (-21.6, 92.8)	0.322	0.285	0.569
	Pressure-time integral [(kPa)*s]	104.3 ± 4.9	104.1 ± 5.7	107.6 ± 6.0	106.7 ± 4.7	100.0 ± 3.8	107.7 ± 5.0	4.1 (-9.4, 17.6)	-0.1 (-15.5, 15.2)	0.927	0.183	0.551
Midfoot	Contact Area [cm^2]	29.0 ± 1.1	29.9 ± 1.7	27.9 ± 2.0	31.0 ± 1.0	31.3 ± 1.3	32.5 ± 1.5	-1.4 (-5.7, 2.9)	-4.7 (-9.6, 0.3)	0.163	0.526	0.122
	Peak Pressure[kPa]	184.7 ± 12.8	176.4 ± 12.4	175.0 ± 14.9	194.2 ± 8.9	191.0 ± 12.4	204.1 ± 13.8	-14.6 (-48.9, 19.7)	-29.1 (-69.0, 10.8)	0.243	0.685	0.543
	Pressure-time integral [(kPa)*s]	70.6 ± 5.8	63.1 ± 5.67[1]	71.9 ± 9.4	84.4 ± 5.9	81.6 ± 6.9[1]	86.5 ± 6.6	-18.5 (-36.0, -1.0)[1]	-14.6 (-37.2, 8.0)	**0.047**	0.332	0.786
Forefoot	Contact Area [cm^2]	51.6 ± 1.0	665.5 ± 51.3	53.2± 1.8	53.0 ± 0.9	53.9 ± 1.2	54.2 ± 1.3	-0.3 (-3.9, 3.4)	-0.99 (-5.3, 3.3)	0.588	0.192	0.529
	Peak Pressure[kPa]	586.7 ± 37.6[a, b]	303.6 ± 64.5[a]	715.0 ± 61.7[2,b]	561.3 ± 30.2	594.4 ± 33.4	557.8 ± 30.4[2]	71.0 (-49.0, 191.0)	157.2 (22.4, 292.1)[2]	**0.049**	**0.027**	0.076
	Pressure-time integral [(kPa)*s]	199.9 ± 13.0	217.7 ± 17.7	251.8 ± 22.1[*]	203.8 ± 11.1	202.7 ± 11.8	195.2 ± 9.3[*]	15.0 (-26.8, 56.8)	56.6 (9.7, 103.5)[*]	0.208	0.105	**0.008**
Hallux	Contact Area [cm^2]	10.3 ± 0.3	10.4 ± 0.4	10.3 ± 0.45	11.0 ± 0.2	11.1 ± 0.3	11.0 ± 0.2	-0.7 (-1.7, 0.3)	-0.7 (-1.7, 0.4)	0.072	0.959	0.996
	Peak Pressure[kPa]	391.6 ± 33.2	457.4 ± 54.3	428.0 ± 62.3	440.9 ± 41.3	403.9 ± 40.5	401.7 ± 57.1	53.5 (-79.3, 186.4)	26.3 (-139.3, 191.8)	0.869	0.795	0.088
	Pressure-time integral [(kPa)*s]	97.6 ± 11.3	106.4 ± 16.1	100.3 ± 19.3	111.7 ± 11.1	95.3 ± 9.5	97.8 ± 13.0	11.0 (-25.6, 47.7)	2.5 (-43.2, 48.1)	0.999	0.815	0.174
Toes	Contact Area [cm^2]	9.5 ± 0.5	9.7 ± 0.7	10.2 ± 0.8	10.3 ± 0.5	9.8 ± 0.7	10.7 ± 0.8	-0.1 (-2.0, 1.8)	-0.5 (-2.7, 1.8)	0.598	0.213	0.603
	Peak Pressure[kPa]	172.5 ± 15.2	177.3 ± 22.8	204.1 ± 32.4	199.6 ± 21.5	175.3 ± 27.7	206.1 ± 36.1	1.9 (-68.4, 72.3)	-2.0 (96.9, 93.0)	0.786	0.037	0.555
	Pressure-time integral [(kPa)*s]	47.1 ± 4.9	44.2 ± 5.2	50.2 ± 6.8	61.9 ± 8.4	49.1 ± 7.9	59.4 ± 11.1	-5.0 (-23.6, 13.6)	-9.2 (-34.7, 16.3)	0.305	0.036	0.594

Table 3. Estimated mean and SE, p-values from GEE, and between-group mean differences at 12 and 24 weeks (95% confidence interval) for the plantar pressure variables during gait in the Intervention Group and Control Group. [1]Group effect $p=0.047$, between-group difference at 12-week (post hoc $p=0.038$). [2]Group effect $p=0.049$, between-group difference at 24-week (post hoc $p=0.022$). [*]Tnteraction effect $p=0.008$, group effect $p=0.208$, between-group difference at 24-week (post hoc $p=0.018$). [a]Time effect $p<0.027$, difference between baseline and 12-week in the intervention group (post hoc $p=0.044$). [b]Time effect $p<0.027$, difference between baseline and 24-week in the intervention group (post hoc $p=0.026$).

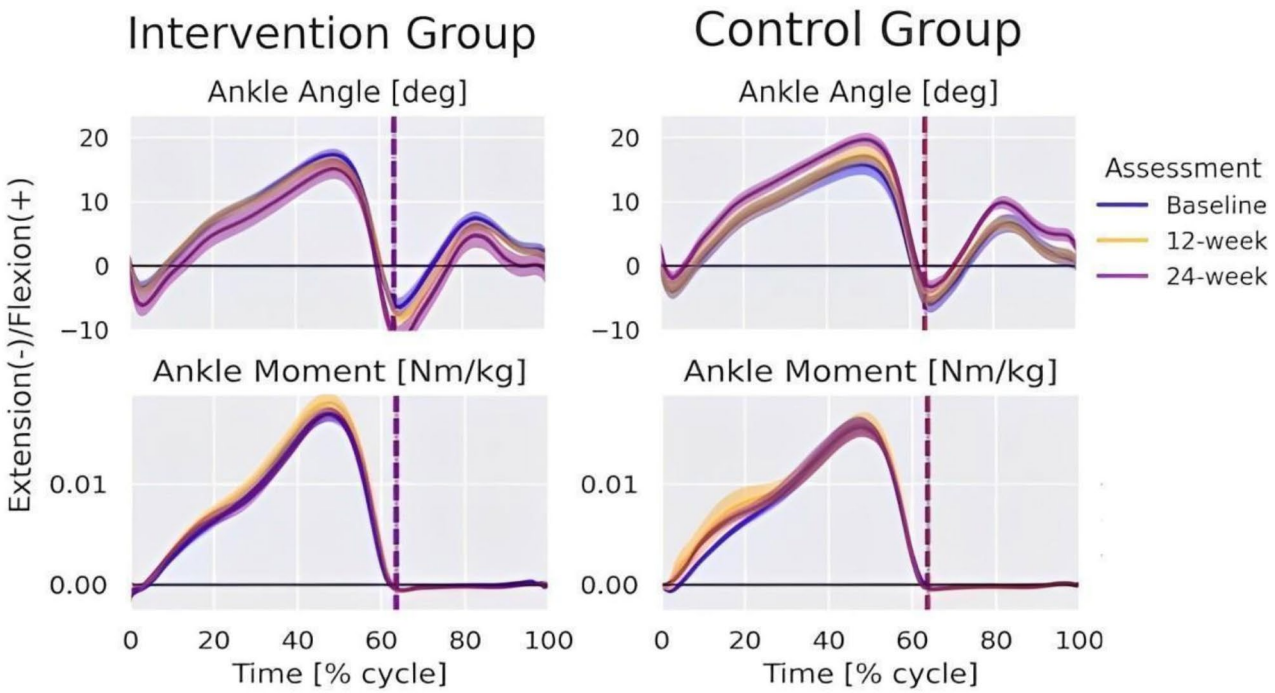

Fig. 2. Ankle moments and Ankle angles (mean ± 1 SD) during gait cycle (0–100%) in the Intervention Group and Control Group at baseline (blue), after 12 weeks (orange), and after 24 weeks (purple). The dashed vertical lines represent the average end of the stance phase.

changes in the primary (DPN symptoms) and secondary (foot pain, ankle motion, and pressure parameters) outcomes even after the 12-week period.

It is worth mentioning that the development and validation of the SOPeD included rigorous safety assessments, integrating feedback from both experts and users. We conducted a comprehensive feasibility study[44] to ensure clinical safety, employing a specially developed and validated safety questionnaire. The results confirmed the SOPeD safety, with only mild adverse events reported in the RCT. This robust validation process underscores the SOPeD reliability and effectiveness in a clinical setting.

The SOPeD significantly reduced foot pain and improved functional balance and foot function compared to usual care, indicating its effectiveness. An IWGDF meta-analysis revealed that foot-ankle exercise programs can improve joint mobility and alleviate DPN signs and symptoms[13]. Notably, the analyzed interventions in the IWGDF meta-analysis lacked the incorporation of rehabilitation technology, such as web-based programs. Foot-ankle exercises delivered through web-based software like SOPeD appear to be equally effective as face-to-face or home-based therapeutic programs, except that face-to-face interventions show better outcomes for foot and ankle range of motion, as indicated in the literature[13].

The improvements, while modest and predominantly observed at 24 weeks, demonstrated the effectiveness of the exercises program in alleviating foot pain and enhancing foot function. These results suggest that the effects of the program could be more pronounced over time, requiring a longer intervention duration for a more noticeable clinical improvement. Earlier studies[45–47] support the positive impact of foot-ankle exercises on DPN symptoms. However, it is possible that the progression of DPN symptoms is complex, and other factors may have interfered with these changes throughout the study period. The improvement in DPN symptoms for both groups at 24 weeks compared to baseline could be due to better glycemic control rather than the exercise program, as higher glycemic levels are linked to more severe DPN-related symptoms[48,49]. This hypothesis arises from the fact that glycemic control was not measured in our study. Unfortunately, this study lacked metabolic control over the 24-week period, making it challenging to solely credit the foot-ankle exercise program for the improvement in DPN symptoms.

High peak pressures are recognized risk factors for ulcers in individuals with DPN[50–52]. Therefore, it is recommended that these plantar loadings be monitored to maintain them within a safe threshold below 200 kPa when wearing footwear[24] and below 402 kPa when barefoot[53]. The IG exhibited reduction in forefoot peak pressure of 283 kPa from baseline to 12 weeks; however, at the 24-week follow-up, there was an increase in forefoot peak pressure compared to both the baseline (128 kPa) and the mean difference between the IG and CG was 157 kPa. Clearly, attention should be paid to keeping plantar pressures below the ulcer risk thresholds, however this modification may be linked to the gain in ankle ROM and plantarflexion degree during push-off in the IG, manifesting only after 24 weeks of intervention, which is a positive result. The exercises program may have led to an improvement in the foot rollover due to the gain in the ankle motion and shifted more pressure towards the forefoot region. The increase in the forefoot plantar loads after 24 weeks of intervention may suggest

	Intervention Group ($n=31$)			Control Group ($n=31$)			Between-Group Difference (CI 95%)		GEE Analysis (p-values)		
Variables	Baseline Estimated mean (SE)	12-week Estimated mean (SE)	24-week Estimated mean (SE)	Baseline Estimated mean (SE)	12-week Estimated mean (SE)	24-week Estimated mean (SE)	12-week (Intervention X Control Group)	24-week (Intervention X Control Group)	Group	Time	Group x Time (interaction effect)
FOOT-ANKLE kinematics and Kinetics											
Ankle ROM (degree)	24.52 ± 0.87	23.49 ± 0.89[a]	26.41 ± 1.07[a]	23.74 ± 0.55[c]	23.88 ± 0.60[b]	25.56 ± 0.66[b, c]	-0.38 (-2.50, 1.72)	0.85 (-1.62, 3.32)	0.665	**0.001**	0.407
Ankle dorsiflexion at heel strike (degree)	3.90 ± 0.61	3.04 ± 0.57	2.78 ± 0.66	3.13 ± 0.45	4.25 ± 1.06	4.81 ± 0.68	-1.20 (-3.58, 1.16)	-2.03 (-3.89, -0.16)	0.222	0.961	0.051
Ankle plantarflexion at push off (degree)	2.00 ± 0.94	2.50 ± 1.17	5.12 ± 0.01[1]	4.49 ± 0.64	2.78 ± 0.38	2.30 ± 0.71[1]	–0.27 (-2.70, 2.14)	2.82 (1.42, 4.22)[1]	**0.038**	0.298	0.955
Hindfoot to tibia ROM (degree)	23.22 ± 1.04	23.99 ± 1.39	24.15 ± 1.95	22.63 ± 0.92	24.86 ± 1.05	25.89 ± 1.07	-0.86 (-4.29, 2.55)	-1.73 (-6.10, 2.63)	0.666	0.069	0.478
Hindfoot to tibia peak angle (degree)	13.74 ± 1.34	15.95 ± 2.13	11.65 ± 1.31	13.38 ± 0.96	14.86 ± 1.03	14.91 ± 1.14	1.08 (-3.55, 5.73)	-3.25 (-6.68, 0.16)	0.557	0.207	0.147
Forefoot to hindfoot ROM (degree)	13.16 ± 0.88	13.69 ± 1.28	13.41 ± 0.78	12.54 ± 0.72	12.63 ± 1.27	12.34 ± 0.69	1.06 (-2.47, 4.60)	1.06 (-0.98, 3.10)	0.364	0.941	0.926
Forefoot to hindfoot peak angle (degree)	8.34 ± 0.75	6.99 ± 0.99	6.70 ± 0.97	7.88 ± 0.70	7.61 ± 0.97	6.65 ± 0.88	-0.61 (-3.33, 2.10)	0.04 (-2.53, 2.63)	0.956	0.031	0.768
Hallux to forefoot ROM (degree)	24.56 ± 1.48	25.56 ± 2.09	24.86 ± 1.71	21.61 ± 1.51	23.70 ± 1.44	22.65 ± 1.20	1.85 (-3.12, 6.84)	2.20 (-1.90, 6.32)	0.173	0.363	0.839
Hallux to forefoot peak angle (degree)	23.96 ± 1.71	26.31 ± 2.33	25.09 ± 1.89	21.96 ± 1.78	22.10 ± 1.91	21.32 ± 1.72	4.21 (-1.70, 10.12)	3.77 (-1.25, 8.79)	0.121	0.668	0.675
Maximum arch height (cm)	11.30 ± 0.33	10.50 ± 0.28	10.60 ± 0.58	11.67 ± 0.29	11.61 ± 0.46	10.78 ± 0.37	-1.10 (-2.18, -0.02)	-0.17 (-1.53, 1.17)	0.171	0.129	0.269
Minimum arch height (cm)	8.90 ± 0.29[d]	8.13 ± 0.33[d]	8.07 ± 0.55	9.28 ± 0.31	9.17 ± 0.45	8.51 ± 0.34	-1.04 (-2.14, 0.06)	-0.44 (-1.72, 0.83)	0.154	**0.047**	0.328
Ankle flexor moment at heel strike (Nm/(BM*Height)	0.011 ± 0.005	0.021 ± 0.008	0.014 ± 0.005	0.013 ± 0.005	0.016 ± 0.009	0.022 ± 0.005	0.004 (-0.019, 0.029)	-0.008 (-0.024, 0.007)	0.744	0.514	0.693
Ankle extensor moment at push off (Nm/(BM* Height)	1.32 ± 0.03	1.39 ± 0.02	1.38 ± 0.03	1.31 ± 0.02	1.27 ± 0.07	1.36 ± 0.03	0.12 (-0.02, 0.27)	0.02 (-0.07, 0.11)	0.189	0.062	0.353
Ankle peak eccentric power at the push off (W/BM*Height)	2.21 ± 0.07	2.53 ± 0.12	2.42 ± 0.13	2.50 ± 0.12	2.50 ± 0.21	2.54 ± 0.12	0.03 (-0.45, 0.52)	-0.11 (-0.47, 0.24)	0.393	0.158	0.260

Table 4. Estimated mean and SE, p-values from GEE, and between-group mean difference at 12 and 24 weeks (95% confidence interval) for the foot-ankle kinematics, and ankle joint kinetics during gait in the Intervention Group and Control Group at baseline and follow-up assessments. *BM* Body mass, *ROM* Range of motion. [a] time effect $p=0.001$, difference between 12-week and 24-week in the intervention group (post hoc $p=0.018$); [b] time effect $p=0.001$, difference between 12-week and 24-week in the control group (post hoc $p=0.023$); [c] time effect $p=0.001$, difference between baseline and 24-week in the control group (post hoc $p=0.043$);[1] group effect $p=0.038$, between-group difference at 24-week (post hoc $p=0.001$); [d] time effect $p=0.047$, difference between baseline and 12-week in the intervention group (post hoc $p=0.029$).

a delayed response or long-term adaptation to the program. It is possible that the body underwent an adjustment period before fully demonstrating the program's benefits. It is also worth mentioning that the participants' body weight remained almost unchanged throughout the 24 weeks of the study, suggesting that it had no impact on the plantar pressure distribution. In addition, although new ulcers were not original outcomes in our study, we followed them for 12 months and none of the participants developed ulcers during the entire study follow-up period.

At the 24-week follow-up, the IG showed an increase in ankle ROM compared to the 12-week assessment, while the CG demonstrated an increased ankle ROM at both 12 and 24 weeks compared to baseline, with no significant difference between groups. These positive outcomes in both groups may reflect the effects of usual care or a placebo effect from professional care and supportive patient–therapist interactions[41]. Additionally, the IG exhibited a greater plantarflexion angle at push-off compared to the CG at 24 weeks, suggesting an enhanced contribution of the ankle during push-off and a potential change in the foot rollover process. Moderate evidence supports the efficacy of foot-ankle exercise programs in enhancing foot-ankle ROM[13], as confirmed by our findings. Individuals with DPN exhibit limitations in dynamic dorsi and plantarflexion[9,54,55], as well as passive ankle ROM[56]. These motion restrictions can significantly impact the foot rollover pattern during locomotor activities, affecting the load distribution under the foot, as well as balance control[9,24,57,58]. Thus, gaining joint ROM and a pressure redistribution during gait might be seen as a positive outcome. Another change noted at 12 weeks in the IG was a reduction in the minimum arch height. This result may indicate that the arch became more flexible during gait after the intervention, which is a positive outcome, demonstrating increased malleability and greater mobility of the foot tissues.

Although treatment programs of 8 to 12 weeks are recommended by the IWGDF (2023)[24] prevention guidelines, our findings suggest that the proposed intervention duration (12-week) may not have been sufficient to produce significant changes in the analyzed outcomes. A longer intervention period may be needed to achieve more evident and consistent benefits, especially in a web-based program. This could involve increasing the number of sessions, enhancing the difficulty of the exercises, implementing strategies to improve participant adherence and include sessions supervision.

Strengths and limitations

This study's strengths lie in its rigorous methodological design and the provision of a free, globally accessible web-based exercise program, fostering equity, ubiquity and health awareness for individuals with DPN, which is essential for self-care maintenance. Notably, this is the first studyto test specific foot-ankle exercises conducted through a personalized web-based platform for people with diabetes. However, limitations include the lack of direct supervision hindering control over participants' exercises completion and performance. Closer supervision might have ensured better exercise performance and, consequently, greater clinical, functional, and biomechanical gains. Additionally, the study did not monitor metabolic control, potentially impacting DPN-related outcomes. The COVID-19 posed challenges, leading to higher lost-to-follow-up rates, highlighting the need for innovative web-based interventions in global healthcare systems. Another limitation of this clinical trial is that it is underpowered to discern the effects of sex or evaluate the effectiveness of the intervention across different BMI categories and age groups, as we did not perform a sample size calculation that allowed for subgroup analyses. These limitations should be taken into account when interpreting the results, as they indicate the need for further studies to validate the findings in different subsets of people with DPN and gain a better understanding of variations in treatment responses.

Conclusions

Our 12-week web-based foot-ankle therapeutic exercise program (SOPeD) was feasible, acceptable, demonstrating safety with minimal adverse events, and had a very good patient adherence. Improvements in foot pain and function, functional reach, and changes in plantar pressure and plantarflexion degree during gait were noted, but were modest overall, which might indicate a need for a longer and more intense web-based exercise program to achieve more pronounced outcomes in foot-ankle biomechanics and plantar pressure for individuals with DPN. Given the relatively low cost and high benefits of a web-based ankle-foot therapeutic exercise program, we humbly invite researchers and clinicians to replicate it and we will offer help if needed.

Data availability

The datasets generated and/or analyzed during the current study are accessible as anonymized data on the University's public repository at https://repositorio.usp.br/.

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References

1. Pop-Busui, R. et al. Diabetic neuropathy: A position statement by the American diabetes association. *Diabetes Care* **40**(1), 136–154. https://doi.org/10.2337/dc16-2042 (2017).
2. Gordois, A., Scuffham, P., Shearer, A., Oglesby, A. & Tobian, J. A. The health care costs of diabetic peripheral neuropathy in the US. *Diabetes Care* **26**(6), 1790–1795. https://doi.org/10.2337/diacare.26.6.1790 (2003).
3. Ernandes, R., de Brech, C. & Luna, G. C. Impact of Diabetic Neuropathy on quality of life and postural balance in Brazilian older adults. *Acta Ortop. Bras.* **28**(6), 275–279. https://doi.org/10.1590/1413-785220202806234529 (2020).
4. Andersen, H., Gjerstad, M. D. & Jakobsen, J. Atrophy of foot muscles: A measure of diabetic neuropathy. *Diabetes Care* **27**(10), 2382–2385. https://doi.org/10.2337/diacare.27.10.2382 (2004).

5. Andreassen, C. S., Jakobsen, J., Ringgaard, S., Ejskjaer, N. & Andersen, H. Accelerated atrophy of lower leg and foot muscles-a follow-up study of long-term diabetic polyneuropathy using magnetic resonance imaging (MRI). *Diabetologia* **52**(6), 1182–1191. https://doi.org/10.1007/s00125-009-1320-0 (2009).
6. Parasoglou, P., Rao, S. & Slade, J. M. Declining skeletal muscle function in diabetic peripheral neuropathy. *Clin. Ther.* **39**(6), 1085–1103. https://doi.org/10.1016/j.clinthera.2017.05.001 (2017).
7. Sinacore, D. R. et al. Neuropathic midfoot deformity: associations with ankle and subtalar joint motion. *J. Foot Ankle Res.* **6**(1). https://doi.org/10.1186/1757-1146-6-11 (2013).
8. Rao, S., Saltzman, C. & Yack, H. J. Ankle ROM and stiffness measured at rest and during gait in individuals with and without diabetic sensory neuropathy. *Gait Posture* **24**(3), 295–301. https://doi.org/10.1016/j.gaitpost.2005.10.004 (2006).
9. Sacco, I. C. N. et al. Role of ankle mobility in foot rollover during gait in individuals with diabetic neuropathy. *Clin. Biomech. Elsevier Ltd* **24**(8), 687–692. https://doi.org/10.1016/j.clinbiomech.2009.05.003 (2009).
10. Sacco, I. C. N., Trombini-Souza, F. & Suda, E. Y. Impact of biomechanics on therapeutic interventions and rehabilitation for major chronic musculoskeletal conditions: a 50-year perspective. *J. Biomech.* **154**. https://doi.org/10.1016/j.jbiomech.2023.111604 (2023).
11. Fernando, M. E. et al. Plantar pressures are higher in cases with diabetic foot ulcers compared to controls despite a longer stance phase duration. *BMC Endocr. Disord.* **16**(1). https://doi.org/10.1186/s12902-016-0131-9 (2016).
12. Armstrong, D. G., Tan, T. W., Boulton, A. J. M. & Bus, S. A. Diabetic foot ulcers: A review. *JAMA* **330**(1), 62–75. https://doi.org/10.1001/jama.2023.10578 (2023).
13. van Netten, J. J. et al. Clinical and biomechanical effectiveness of foot-ankle exercise programs and weight-bearing activity in people with diabetes and neuropathy: A systematic review and meta-analysis. *Diabetes Metab. Res. Rev.* https://doi.org/10.1002/dmrr.3649 (2023)
14. Ghavami, H., Radfar, M., Soheily, S., Shamsi, S. A. & Khalkhali, H. R. Effect of lifestyle interventions on diabetic peripheral neuropathy in patients with type 2 diabetes, result of a randomized clinical trial. *Agri* **30**(4), 165–170. https://doi.org/10.5505/agri.2018.45477 (2018).
15. Jack, K., McLean, S. M., Moffett, J. K. & Gardiner, E. Barriers to treatment adherence in physiotherapy outpatient clinics: A systematic review. *Man. Ther.* **15**(3), 220–228. https://doi.org/10.1016/j.math.2009.12.004 (2010).
16. Mogre, V., Johnson, N. A., Tzelepis, F. & Paul, C. Barriers to diabetic self-care: A qualitative study of patients' and healthcare providers' perspectives. *J. Clin. Nurs.* **28**(11–12), 2296–2308. https://doi.org/10.1111/jocn.14835 (2019).
17. Kluge, E. H. e-Health promises and challenges: Some ethical considerations. *Stud. Health Technol. Inf.* **164**, 148–153 (2011).
18. Akter, S. & Ray, P. *MHealth - an Ultimate Platform to Serve the Unserved* (2010).
19. Wasson, J. H. et al. The medium is the (health) measure: Patient engagement using personal technologies. *J. Ambul. Care Manage.* **35** (2), 109–117. https://doi.org/10.1097/JAC.0b013e31824a235e (2012).
20. Bornkessel, A., Furberg, R. & Lefebvre, R. C. Social media: Opportunities for quality improvement and lessons for providers - a networked model for patient-centered care through digital engagement. *Curr. Cardiol. Rep.* **16**(7). https://doi.org/10.1007/s11886-014-0504-5 (2014).
21. Wantland, D. J., Portillo, C. J., Holzemer, W. L., Slaughter, R. & McGhee, E. M. The effectiveness of web-based vs. non-web-based interventions: A meta-analysis of behavioral change outcomes. *J. Med. Internet Res.* **6**(4). https://doi.org/10.2196/jmir.6.4.e40 (2004).
22. Delir Haghighi, P. & Burstein, F. Advances in E-Health and Mobile Health Monitoring. *Sensors*. **22**(22). https://doi.org/10.3390/s22228621 (2022).
23. Kreps, G. L. & Neuhauser, L. New directions in eHealth communication: Opportunities and challenges. *Patient Educ. Couns.* **78**(3), 329–336. https://doi.org/10.1016/j.pec.2010.01.013 (2010).
24. Bus, S. A. et al. Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2023 update). *Diabetes Metab. Res. Rev.* **40**(3). https://doi.org/10.1002/dmrr.3651 (2024).
25. Ferreira, J. S. S. P., Siqueira, A. A., Sartor, C. D. & Sacco, I. C. N. National Institute of Industrial Property of Brazil. Diabetic Foot Guidance Software - SOPeD. BR512019002532-6, Submission date: 30 Aug. Grant date: 12 Nov. 2019 (2019).
26. Schulz, K. F., Altman, D. G. & Moher, D. CONSORT 2010 Statement: Updated guidelines for reporting parallel group randomised trials. *BMJ (Online)*. **340**(7748), 698–702. https://doi.org/10.1136/bmj.c332 (2010).
27. Ferreira, J. S. S. P. et al. Study protocol for a randomized controlled trial on the effect of the diabetic foot guidance system (SOPeD) for the prevention and treatment of foot musculoskeletal dysfunctions in people with diabetic neuropathy: The FOotCAre (FOCA) trial i. *Trials*. **21**(1). https://doi.org/10.1186/s13063-019-4017-9 (2020).
28. Altman, D. G. & Bland, J. M. How to randomise. *Br. Med. J.* **319**(7211), 703–704 (1999).
29. Fragala, M. S. et al. *Resistance Training for Older Adults: Position Statement From the National Strength and Conditioning Association*. www.nsca.com (2019).
30. Ferreira, J. S. S. P., Sacco, I. C. N., Siqueira, A. A., Almeida, M. H. M. & Sartor, C. D. Rehabilitation technology for self-care: Customised foot and ankle exercise software for people with diabetes. *PLoS One* **14**(6). https://doi.org/10.1371/journal.pone.0218560 (2019).
31. Sartor, C. D., Oliveira, M. D., Campos, V., Ferreira, J. S. S. P. & Sacco, I. C. N. Cross-cultural adaptation and measurement properties of the Brazilian version of the Michigan neuropathy screening instrument. *Braz J. Phys. Ther.* **22**(3), 222–230. https://doi.org/10.1016/j.bjpt.2017.10.004 (2018).
32. Watari, R. et al. Effect of diabetic neuropathy severity classified by a fuzzy model in muscle dynamics during gait. *J. Neuroeng. Rehabil.* **11**(1), 11. https://doi.org/10.1186/1743-0003-11-11 (2014).
33. McIllhatton, A. et al. Reliability of recommended non-invasive chairside screening tests for diabetes-related peripheral neuropathy: A systematic review with meta-analyses. *BMJ Open. Diabetes Res. Care* **9**(2). https://doi.org/10.1136/bmjdrc-2021-002528 (2021).
34. Perkins, B., DZinman, O. & Bril, B. Simple screening tests for peripheral neuropathy in the diabetes clinic. *Diabetes Care*. **24**(2), 250–256. https://doi.org/10.2337/diacare.24.2.250 (2001).
35. Ferreira, A. F. B. et al. Brazilian version of the foot health status questionnaire (FHSQ-BR): cross-cultural adaptation and evaluation of measurement properties. *Clinics (Sao Paulo)* **63**(5), 595–600. https://doi.org/10.1590/S1807-59322008000500005 (2008).
36. Mickle, K. J., Chambers, S., Steele, J. R. & Munro, B. J. A novel and reliable method to measure toe flexor strength. *Clin. Biomech. Elsevier Ltd.* **23**(5), 682–683. https://doi.org/10.1016/j.clinbiomech.2008.03.024 (2008).
37. Duncan, P. W., Weiner, D. K., Chandler, J. & Studenski, S. Functional reach: A new clinical measure of balance. *Journals Gerontol.* **45**(6), 1–2. https://doi.org/10.1093/geronj/45.6.M192 (1990).
38. Stebbins, J., Harrington, M., Thompson, N., Zavatsky, A. & Theologis, T. Repeatability of a model for measuring multi-segment foot kinematics in children. *Gait Posture* **23**(4), 401–410. https://doi.org/10.1016/j.gaitpost.2005.03.002 (2006).
39. Mickle, K. J. et al. Toe weakness and deformity increase the risk of falls in older people. *Clinical Biomechanics* **24**(10), 787–791. https://doi.org/10.1016/j.clinbiomech.2009.08.011 (2009).
40. Sartor, C. D. et al. Effects of strengthening, stretching and functional training on foot function in patients with diabetic neuropathy: results of a randomized controlled trial. *BMC Musculoskelet. Disord.* **15**(1). https://doi.org/10.1186/1471-2474-15-137 (2014).
41. McKay, C. D. & Verhagen, E. Compliance versus adherence in sport injury prevention: Why definition matters. *Br. J. Sports Med.* **50**(7), 382–383. https://doi.org/10.1136/bjsports-2015-095192 (2016).
42. Testa, M. & Rossettini, G. Enhance placebo, avoid nocebo: How contextual factors affect physiotherapy outcomes. *Man. Ther.* **24**, 65–74. https://doi.org/10.1016/j.math.2016.04.006 (2016).

43. Essery, R., Geraghty, A. W. A., Kirby, S. & Yardley, L. Predictors of adherence to home-based physical therapies: A systematic review. *Disabil. Rehabil.* **39**(6), 519–534. https://doi.org/10.3109/09638288.2016.1153160 (2017).
44. Cruvinel Júnior, R. H. et al. Foot-ankle functional outcomes of using the diabetic foot guidance system (SOPeD) for people with diabetic neuropathy: A feasibility study for the single-blind randomized controlled FOotCAre (FOCA) trial I. *Pilot Feasibility Stud.* **7**(1). https://doi.org/10.1186/s40814-021-00826-y (2021).
45. Suryani, M., Samekto, W., Heri-Nugroho, Susanto, H. & Dwiantoro, L. Effect of foot-ankle flexibility and resistance exercise in the secondary prevention of plantar foot diabetic ulcer. *J. Diabetes Complications* **35**(9). https://doi.org/10.1016/j.jdiacomp.2021.107968 (2021).
46. Kanchanasamut, W. & Pensri, P. Effects of weight-bearing exercise on a mini-trampoline on foot mobility, plantar pressure and sensation of diabetic neuropathic feet; a preliminary study. *Diabet. Foot Ankle.* **8**(1). https://doi.org/10.1080/2000625X.2017.1287239 (2017).
47. Chang, C. F., Chang, C. C., Hwang, S. L. & Chen, M. Y. Effects of buerger exercise combined health-promoting program on peripheral neurovasculopathy among community residents at high risk for diabetic foot ulceration. *Worldviews Evid. Based Nurs.* **12**(3), 145–153. https://doi.org/10.1111/wvn.12091 (2015).
48. Tesfaye, S. et al. Prevalence of diabetic peripheral neuropathy and its relation to glycaemic control and potential risk factors: The EURODIAB IDDM complications Study. *Diabetologia.* **39**(11), 1377–1384. https://doi.org/10.1007/s001250050586 (1996).
49. Oyibo, S. O., Prasad, Y. D., Jackson, N. J., Jude, E. B. & Boulton, A. J. The relationship between blood glucose excursions and painful diabetic peripheral neuropathy: A pilot study. *Diabet. Med.* **10**, 870–873. https://doi.org/10.1046/j.1464-5491.2002.00801.x (2002).
50. Lavery, L. A., Armstrong, D. G., Vela, S. A., Quebedeaux, T. L. & Fleischli, J. G. *Practical Criteria for Screening Patients at High Risk for Diabetic Foot Ulceration*. https://jamanetwork.com/.
51. Veves, A., Murray, H. J., Young, M. J. & Boulton, A. J. M. *The Risk of Foot Ulceration in Diabetic Patients with High Foot Pressure: A Prospective Study* Vol 35 (Springer, 1992).
52. Frykberg, R. G. Diabetic foot ulcers: Current concepts. *J. Foot Ankle Surg.* **37**(5), 440–446. https://doi.org/10.1016/S1067-2516(98)80055-0 (1998).
53. Abbott, C. A. et al. Site-specific, critical threshold barefoot peak plantar pressure associated with diabetic foot ulcer history: a Novel approach to determine DFU risk in the clinical setting. *Medicina (Lithuania).* **58**(2). https://doi.org/10.3390/medicina58020166 (2022).
54. Alam, U. et al. Diabetic Neuropathy and Gait: A review. *Diabetes Therapy* **8**(6), 1253–1264. https://doi.org/10.1007/s13300-017-0295-y (2017).
55. Fernando, D. J. S., Masson, E. A., Veves, A. & Boulton, A. J. M. *Relationship of Limited Joint Mobility to Abnormal Foot Pressures and Diabetic Foot Ulceration*. http://diabetesjournals.org/care/article-pdf/14/1/8/440238/14-1-8.pdf
56. Martinelli, A. R. et al. Muscle strength and ankle mobility for the gait parameters in diabetic neuropathies. *Foot* **23**(1), 17–21. https://doi.org/10.1016/j.foot.2012.11.001 (2013).
57. Mueller, M. J., Minor, S. D., Sahrmann, S., a, Schaaf, J. & Strube, M. J. Differences in the gait characteristics of patients with diabetes and peripheral neuropathy compared with age-matched controls. *Phys Ther.* **74**(4), 299–308. https://doi.org/10.1016/S0966-6362(98)00015-0 (1994). (**discussion 309–313**).
58. Hernández-Guillén, D. et al. Association ankle function and balance in community-dwelling older adults. *PLoS One* **16**(3 March). https://doi.org/10.1371/journal.pone.0247885 (2021).

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Author contributions

All authors have made substantial contributions to all sections of the manuscript, the conception and design of the study, the acquisition of data, and analysis and interpretation of data, drafting the article or revising it critically for important intellectual content, and final approval of the version to be submitted. JSSPF was responsible for the study design, interpretation of the data, writing the report, submission of the manuscript and management. RHCJr is responsible for the study design, data collection, analysis, and interpretation, writing the report and submission of the manuscript. ESQ and RLM are responsible for the study design, data collection, review and editing. ICNS is responsible for the study design, fundings for the study, interpretation of the data, writing the report and submission of the manuscript. JLV, CG and MD contributed to drafting and revising the manuscript. All authors read, provided feedback and approved the final manuscript. No professional writers have been involved.

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Competing interests

The authors declare no competing interests.

Additional information

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