The Effects of Range-of-Motion Therapy on the Plantar Pressures of Patients with Diabetes Mellitus

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A randomized controlled study of 19 patients with diabetes mellitus (10 men, 9 women) was undertaken to determine the effects of home exercise therapy on joint mobility and plantar pressures. Of the 19 subjects, 9 subjects performed unsupervised active and passive range-of-motion exercises of the joints in their feet. Each subject was evaluated for joint stiffness and peak plantar pressures at the beginning and conclusion of the study. After only 1 month of therapy, a statistically significant average decrease of 4.2% in peak plantar pressures was noted in the subjects performing the range-of-motion exercises. In the control group, an average increase of 4.4% in peak plantar pressures was noted. Although the joint mobility data revealed no statistically significant differences between the groups, there was a trend for a decrease in joint stiffness in the treatment group. The results of this study demonstrate that an unsupervised range-of-motion exercise program can reduce peak plantar pressures in the diabetic foot. Given that high plantar pressures have been linked to diabetic neuropathic ulceration, it may be possible to reduce the risk of such ulceration with this therapy. (J Am Podiatr Med Assoc 92(9): 483-490, 2002)

Cutaneous ulceration is one of the most serious sequelae that can occur in the diabetic foot. Unresolved, a diabetic foot ulceration may eventually lead to lower-extremity amputation.[1, 2] Insensitivity, dehydrated integument, limited joint mobility, and repetitive pressures have been suggested to contribute to dermal pathology and eventual ulceration.[3-11] This study focused on reducing limited joint mobility and the corresponding changes in peak plantar pressures in the diabetic foot.

Limited joint mobility has been found to be a common complication of diabetes mellitus. It has been reported to be present in up to 30% of children with type 1 diabetes[12, 13] and in up to 45% of adults with type 2 diabetes.[14] The etiology of limited joint mobility has been described as an increase in the nonenzymatic glycosylation of collagen that leads to a thickening of various soft-tissue structures.[15, 16] Limited joint mobility has been associated with a variety of systemic pathologies such as hypertension and peripheral neuropathy.[17] Some studies of upper

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extremity joints have suggested that the inability to approximate the palmar surfaces, or to make the "prayer" sign, demonstrates significant limited joint mobility in all joints (Fig. 1).[12, 13] It is clear that limited joint mobility constitutes a significant biomechanical abnormality when it affects the joints of the lower extremity. For example, if a reduction in flexibility were present at the first metatarsophalangeal joint during propulsion, one would expect an alteration in forefoot pressures. Indeed, the presence of limited joint motion in the foot has been shown to result in increased plantar pressures, which may lead to ulceration in the presence of comorbidities such as neuropathy.[3, 4, 18-25]

Currently, there is little information available on the treatment of high peak plantar pressures in conjunction with limited joint mobility. Studies have suggested that any treatment protocol for neuropathic ulceration must address the increased plantar pressures by off-loading weight in the area or reducing plantar pressures by another method such as combined therapy, bracing, or even surgery.[5, 6, 8, 24, 26-29] It has been determined that limited joint motion significantly increases plantar pressures in subjects with diabetes mellitus.[21, 30, 31] One preliminary study determined that several months of scheduled visits with a physical therapist trained in passive range-of-motion exercises resulted in a significant increase in the range of motion of joints in the feet of neuropathic diabetic subjects compared with a nondiabetic control group.[32] As the health-care system is already overburdened and is currently devoting $98 billion annually to diabetes care, the provision of this specialized therapy is not realistic for the 17 million diabetic patients in the United States today.[33]

Figure 1. The "prayer" sign demonstrates the inability of the patient to approximate the palmar surfaces of the hands.

The purpose of this randomized controlled study was to determine the effect of unsupervised active and passive range-of-motion exercises on plantar pressures in subjects with diabetes. The authors hypothesized that after performing these exercises, subjects would demonstrate an increase in the mobility of the joints in their feet and a decrease in peak plantar pressures.

Materials and Methods

Twenty-one diabetic subjects were referred from Northwestern University Medical Center in Chicago, Illinois. Subjects were required to have a history of diabetes mellitus and no history of pedal ulceration. Exclusion criteria included pedal amputations and arthritides. Subjects who were pregnant, who had been diagnosed with generalized osteoporosis, or who had fractures of any bones in the lower extremity were excluded. Moreover, subjects displaying gross musculoskeletal problems or significant scar tissue or calluses on the feet were excluded from the project. Participating subjects were required to be able to walk 10 m unassisted.

Subjects were assigned to either a treatment group or a control group by computer randomization. Each treatment group and control group subject agreed to follow the standard instructions given to each group and signed an informed consent form that had been approved by the university institutional review board. A single, trained investigator evaluated all subjects and collected all data to eliminate interinvestigator error. During the initial visit, the subjects received study information and instructions. Subject health status, age, sex, race, medications, type of diabetes, duration of diabetes, frequency of checking blood glucose level, last serum glucose level reading, and results of last hemoglobin A_{1c} (HbA_{1c}) examination were obtained and recorded. The following clinical findings were collected from each subject: ability to sense a 5.07 and 6.10 Semmes-Weinstein monofilament on the ten locations of the foot as described by the Gillis W. Long Hansen's Disease Institution,[34] length of time subjects were able to sense a vibrating 128-Hz tuning fork, strength of pedal pulses (dorsalis pedis and posterior tibial pulses) on a scale of 0 to 4, and cutaneous temperatures at the plantar aspect of the distal phalanx of the hallux, plantar aspect of the first metatarsophalangeal joint, and plantar aspect of the calcaneus using digital thermography.

The dominant foot was determined by asking the subject to kick a ball. The foot used was deemed dominant, and this information was recorded.

Limited joint mobility was assessed by 1) the subject's ability to demonstrate the upper-extremity "prayer" sign, 2) the extent of ankle range of motion, and 3) the extent of first metatarsophalangeal joint range of motion. Subjects demonstrating limited joint mobility due to a bony block were excluded from the study.

In order to ensure neutral positioning for the data collection, the lower extremities of each subject from both groups were examined by placing the lower extremity in a standardized jig (Fig. 2). A twin-axis digital goniometer (SG65, Biometrics Ltd, Cwmfelinfach, United Kingdom) and force transducer (BG50, Mark-10 Corp, Hicksville, New York) were used to determine joint range of motion. To measure the range of motion at both the ankle and the first metatarsophalangeal joint, the goniometer was placed across the joint's axis. In separate trials, force was applied across the plantar aspect of the metatarsal heads to measure range of motion at the ankle, and across the plantar aspect of the hallux interphalangeal joint to examine the range of motion at the first metatarsophalangeal joint (Fig. 3). In both cases, the force transducer was kept orthogonal to the joint axis. The joint rotation angles and applied force were simultaneously recorded using the LabVIEW software program and PCI-6030E analog to digital card sampling at 250 Hz (National Instruments Corp, Austin, Texas).

Plantar pedal pressures of each subject were recorded using the Musgrave Footprint System (Musgrave Systems Ltd, Llangollen, United Kingdom) (Figs. 4 and 5). Subjects were asked to walk barefoot "at a comfortable pace" and data were collected using a midgait method. Six separate trials were conducted. Each trial was required to be within 50 msec of the mean duration of the stance phase for each subject.

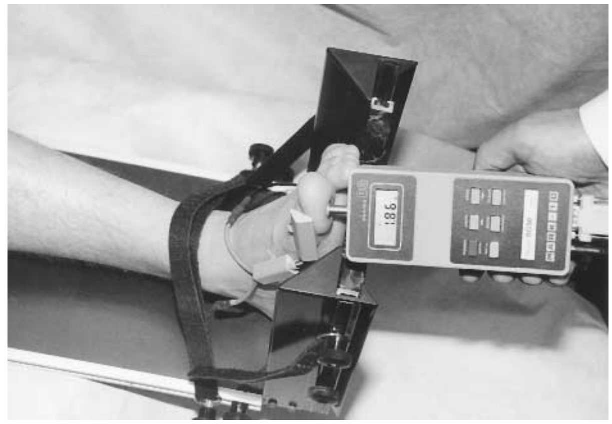

Figure 3. Setup of the apparatus used to measure stiffness of the first metatarsophalangeal joint.

The position of the plates was noted and the distance from sensor 1 of plate A to sensor 1 of plate B was used to calculate step length and walking speed.

Subjects assigned to the control group were advised to continue their prestudy lifestyle. A single investigator instructed those in the treatment group in how to perform the therapeutic exercises. The investigator demonstrated the proper way to perform the exercises, and each study subject was required to demonstrate the proper technique. Each subject received an exercise manual and a standardized videotape produced by the investigators that demonstrated the methodology for performing the exercises. The therapy program is outlined in Table 1. The treatment group subjects were instructed to perform the exercises up to three times per day. Subjects were re-

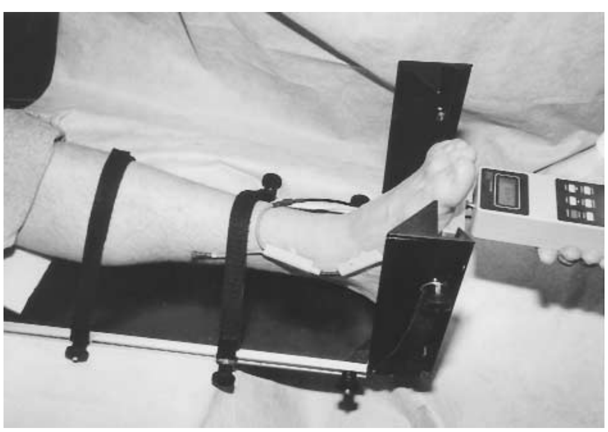

Figure 2. Setup of the apparatus used to collect ankle force and angle data.

Figure 4. Patients walked barefoot across pressure plates before and after the therapeutic intervention.

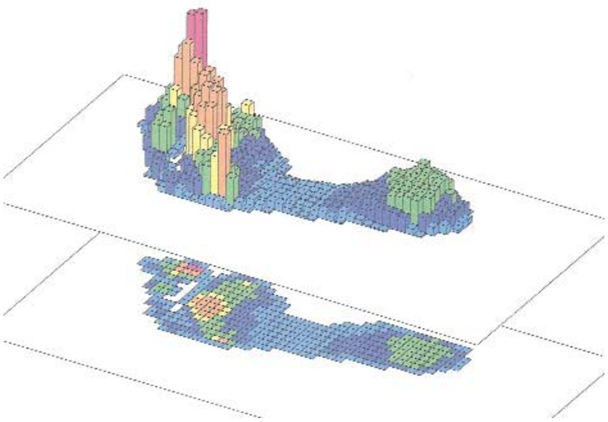

Figure 5. Representative three-dimensional plot of the plantar pressure data.

quired to document the amount of physical therapy completed each day and were contacted on a weekly basis to review any relevant findings from the previous week of exercising. All complications and perceived benefits were noted.

The second visit was scheduled approximately 4 weeks after the initial visit. At this visit, the medical history was reviewed and any changes were documented. The physical activity for the month was assessed to ensure the integrity of the study. Neurovascular parameters, plantar pressures, and joint range of motion were remeasured and recorded using the previously described methods.

Table 1. Outline of the Exercise Program

Warm-up
Draw the alphabet using the hallux, bilaterally

Stretching Exercises (5 sets each)
1. Passive dorsiflexion and plantarflexion of the metatarsophalangeal joints, holding each direction for 10 sec
2. Active dorsiflexion and plantarflexion of the metatarsophalangeal joints, holding each direction for 10 sec
3. Seated passive dorsiflexion and plantarflexion with application of partial body weight at the metatarsophalangeal joints, holding each direction for 10 sec
4. Active dorsiflexion and plantarflexion of the ankles, holding each direction for 10 sec
5. Active supination and pronation of the subtalar joints, holding each direction for 10 sec
6. Standing gastrocnemius stretch, holding for 10 sec
7. Standing soleal stretch, holding for 10 sec

Cool-down
Soft-tissue manipulation, 30 sec at the forefoot, midfoot, rearfoot, and posterior aspect of the distal one-third of the leg, bilaterally

Data Analysis

Range-of-motion data were filtered using a low-pass filter in a SigmaStat software program (SPSS Science, Chicago, Illinois). A stress-strain curve was obtained by plotting the range-of-motion data against the applied force data (Fig. 6). From these data, a simple joint stiffness value was determined by dividing the force by the corresponding displacement within the elastic region of the load-displacement curve. The elastic modulus (Young's modulus) was calculated using the ratio of stress to strain for the linear portion of the load-displacement curve. This ratio for the resultant curve was plotted on a graph and a constant modulus was observed for each joint (Fig. 7). This constant integral was evaluated at each joint, at the beginning and at the conclusion of the study, for both dominant and nondominant feet. The plantar pressures of all trials during each session were averaged, and the peak plantar pressures for 0% to 20%, 21% to 50%, 51% to 80%, and 81% to 100% of the gait cycle were obtained.

SPSS for Windows, version 10 (SPSS Science) was used for statistical analysis and data management. Weight, body-mass index, HbA_{1c}, and the average number of exercise sessions performed per day were examined for statistically significant differences between the control and treatment groups using the nonparametric Mann-Whitney test. Sex, race, domi-

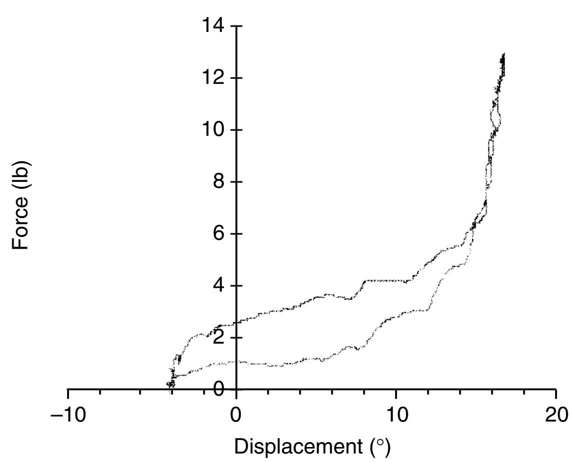

Figure 6. Force *versus* displacement plot for the right ankle of subject 13. The unevenness is probably due to the subject "assisting" in the motion and oversampling errors.

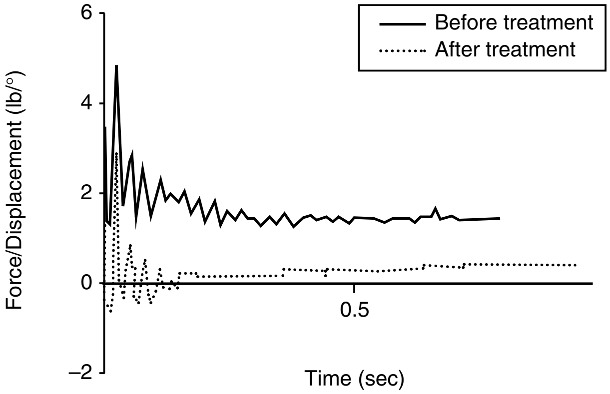

Figure 7. Plot of the elastic modulus for the right ankle joint of subject 8. The initial part of the graph represents the nonlinear portion of the stress-strain curve. Note how the plot settles to a near constant variable representing Young's modulus in the linear portion of the stress-strain curve.

nant foot, type of diabetes, and positive "prayer" sign were examined for statistically significant differences between the groups using Fisher's exact test. Pooled-variance and separate-variance *t*-tests were used to determine any statistically significant differences with regard to age, duration of diabetes, and days between study sessions. The nonparametric Friedman test was performed separately for each group to investigate differences between pretreatment and post-treatment measures for non-nominal variables that did not have statistically normal distributions such as grades for pedal pulses, Semmes-Weinstein measurements, and Young's modulus. For variables with statistically normal distributions—plantar pressure, cutaneous temperature, and vibration sensation—three-factor repeated-measures analysis of variance (ANOVA) was performed, with the within-subjects factor time (pretreatment and post-treatment) and two between-subjects factors, group (control and treatment group) and sex (women and men). Data for the dominant and nondominant feet were analyzed separately using Friedman tests and ANOVAs.

Results

Nine subjects completed the range-of-motion therapy program, with two lost to follow-up. Ten control subjects completed the study. There were no statistically significant differences between the treatment and control groups with regard to age, sex, duration of diabetes, type of diabetes, HbA_{1c} scores, body-mass index, weight, time between initial and concluding visits, ability to perform the "prayer" sign, ability to sense vibration, or ability to detect the Semmes-Weinstein monofilament (5.07 and 6.10).

Joint stiffness as determined by Young's modulus showed a trend for a decrease in stiffness in the treatment group, especially in the dominant foot. A stiffer joint requires greater force for a corresponding displacement; thus the slope of the curve would be higher. As the patients gained more flexibility, the joint would be more lax, and less force would produce more motion; thus there would be a reduction in the slope of the curve and therefore in the elastic modulus. There appeared to be a corresponding trend for increased stiffness in the control subjects (Figs. 8 and 9); however, the difference was not statistically significant ($P < .05$). Further investigation is required.

Peak plantar pressures decreased an average of 4.2% for each period of the gait cycle in the treatment group, while they increased an average of 4.4% for each period of the gait cycle in the control group. The results of each period are shown in Figures 10 through 13. There was a statistically significant difference ($P = .024$) between the control and treatment groups during 0% to 20% of the gait cycle for the dominant foot. Statistical significance ($P = .049$) was also reached during 81% to 100% of the gait cycle for the nondominant foot.

Three treatment subjects felt more flexibility in their feet, and one subject described her Achilles tendon as being "looser." Three treatment subjects described the exercises as feeling good. Two treatment subjects felt that the exercise program demanded too much time per day. One treatment subject felt sore after the first day of exercises, and two subjects said they would continue the exercise program on conclusion of the study.

Discussion

The physiologic manifestations of diabetes are extremely variable and can be influenced by many factors. No statistically significant differences in terms of patient demographics were noted between the control and treatment groups in this study. There were no statistically significant differences in cutaneous temperature within and between groups at onset and conclusion of the study. It is therefore unlikely that temperature affected the elasticity of the soft tissues during data collection. It is also unlikely that changes in neurologic status contributed to alterations in pressure and joint stiffness, as the neurologic tests performed on the subjects showed no statistically significant differences within or between study groups

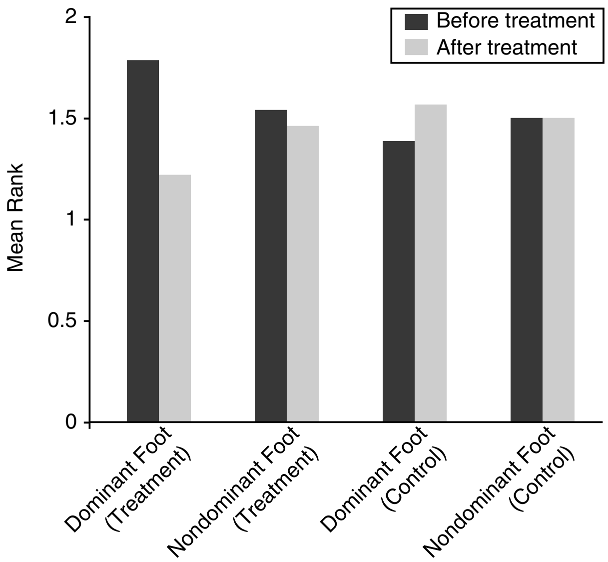

Figure 8. Ankle joint stiffness (elastic modulus). Note the large reduction in stiffness after treatment for the dominant foot and the increase in stiffness for the control group.

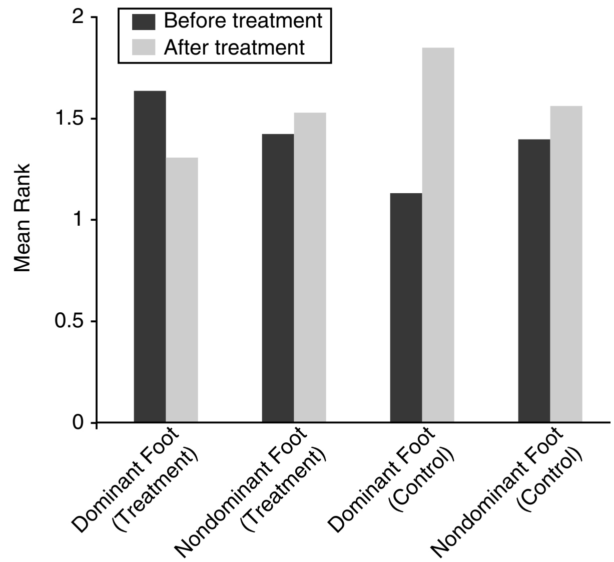

Figure 9. First metatarsophalangeal joint stiffness (elastic modulus). As for the ankle joint, the dominant foot demonstrated the greatest differences between the treatment and control groups.

between observations. It may have been possible to use a more sensitive neurologic test such as two-point discrimination with pressure transducers, but the authors believe that the length of time a subject can sense a vibrating 128-Hz tuning fork is a very sensitive and reliable indicator of the level of neuropathy.

The flexibility data showed a trend for an increase in flexibility at the first metatarsophalangeal joint and ankle joint after performing this exercise program. These data were inconclusive because the dif-

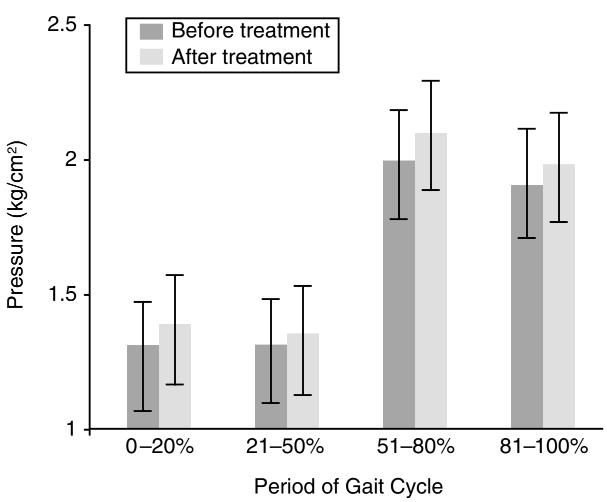

Figure 10. Dominant foot plantar pressures in the control group. Note the increase in pressure after 1 month, with the greatest pressures during the propulsive phases of the gait cycle.

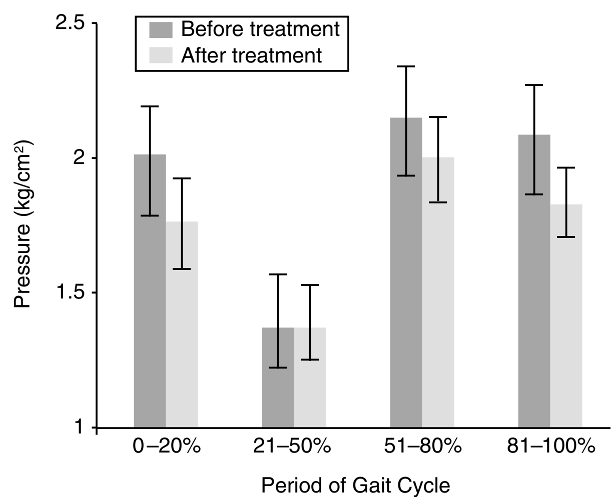

Figure 11. Dominant foot plantar pressures in the treatment group. The greatest changes occurred at the initial loading response and during the propulsive phases of the gait cycle. This may be due to the fact that the exercises focused on the ankle and first metatarsophalangeal joints, which may be more active during these periods.

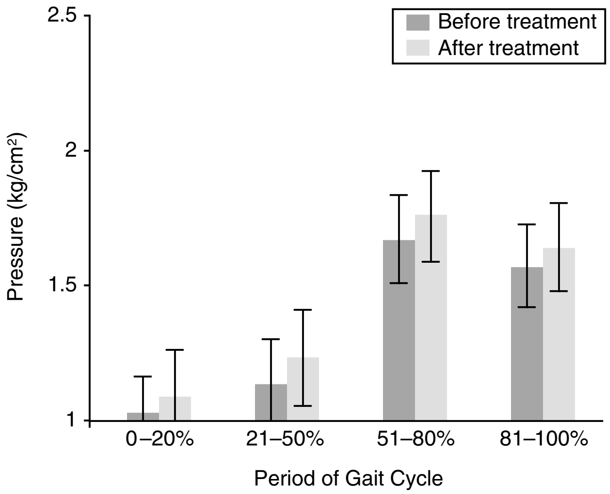

Figure 12. Nondominant foot plantar pressures in the control group. Note the lower heel-strike pressures in the nondominant foot as compared with the dominant foot (Fig. 10).

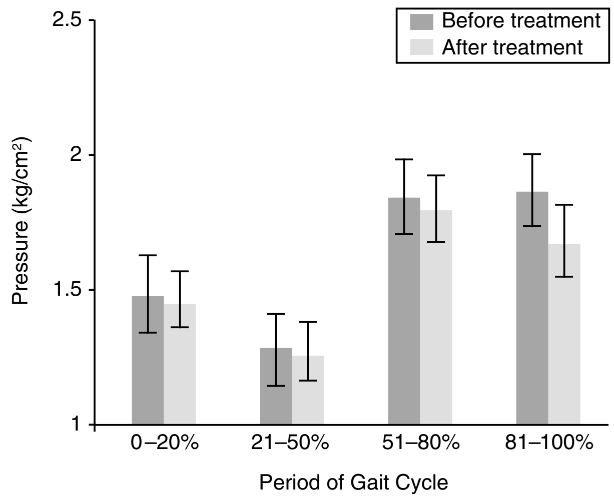

Figure 13. Nondominant foot plantar pressures in the treatment group. The change in the nondominant foot was not as large as in the dominant foot (Fig. 11).

ference did not reach statistical significance; however, a larger sample size may have resulted in statistical significance. The decision to break the subjects down into dominant and nondominant feet instead of combining right and left feet into one group effectively reduced the data set. The authors feel strongly that all lower-extremity data should be broken down into dominant and nondominant sets rather than broken down into right feet and left feet or, worse yet, combining the data into a data set comprising both right and left feet on the assumption that both sides behave similarly. The authors' data indicate that the dominant foot responds faster and to a greater extent to therapeutic intervention than the nondominant foot (Figs. 10–13).

Another possible limitation of these data was an error in collection due to oversampling. The joint was moved at a frequency of close to 1 Hz. An appropriate sampling rate would have been ten times the naturally occurring frequency (Nyquist frequency), or 10 Hz in this case. An error during the initial programming in LabVIEW set the sampling rate to 250 Hz, leading to oversampling. This produced large amounts of data that had to be excessively smoothed to produce a usable data set.

The plantar pressure data indicate that subjects who perform a relatively simple active and passive range-of-motion exercise program for 1 month can significantly lower their peak plantar pressures. Statistical significance was not reached at every period of the gait cycle for dominant and nondominant feet. It should be noted that there were not significant reductions in plantar pressures during the middle period of the gait cycle (21–80%). The greatest change in plantar pressure was observed from heel contact (0%) to 20% and again at terminal stance from 81% to toe-off (100%). It is possible that the joints of the foot that the therapy focused on are utilized to a greater extent during these parts of the gait cycle, resulting in a greater influence on plantar pressures during these periods (Figs. 11 and 13). Alternatively, the variation may be due to the small sample size of the study. It is important to note that the study consisted of only 1 month of exercise and that, with a greater study duration, a more significant reduction in pressure might have been achieved. Another limiting factor of this study was the health of this diabetic population, whose illness was well controlled. This population was expressly chosen by the authors in an attempt to avoid any harm to the subjects from the exercise program. A population whose diabetes was less well controlled and that was more affected by limited joint mobility might demonstrate a greater reduction in peak plantar pressures with the use of this exercise program.

Future studies should address the limitations of this study and focus on creating an optimal exercise program to increase joint mobility and reduce plantar pressures in diabetic subjects.

Conclusion

The results of this study demonstrate that an unsupervised range-of-motion exercise program can significantly reduce peak plantar pressures in diabetic subjects within a relatively short period of time. It is possible that a simple home exercise program for diabetic patients could result in fewer ulcerations of the plantar aspect of the foot. Given the complex nature of this disease and the enormous cost associated with current treatments, clinicians and patients alike should be searching out such therapies and be willing to implement them to assist in the treatment of diabetes mellitus.

Acknowledgment. David S. Oyer, MD, of Northwestern University in Chicago, Illinois, for his project protocol suggestions and his participation in the recruitment of subjects for the study; Julie-Kate Wade-Webster, DPM, for her early work; and Jim West for assistance in production of the standardized exercise video.

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