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The Effects of a 12-Week-Long Sand Exercise Training Program on Neuromechanical and Functional Parameters in Type II Diabetic Patients with Neuropathy

Thesis of Doctoral (Ph.D.) Dissertation

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1. Introduction

Currently, more than 500 million people are affected by diabetes, accounting for over 10.5% of the adult population worldwide. Various types of neuropathies, the most common late complications of diabetes, can affect approximately up to 50% of patients. Among these, diabetic peripheral neuropathy (DPN) is the most prevalent (Tesfaye and Boulton, 2009) The increasing prevalence of obesity and the consequent rise in type 2 diabetes incidence could double these numbers by 2030. The occurrence of DPN may also increase with prolonged duration of diabetes and inadequate glycemic control (Martin et al., 2006). In the case of DPN, the lower extremities are most affected by motor dysfunction, which affects diabetic patients.

Impact of DPN on the Musculoskeletal System

In DPN patients, muscle strength is reduced, affecting the plantar and dorsiflexor muscles of the ankle under both dynamic and static conditions. Muscle dysfunction in the lower leg may result from atrophy of the calf and foot muscles. DPN patients exhibit over 10% lower torque values in plantar and dorsiflexor directions during maximal isometric exertion measured by a dynamometer compared to healthy controls (Andersen et al., 2004).

Reduced joint mobility is another common long-term consequence of diabetes that affects DPN patients, mainly due to soft tissue alterations. As a result of tissue changes, ankle and foot joints exhibit greater contracture, hindering proper mobility and adequate rolling of the foot (Salsich et al., 2000).

DPN leads to increased body instability due to decreased peripheral nerve function, especially in unexpected unstable conditions. In their case, the time to perform the Timed Up and Go (TUG) test is longer compared to non-DPN patients (Riandini et al., 2018). This is attributed to decreased walking speed, step length, and longer step duration.

The collective motor and functional limitations caused by DPN lead to postural instability and changes in gait kinetics, increasing the risk of falls and their life-threatening consequences (Rojhani et al., 2017). Complications affecting the diabetic foot generally follow the course of peripheral neuropathy, which may lead to lower extremity amputation following ulceration development. These progressively occurring limitations significantly impair patients' daily activities and quality of life.

Treatment options for DPN

The first step involves intensive blood glucose control and effective lifestyle changes. Additionally, pharmacological therapies and non-pharmacological interventions form the basis of DPN treatment (Quiroz-Aldave et al., 2023). Recommendations for pharmacological treatment of DPN have not yet reached consensus, often leading to mismanagement of DPN patients. Another challenge is the numerous side effects of medications used in treatment, which not only impose further financial burdens on patients but may also worsen their quality of life. Non-pharmacological therapies include electrotherapy, acupuncture, moxibustion, and antioxidant treatments, primarily aimed at pain relief (Khdour, 2020).

It is important to explore therapeutic options targeting other negative effects of DPN on the body's motor function. Research on the effects of resistance training interventions yields conflicting results. A study employing 12 weeks of resistance training failed to increase peak torque in plantar and dorsiflexion at the ankle joint (Tuttle et al., 2012). Another 12-week intervention using resistance exercises did not improve dorsiflexion force but only in plantar flexion (Sartor et al., 2014).

Increased stiffness of the calf muscles in DPN can abnormally affect the cooperation of agonist-antagonist muscles. Measuring antagonist muscle coactivation is a common method to test the efficacy of neural adaptation and agonist contraction induced by physical activity, but such information is scarce in DPN.

Studies targeting ankle joint range of motion (ROM) and balance improvement also yield contradictory results. No improvements were found after home-based exercises, whereas significant improvements were observed following programs led and supervised by professionals (Monteiro et al., 2022).

Different (solid and soft) surface training

In addition to the favorable effects of resistance and balance exercises demonstrated in some studies, adverse effects on DPN patients must be considered. For instance, in the presence of limited joint mobility, the foot may not provide adequate shock absorption on solid ground and may lose the ability to maintain normal plantar pressure (Andersen, 1999). Therefore, the properties of surfaces used for exercises must be considered. The American Diabetes Association (ADA) has issued precautions regarding physical activity, as certain activities are not safe for individuals with neuropathy (American Diabetes Assocation, 2022). Acute injuries in DPN patients, such as calf muscle strain during treadmill walking, Achilles tendon pain after exercise on solid surfaces, or muscle soreness, have been reported (Sartor et al., 2014). To avoid such negative effects, exercising on soft surfaces may be an alternative for DPN patients, providing resistance and an unstable surface. The shock-absorbing capacity of sand and the sliding of sand grains against each other during muscle contraction may allow for increased contraction time, making the muscles more active. Additionally, the displacement in the ankle joint due to placing greater body mass on different parts of the foot creates a stretching effect, although this has not been proven. Therefore, sand-based training may facilitate favorable strength, balance, and functional changes in DPN patients while reducing the risk of injuries, although this hypothesis has not been investigated.

2. Problem statement and objectives

Despite the prevalence of functional limitations resulting from decreased motor abilities in DPN patients, the number of studies on pharmacological treatments far exceeds those utilizing physical activity, which plays an essential role in disease management. Data related to physical activity in DPN suggest that home-based exercises aimed at reducing treatment costs may not contribute to improving the condition of DPN patients; hence, professional supervision is a crucial element for improving strength, joint range of motion, and balance. Another problem during exercises is the potential negative impact on soft tissue structures when performing exercises on solid ground.

One of the aims of our research is to investigate the relationships between anthropometric and biomechanical factors influencing motor dysfunction contributing to daily activities. Due to possible issues with various solid surfaces during exercise, safer exercise modes should be developed to improve foot function while avoiding adverse effects in these patients. Besides the lower risk of injury, sand exercises may potentially improve foot function through combined, simultaneous strengthening, balancing, and stretching stimuli. Therefore, another goal was to examine the effects of a 12-week sand training program following a 12-week control period on the lower limb function of DPN patients. Furthermore, we investigated the impact of the quantitative biomechanical and functional results on the daily physical and sports activities of DPN patients.

3. Hypotheses

Based on the preliminary investigations of our research, we have formulated the following hypotheses.

Hypothesis 1 (H1): We hypothesize that anthropometric (age, height, body mass, BMI, body fat percentage, skeletal muscle mass) and biomechanical (sagittal plane joint range of motion at the ankle joint, static maximal force production capacity in plantar and dorsiflexion, relative strength) parameters influence the walking and balancing ability that determine everyday activities.

Hypothesis 2 (H2): We hypothesize that contrary to the 12-week control period, changes occur in static maximal force production capacity in plantar and dorsiflexion, agonist-antagonist muscle coactivation, balance, sagittal plane ankle joint range of motion parameters, and walking ability in patients with DPN during the 12-week intervention.

Hypothesis 3 (H3): We hypothesize that the subjectively assessed performance in movement forms associated with everyday life and sports will increase in patients. Furthermore, we assume that the extent of improvement in subjectively assessed performance correlates with the magnitude of changes in quantitative biomechanical and functional values.

4. Materials and Methods

In the study, 11 DPN patients (n = 4 females, 7 males) participated (age= 64,9 ± 9,6 years; body mass = 99,2 ± 21,7 kg; height = 173,5 ± 8,4 cm) (ethical approval: 5812.-PTE2016). Information regarding the patients' health status and physical abilities was obtained through verbal interviews, and inclusion and exclusion criteria were determined. The study participants provided written consent in accordance with the Helsinki Declaration after receiving verbal and written explanations of the experimental protocol and its potential risks.

Our research consisted of a control (12 weeks) and an intervention (12 weeks) period. DPN patients served as their own controls (Macaulay et al., 2022), and all tests associated with the protocol were conducted at three time points: before the control period (1st test), at the end of the control period, which marked the beginning of the intervention period (2nd test), and at the end of the intervention period (3rd test). During the control period, participants continued their usual medical care without additional exercises. In the intervention period, in addition to medical care, participants performed supervised ankle exercises three times a week. Study participants were required to appear for laboratory tests four times; the first occasion was for familiarization, during which they became acquainted with the test tasks, and the actual measurements were conducted on the second through fourth occasions. Each test day commenced with the completion of the Foot and Ankle Ability Measure (FAAM) test, followed by determination of body composition, strength tests, measurement of plantar and dorsiflexion torque of the ankle, and measurement of electromyographic activity (EMG) of the tibialis anterior (TA), medial and lateral gastrocnemius (MG, LG) muscles. Subsequently, ankle joint range of motion in the sagittal plane was examined, followed by measurement of functional tests (balance and TUG test) duration. Prior to strength tests using a dynamometer, a 5-minute warm-up on a stationary bicycle was administered. Statistical analyses were conducted after the

3rd test. The intervention period was initiated by 9 study participants, with an additional two dropping out, resulting in a total of 7 patients completing the research investigations.

The training sessions were conducted three times a week for 12 weeks in groups on a heated, 4x5 m, 30 cm deep sandy surface, where participants worked barefoot. Each session included a low-intensity dynamic warm-up (5 minutes) and lower leg- and ankle-specific exercises (25 minutes). The duration of sessions gradually increased every four weeks depending on the number, complexity, and repetitions of exercises.

5. Results

Results necessary for testing the H1 hypothesis

According to our measurements, we found positive correlations among several anthropometric parameters, such as height with skeletal muscle mass ($p = 0.000$), body mass with BMI and skeletal muscle mass ($p = 0.000$, $p = 0.004$), and BMI with body fat percentage ($p = 0.004$).

Among anthropometric and biomechanical parameters, height, body mass, and skeletal muscle mass showed significant positive correlations with the strength of dorsiflexor muscles ($p = 0.010$, $p = 0.029$, $p = 0.002$), and skeletal muscle mass also positively correlated with maximal isometric force production in dorsiflexion (M_{DF}) ($p = 0.048$).

Regarding biomechanical parameters, we found significant positive correlations for peak torque during plantarflexion (M_{PF}) with other biomechanical indicators, such as M_{DF}, relative M_{PF} and relative M_{DF} ($p = 0.012$, $p = 0.001$, $p = 0.002$) and M_{DF} also showed a positive correlation with relative M_{DF} ($p = 0.000$).

Among anthropometric and functional parameters, only body mass showed a significant negative correlation with balance ($p=0.037$).

Between biomechanical and functional parameters, relative M_{PF} showed a significant correlation with balance ($p=0.034$), and both M_{PF} and relative M_{DF} correlated negatively with Time Up and Go (TUG) test performance ($p=0.023$, $p=0.041$).

Results necessary for testing the H2 hypothesis

No significant differences were found between the values measured during the control period in either parameter following the 12-week period.

From the second test to the third test, changes were observed in several parameters. Among biomechanical variables, peak static torque during plantarflexion significantly increased by 42% ($p = 0.033$), while peak static torque during dorsiflexion remained unchanged.

All EMG data during plantarflexion remained unchanged. During dorsiflexion, EMG activity of LG and MG significantly decreased by 30% (p = 0.002) and 37% (p = 0.005), respectively. TA EMG activity did not change significantly.

Among functional parameters, ankle ROM significantly increased in both plantarflexion and dorsiflexion directions by 18% (p = 0.032) and 140% (p = 0.021), respectively. In the balance test, body sway decreased by 16% (p = 0.021), and the time required to complete the TUG test also decreased by 18% (p = 0.002).

Anthropometric parameters, including body mass, body fat, and muscle mass, did not change statistically.

Results necessary for testing the H3 hypothesis

Based on the scores obtained from responses to the FAAM test items related to activities of daily living (ADL), the percentage-expressed performance levels significantly decreased by 13% from the first to the second test (p = 0.001) and increased by 33% from the second to the third test (p=0.001)

Regarding responses to items related to sports activities (SA) in the FAAM test, performance levels did not change from the first to the second test but significantly increased by 82% from the second to the third test (p = 0.001).

The level of participants' current function during usual ADL subjectively assessed significantly changed from the first to the second test and from the second to the third test. It decreased by 13% during the control period (p = 0.038) and increased by 17% during the intervention period (p = 0.001).

Subjective assessment of physical function related to SA showed no change from the first to the second test but significantly increased by 27% from the second to the third test (p = 0.021).

Furthermore, we examined whether the values of objective, measured parameters could be related to the results obtained based on participants' subjective assessments regarding changes in their physical condition. No correlation was found between objective and subjective measurements.

6. Discussion

Anthropometric and biomechanical parameters influencing walking and balancing abilities determining everyday activities in DPN

In our study, among the anthropometric parameters, we only found a correlation with balance in the case of body mass. According to the negative correlation, our results indicate that the higher the body mass, the lower the level of balancing ability.

Among the biomechanical parameters, the relative strength of the plantarflexor muscles of the ankle joint showed a significant correlation with balance. The strength of the plantarflexor muscles plays a decisive role in regulating forward sway (which is greater compared to other directions). The strong correlation between balance measurement and lower limb muscle strength indicates that these neuromuscular components are related and not independent of each other. A similar neural structure plays a role in regulating balance and lower limb muscle strength, thus performance achieved in one component can (partly) transfer to the other. Based on this, the increase in lower limb muscle strength induced by training (e.g., maximal strength of plantarflexors) may affect balance performance or vice versa.

Among the biomechanical parameters, the strength of the ankle plantarflexor muscles and the relative strength of the dorsiflexor muscles were negatively correlated with the time achieved in the TUG test. It is known that lower plantarflexor strength negatively influences step length, which in turn affects walking speed. During the gait cycle, plantarflexors control tibial rotation and assist in the forward swing of the shank in single-limb support, while dorsiflexors provide push-off from the ground and proper foot clearance.

The effect of a 12-week sand-based training on various biomechanical and functional parameters in DPN

The strength of the ankle plantarflexor muscles improved by 42%, consistent with previous research where patients participated in combined strength and balance training. In our study, we found no increase in EMG activity in any plantarflexor muscle during maximal plantarflexion isometric strength testing, indicating that intramuscular coordination was not responsible for the strength increase. Additionally, there was no change in TA activity during maximal plantarflexion isometric strength testing after the 12-week training, suggesting that the improvement in plantarflexion strength was also independent of antagonist coactivation. However, there was an increasing trend in both MG and LG EMG results after the 12-week training, indicating that the intervention duration may have been too short to achieve statistically significant changes.

One possible explanation for the increase in plantarflexor muscle strength is the inclusion of exercises in the frontal plane in addition to those in the sagittal plane, which may have enhanced coordination between muscles, involving those that move the foot sideways as synergists in plantarflexion. However, it is important to note that in our study, we did not measure the contribution of synergistic muscle activation during either plantar or dorsiflexion strength testing, which is an important limiting factor.

In our study, the level of maximal dorsiflexion strength of the ankle joint did not change during the intervention period. The lack of dorsiflexion strength increase in our participants may be attributed to the fact that torque was measured only at a 90-degree angle (neutral position). We found a 140% improvement in dorsiflexion joint range of motion, suggesting that the optimal muscle length (i.e., the length at which the muscle can exert the greatest force) may have changed, and the greatest torque during dorsiflexion occurred at other joint angles.

In our study, we found reduced EMG activity in MG and LG during maximal voluntary isometric contraction testing in dorsiflexion direction after the intervention period. However, the reduced antagonist coactivation alone was not sufficient to lead to increased agonist strength in our case. Even with body weight and resistance from sand, these stimuli did not appear sufficient to increase dorsiflexion strength. We also know that neuropathic patients are more often unable to perform heel rise compared to toe standing, indicating that sand made the exercises even more challenging in achieving proper dorsiflexion execution. At the beginning of the intervention, the ankle joints of the subjects allowed only limited movement in the dorsiflexion direction, reducing the possibility of achieving more effective strengthening effects and thus potentially inhibiting dorsiflexor strength increase. Our results suggest that greater emphasis should be placed on exercise intensity with the application of appropriate external loads.

In our study, the range of motion of the ankle joint increased in both plantar and dorsiflexion directions. We designed exercises where the legs were forced to move along the full range of motion of the ankle joint. Pulling and pushing sand forward and backward with the plantar and dorsal surfaces of the feet created passive stretching effects due to sand resistance, which may help improve ankle joint range of motion.

In our study, both bilateral static posture stability and walking speed improved after the intervention period. Although we did not examine the effectiveness of the same exercises on a solid surface in our study, previous studies have shown that balance training on unstable surfaces effectively improves balance in older adults, and this improvement occurs earlier than with balance exercises on stable surfaces. This suggests that balance exercises on unstable surfaces facilitate faster balance development.

In our study, the time required to complete the TUG test decreased after the 12-week intervention period. We placed great emphasis on strengthening and stretching the muscles around the ankle joint, applying exercises in all planes and directions. The increase in strength of the muscles surrounding the ankle joint and the mobility of the ankle joint may contribute to the improvement in walking speed, indicating that simultaneous strengthening and mobilization of the ankle joint play a significant role in achieving proper walking function.

The effect of 12 weeks of sand training on the performance level of everyday and sports-related movements in DPN

According to our results, the subjects rated their performance levels during everyday activities lower after the control period but reported higher levels of performance after the intervention period, both in everyday activities and those related to sports. Our findings are supported by a study examining the effects of four weeks of training, where subjects who showed significant improvement in measured parameters after the intervention period achieved an average of 8 to 9 points higher on the MET and ST scales compared to those who did not achieve significant improvement. However, no correlation was found between biomechanical and functional parameters and subjective performance levels, likely due to the small sample size of the participants in the study.

7. Summary of new findings

1. Body mass and the relative strength of the plantarflexor muscles of the ankle joint influences the balance ability in patients with DPN.
2. The strength of the plantarflexor muscles and the relative strength of the dorsiflexor muscles affect the walking ability in DPN patients.
3. A 12-week training on sand surfaces improved the peak torque of plantarflexor muscles and the ability of antagonist muscles to relax during dorsiflexion in DPN patients.
4. Training on sand surfaces for 12 weeks enhances the balance ability in DPN patients.
5. A 12-week training on sand surfaces increases ankle sagittal joint range of motion in both plantar and dorsiflexion and walking speed in DPN patients.
6. A 12-week training on sand surfaces improved the performance levels of everyday and sports-related activities in DPN patients.

7. Sand surface enables safe, side-effect-free, and injury-free capacity development for DPN patients.

8. References

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9. Publications and Presentations Related to the Candidate's Topic

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- **Prókai J.,** Atlasz T., Váczi M. (2024): Antropometriai, biomechanikai és funkcionális paraméterek összefüggései neuropátiával járó diabétesz mellituszban szenvedő betegekben. *Magyar Sporttudományi Szemle,* (accepted for publication)

- **Prókai J.,** Murlasits Zs., Bánhidi M., Csóka L., Gréci V., Atlasz T., Váczi M. (2023): The Effects of a 12-Week-Long Sand Exercise Training Program on Neuromechanical and Functional Parameters in Type II Diabetic Patients with Neuropathy. *International Journal of Environmental Research and Public Health,* 20 7 Paper 5413. 12 p.

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