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Jarom Bridges

Brigham Young University - Provo

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The Effect of Foot Strengthening Exercise on Dynamic Function
of the Medial Longitudinal Arch in Runners:
A Preliminary Report

Jarom Bridges

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

A. Wayne Johnson, Chair
Sarah T. Ridge
J. William Myrer
Iain Hunter

Department of Exercise Sciences
Brigham Young University
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ABSTRACT

The Effect of Foot Strengthening Exercise on Dynamic Function of the Medial Longitudinal Arch in Runners: A Preliminary Report

Jarom Bridges
Department of Exercise Sciences, BYU
Master of Science

Therapeutic exercise has previously been shown to alter the static height of the medial longitudinal arch (MLA). It is still unknown, however, if these effects carry over into dynamic activities.

PURPOSE: To determine if an 8-week foot strengthening exercise program increases static arch height and reduces vertical deformation of the MLA during mid-stance in running.

METHODS: Thirty-four recreational runners (17 males, 17 females) have completed this ongoing study (age 24.06 ± 3.61 years, body mass 68.63 ± 12.95 kg, and height 173.34 ± 9.54 cm). To date, 22 subjects have been assigned to the control group (8 weeks of normal running) and 12 to the foot strengthening group (8 weeks of foot strengthening, along with normal running). Static arch height (SAH) and dynamic arch drop (DAD) were measured at baseline and following the 8-week intervention using Vicon motion analysis. Reflective markers were placed on the proximal and distal ends of the 1st and 5th metatarsals. These 4 markers were recorded in static double leg stance to estimate SAH, and in single leg mid-stance to give a measure of DAD during treadmill running at a self-selected pace. Ten-second trials were recorded at minutes 3 and 4 during running and DAD was evaluated for right and left feet by comparing arch height in mid-stance to the SAH. Following the intervention, data for SAH and DAD were compared across time points and statistical analysis performed to identify differences in the amount of change in SAH and DAD between groups.

RESULTS: There was no difference noted in DAD between the groups as a whole, but the change in DAD from baseline to the end of week 8 was statistically significant for those in the foot strengthening group with an initial DAD of ≥ 3.80 mm ($p < .028$). There was also a statistically significant increase in SAH in the foot strengthening group compared to the control group ($p = .013$).

CONCLUSIONS: These preliminary data suggest that the foot strengthening intervention was effective in increasing SAH compared to the control group. The intervention was most effective at decreasing DAD in those with the largest amount of DAD at baseline. At this time it is unknown whether this decrease in arch drop is associated with performance benefits or decreased injury risk in the recreational runner, and further research is needed to determine the clinical significance of these findings.

Keywords: therapeutic exercise, biomechanics, arch height

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Table of Contents

| | |
|----------------------------|-----|
| Title Page | i |
| Abstract | ii |
| Acknowledgments | iii |
| Table of Contents | iv |
| List of Tables | v |
| List of Figures | vi |
| Introduction | 1 |
| Methods | 3 |
| Subjects | 3 |
| Procedures | 4 |
| Statistical Analysis | 6 |
| Results | 6 |
| Discussion | 7 |
| Conclusions | 11 |
| References | 13 |
| Tables | 15 |
| Figures | 16 |
| Appendix A | 20 |

List of Tables

Table

1. Average measures pre- and post-intervention.....15

List of Figures

Figure

1. Dropouts from control and foot strengthening groups.....16
2. Vicon Oxford Foot Model marker placement.....17
3. Markers used for calculation of arch height18
4. Change in arch drop relative to baseline arch drop.....19

INTRODUCTION

Distance running is a common fitness practice in the United States and throughout the world. Injuries in the running population are also very common, the incidence of which has been determined to be between 30–79%, with an estimated 7–59 injuries occurring for every 1000 hours of running.² There appears to be an association between the development of injury in runners and the height of the medial longitudinal arch, both in those with excessively low or excessively high arches.^{3,8,10,13-14,19,23} The foot, as the only body part which contacts the ground in upright running, plays a key role in the dispersion of ground reaction force.⁶ The medial longitudinal arch of the foot is particularly important in that it has a spring-like quality, such that it can absorb strain energy occurring during foot strike in running.¹¹ In those with low or flat arches, the ability to properly absorb and disperse force may be impaired, predisposing the individual to injuries throughout the kinetic chain, including plantar fasciitis, stress fracture, knee pain, and low back pain, among others.^{8,10,13-14,19}

The presence of low arches or excessive arch drop (as seen in hyperpronation and dynamic or flexible pes planus) have been associated with a number of lower extremity injuries.^{4,10,13,19} Dynamic pes planus has been linked with the development of lower extremity overuse injuries occurring during training of young, healthy US Naval recruits, most specifically the development of stress fractures.¹⁰ Knee and low back pain have been found to be equivalent in military recruits with a mild pes planus as compared to controls, but in those with moderate and severe pes planus the prevalence of knee and low back pain was twice that of controls.¹³ In runners specifically, Pohl et al¹⁹ found that those presenting with symptoms of plantar fasciitis had lower arch indexes than healthy controls, and Busseuil et al⁴ identified increased prevalence of static and dynamic foot pronation in runners suffering from overuse pathology. In those with

excessively low arches or excessive arch drop, an intervention that reduces arch drop may be expected to decrease the incidence of these injuries.

Due to the prevalence of running injuries, there has been increased interest in recent years in barefoot or minimalist shoe running as a method to improve running form and decrease the incidence of injury.^{15,21} A number of studies have found positive outcomes from minimalist running, such as muscle hypertrophy,^{1,9,16} decreased knee joint moments,¹² and decreased impact force.¹⁵ However, during the transition to minimalist running, runners are at risk for developing other injuries of the lower leg and foot.^{7,20} Ridge et al²⁰ studied the effects of a gradual transition to minimalist shoe running over a 10-week period on bone marrow edema in the foot. At the end of the 10-week period, it was found that over 50% of those performing this transition experienced significant increases in bone marrow edema, with 2 of 19 runners developing stress fractures. One cause for these injuries may be a sudden reduction of external support and cushioning provided by standard running shoes, thus requiring the support to be provided by anatomical structures such as bones, ligaments and muscles. A strengthening program performed prior to or during this transition may be helpful in reducing the incidence of injury in these individuals.

It has previously been demonstrated that therapeutic exercise alters arch drop in static standing in some populations. Mulligan et al¹⁷ studied the effects of a 4-week training program employing the short foot exercise on navicular drop, a commonly used indicator of functional arch drop. Navicular drop was calculated as the difference between navicular height in relaxed stance and navicular height measured in stance after placing the subject's foot in the subtalar neutral position. After 4 weeks of performing the prescribed exercises, subjects experienced a mean reduction in navicular drop of 1.8 mm ($p = .04$), and additional follow-up measures at 8

weeks showed a mean reduction of 2.2 mm in navicular drop ($p = .01$). While therapeutic exercise appears to be effective in altering arch drop in a static condition, it is unknown whether this effect carries over in runners in such a way as to decrease arch drop during dynamic loading. The purpose of this study was to determine if a series of therapeutic exercises designed for strengthening the foot muscles would be effective in altering static arch height and dynamic arch drop in recreational runners.

We hypothesize that the foot strengthening exercise intervention group will experience a decrease in dynamic arch drop following completion of an 8-week strengthening program compared to the control group. We expect that the same program will produce an increase in static arch height in the foot strengthening group. We also hypothesize there will be no difference in response to a strengthening program for dominant feet compared to nondominant feet.

METHODS

Subjects

To date, fifty subjects have been recruited to this study, however, 16 subjects have been lost due to dropout, mechanical failure of lab equipment, or insufficient data (see Figure 1). At this time, 34 recreational runners have completed this ongoing study (17 male, 17 female, age 24 ± 3.58 years, body mass 68.75 ± 12.77 kg, and height 173.43 ± 9.41 cm) and were included in our analysis. Subjects were recruited by means of fliers posted physically in the community and digitally on social media, as well as by word of mouth. In order to be eligible for the study, subjects had to be age 18–45 years with no history of injury to the lower extremity in the past 6 months, no more than 3 days of minimalist running (running barefoot or in “minimalist shoes” with less than an 8 mm drop) in the past 6 months, and had to be running at

least 3 times weekly for a total of 15–40 miles per week in the past 3 months.

Procedures

Once cleared for participation, subjects were assigned to either a control group (8 weeks of running only) or foot strengthening group (8 weeks of running + therapeutic exercise). To date, 22 subjects in the control group (12 male, 10 female, age 24.86 ± 4.16 yrs, height 171.33 ± 9.67 cm, weight 67.65 ± 12.95 kg) and 12 subjects in the foot strengthening group (5 male, 7 female, age 22.58 ± 1.56 yrs, height 177.02 ± 8.45 cm, weight kg) have completed the study. Subjects reported to the Human Performance Research Center (HPRC) at Brigham Young University for baseline measurements on day 0 of the 8-week intervention. Measures of height and weight were taken, and 43 reflective markers were placed on the subject according to the protocol for the Vicon Plug-in Gait + Oxford Foot Model (see Figure 2).²² In addition to numerous other values, this model provides an output of arch height, which is calculated as the vertical difference between a marker placed at the proximal dorsal aspect of the first metatarsal (P1M), and the horizontal plane created between three markers placed at the distal 1st metatarsal (D1M), the distal 5th metatarsal (D5M,) and the proximal 5th metatarsal (P5M) (see Figure 3).

Static arch height (SAH) was taken for each foot as the average arch height in a static standing trial where the subject was instructed to stand as still as possible with their feet shoulder-width apart. The subject then performed a 3-minute warm-up at a walking speed of 3 mph, followed by 5 minutes of running at a self-selected pace. Running pace was determined by the subject as the pace at which they could comfortably complete a 5-mile training run. Ten-second recordings were taken at minutes 3 and 4, and arch height was later analyzed during the midstance phase in running for both feet. Minimum arch height values during midstance were identified and compared to the SAH in static standing in order to give a measure of dynamic arch

drop (DAD).

Upon completion of baseline measurements, subjects assigned to the control group were instructed to continue their regular running regimen for the next 8 weeks. Those assigned to the foot strengthening group were provided with a schedule of therapeutic exercises to perform 5 days per week in addition to their normal running (see Index A) and were instructed in the proper performance of the first week's exercises. The exercise program used was developed at the Spaulding National Running Center (SNRC) in Cambridge, MA, and consists of 10 different exercises including towel curls, toe spread, toe squeeze, doming (aka "short-foot exercise"), doming while hopping in place, doming while hopping in a square pattern, single leg heel raises on a flat surface, single leg heel raises at the edge of a step, double leg heel raises on a flat surface and double leg heel raises at the edge of a step (see Index A).

The combination of exercises was progressively advanced from week to week as per the SNRC protocol, and subjects in the foot strengthening group reported back to the HPRC at the beginning of each week for instruction in their new exercises. Subjects were also provided with an online link they could access at home with videos demonstrating proper technique of each of the prescribed exercises.

Throughout the duration of the study, subjects reported completion of training runs and exercises each day in an online compliance form created for this purpose. For training runs, subjects reported the date, distance run, duration, and the primary type of terrain they were running on (pavement, dirt, grass, treadmill, etc). When logging exercises, subjects reported the date completed, and selected the exercises completed from a checklist. At the end of the 8-week intervention, all subjects returned to the HPRC to repeat testing for the same measures performed at baseline.

Statistical Analysis

Prior to beginning the study, a power analysis was conducted to determine the appropriate sample size based on an alpha of .05 and $\beta = .20$. The clinically important difference for DAD has yet to be determined, as measures of DAD have not previously been evaluated to our knowledge. However Mulligan et al¹⁷ previously identified a minimal detectable change for navicular drop as typically measured in static standing to be approximately 6 mm. Based on this supposition and a standard deviation in navicular drop of up to 7.1 mm as reported by Mulligan et al¹⁸ in preliminary data, it was determined that a sample size of 44 subjects (22 in each of 2 treatment groups) would be sufficient to identify a treatment effect.

Post-trial data were analyzed in SAS (Statistical Analysis System) using a mixed linear model blocking on subject in order to identify differences between the treatment and control groups in change in SAH and DAD from baseline to the end of week 8. The model was adjusted to include variables that were identified through stepwise regression as having a significant association with treatment outcomes. When a significant interaction was found, we performed a post hoc analysis, which included comparing values along the line of best fit for each group to determine where significant differences occurred. Additional analysis was also performed to identify possible differences in treatment responses between dominant and nondominant feet both within each group and between groups.

RESULTS

Sex, age, weight, height and running speed were not found to be significant covariates in the models for change in SAH and DAD. However, initial SAH was a significant covariate in the model for change in SAH, and a significant difference in change in SAH between groups was identified following the 8-week foot strengthening intervention ($p = .013$). The foot

strengthening group had an average within-group increase in SAH of .33 mm, while the control group experienced an average within-group decrease of 1.31 mm, with an overall difference between groups of 2.24 mm after the 8-week intervention. When comparing absolute change in DAD, no significant differences were found between groups at the end of the 8-week intervention ($p = .371$). However, there was a significant interaction between the initial amount of DAD and the change in DAD following the 8-week intervention, such that those with the greatest amount of DAD at baseline showed the greatest effect from the exercise intervention ($p = .005$; see Figure 4 and Table 1).

To better understand the interaction between initial DAD and group, we performed independent t-tests comparing values along respective lines of best fit for integers in the range of initial DAD values in our subject population. For subjects with an initial DAD of 3 mm, change in arch drop was not significant between groups ($p = 0.140$), but for those with an initial DAD of 4 mm the change in arch drop was significant ($p = 0.019$). As the average initial DAD of both groups combined was 3.8 mm, this value was evaluated to see if there was a significant difference between outcomes for the two groups at the average for our study population. This value and all initial DAD values ≥ 3.80 mm were identified as having significantly different changes in arch drop between groups ($p < .028$).

There were no significant differences found when comparing treatment responses between dominant and nondominant feet ($p = .192$).

DISCUSSION

The purpose of this study was to identify whether a program of therapeutic exercise designed to strengthen intrinsic and extrinsic muscles of the foot would be effective in increasing arch height in static stance and decreasing the magnitude of arch drop during running. Although

our intervention did not produce significant changes in DAD in the foot strengthening group as a whole compared to the control group, we did identify a significant interaction between baseline DAD and the change in DAD seen as a result of the 8-week intervention. In those runners in the treatment group who had a large amount of DAD at baseline (≥ 3.80 mm), an 8-week program of therapeutic exercise produced a statistically significant decrease in DAD while running. These individuals experienced an average decrease in DAD of 2.41 mm, which amounts to nearly a 50% decrease from their average baseline DAD of 5.15 mm. While the magnitude of change in arch drop needed to produce a clinically important difference is unknown, this decrease in DAD is comparable to the 2.2 mm decrease in navicular drop seen by Mulligan et al¹⁷ in static trials following completion of an exercise program.

We identified a significant difference in the change in SAH between groups following the 8-week strengthening intervention. While the average increase in SAH for the foot strengthening group was anticipated based on our initial hypotheses, the average decrease in SAH in the control group was unexpected. The trend of change in static and dynamic measures was of a similar pattern in the foot strengthening group compared to the control group. Foot strengthening subjects experienced an average increase in SAH, and an average decrease in DAD following a strengthening intervention. Conversely, the control group experienced a decrease in average SAH paired with an increase in average DAD as they continued in their normal running program.

In active populations, pes planus, hyperpronation, and DAD have previously been demonstrated to have a significant association with the development of low back pain and lower extremity overuse injuries including stress fracture, plantar fasciitis, and knee pain.^{4,10,13,19} Subjects in this study who had an excessively high initial DAD or excessively low initial SAH

may be at greater risk for these pathologies. Additionally, prevalence of these pathologies appears to increase with decreased SAH or increased DAD.¹³ Individuals in our study who had the greatest amount of DAD at baseline were those who experienced the greatest effect from our exercise intervention. If reducing DAD reduces the risk of developing injury, then our intervention may be beneficial as a method of injury prevention in these runners. Evaluation of foot mechanics should be considered an integral part of the assessment process for the recreational runner, and, where markedly excessive DAD or decreased SAH exist, therapeutic exercise may be warranted as a means of reducing that deficiency.

As a secondary analysis, we compared results between dominant and nondominant feet to identify possible differences in response to the foot strengthening intervention based on foot dominance. We suspected that the muscles of the nondominant foot might be weaker at baseline and, as such, would have more room for improvement. We also hypothesized that subjects might have improved motor control in the dominant foot compared to the nondominant foot, and as a result would perform the prescribed exercises more accurately with the dominant foot, resulting in improved benefit from those exercises. In accordance with our expectations, we did not find a significant difference in the change in DAD when comparing dominant to nondominant feet, and improvement in DAD following our exercise protocol in the subset of runners identified above appears to be effective bilaterally.

In a survey by Rothschild²¹ regarding interest levels and participation in barefoot running, the primary motivating factor for those choosing to transition to barefoot and minimalist running is to prevent future injury. Increases in strength and cross sectional area of the muscles supporting the foot have been demonstrated in those who include minimalist shoe running as a part of their training.^{1,9} In addition, the mid- to forefoot landing pattern associated with

minimalist running has been shown to decrease patellofemoral pain in some runners.⁵ This is a controversial topic, however, as even a gradual, supervised transition to minimalist running has been shown to be associated with an increase in tissue pathology as indicated by increased bone marrow edema.²⁰ The fear of injury²¹ preventing many from attempting this transition is not unfounded. However, the benefits seen from our strengthening protocol suggest that exercise interventions performed prior to a transition to minimalist running may be effective in improving dynamic control of the medial longitudinal arch and, as a result, may be a helpful component in the prevention of injuries occurring during this transition. However, this assumption needs to be tested.

Our study had a number of limitations. As this is a preliminary report, the current number of subjects included in our data is less than that indicated in our original power analysis. This may have decreased our statistical power and limited our ability to identify significant changes. Additionally, as the subject population consisted primarily of healthy, college-aged runners, the results of our intervention may not be generalizable to other age groups or those with a current or recent episode of lower extremity injury. The nature of the exercises included in our strengthening program may also have presented somewhat of a limitation, as many of these exercises were new to our subjects. We anticipated that those with greater foot dexterity might perform the exercises more accurately and, as a result, might have a greater benefit from the intervention. In order to address this, each subject in the exercise group was required to report to the HPRC at the beginning of every week to review that week's exercises. Following demonstration of the exercises by a research assistant, subjects performed each exercise under supervision with corrective feedback to assure that the exercises were performed properly. Subjects were also provided with a link to instructional videos so that they could review the

proper form of the exercise during their home exercise sessions throughout the week if needed.

Another limitation was that the use of the Vicon Oxford Foot Model to evaluate measures of arch height required that the runners perform their running trials barefoot, a condition to which these subjects were unaccustomed. As a result, running patterns during testing may not have been fully representative of the individual's typical kinematics, and it is unknown how our intervention may alter foot mechanics when running in the shod condition. This method of motion analysis also has some inherent possibilities for measurement error dependent on the accuracy of the camera system, accuracy of marker placement, and the potential for skin movement over the bony landmarks where reflective markers were placed. As the changes in our primary measures amounted to a matter of millimeters, any of the above factors relating to measurement error may have impaired our ability to detect this change with the desired level of accuracy. The measures for change in SAH may have been particularly sensitive to operator error, as accuracy of this measure was dependent upon consistency of marker placement across trials. Differences in DAD were less likely to be affected by operator error as this was a measure of excursion relative to the static positioning of that particular day. To account somewhat for possible measurement error, the technician performing baseline measures for a given individual also performed their post-intervention measures in order to improve consistency across trials.

CONCLUSIONS

While our foot strengthening exercise protocol was not effective in decreasing the amount of DAD in all recreational runners, it was found to be effective for those with the greatest amount of DAD at baseline. Based on these preliminary results, it appears that recreational runners in our study with a DAD of ≥ 3.80 mm were able to decrease DAD through performance of an 8-week program of therapeutic exercise designed to strengthen the intrinsic

and extrinsic muscles of the foot. There was also a significant difference in the change in SAH between the two groups, with the foot strengthening group experiencing an average increase in SAH compared to the control group. Whether these changes will be clinically significant as they relate to injury prevalence in recreational runners is unknown, and additional studies focusing on the occurrence of injury in the period following this type of strengthening program are still needed.

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Table 1. Average measures pre- and post-intervention.

| | Week 0 Averages (mm) | | | Week 8 Averages (mm) | | | Dynamic Arch Drop Change (mm) | Static Arch Height Change (mm) |
|--|----------------------|---------------------|-------------------|----------------------|---------------------|-------------------|-------------------------------|--------------------------------|
| | Static Arch Height | Dynamic Arch Height | Dynamic Arch Drop | Static Arch Height | Dynamic Arch Height | Dynamic Arch Drop | | |
| Controls | 14.38 ± 3.03 | 10.32 ± 4.84 | 4.06 ± 3.44 | 13.07 ± 3.47 | 9.05 ± 4.52 | 4.02 ± 3.20 | -0.04 ± 1.61 | -1.31 ± 3.75 |
| Exercise (all) | 14.99 ± 4.84 | 11.82 ± 5.25 | 3.17 ± 1.87 | 15.31 ± 3.36 | 12.71 ± 3.23 | 2.60 ± 1.76 | -0.57 ± 2.33 | .33* ± 3.65 |
| Exercise (≥ 3.8 mm initial drop) | 15.04 ± 4.51 | 9.89 ± 4.44 | 5.15 ± .92 | 14.10 ± 2.68 | 11.36 ± 3.05 | 2.74 ± 2.06 | -2.41† ± 2.28 | -.94 ± 2.72 |

*Significant difference in change in Static Arch Height between groups ($p = .013$)

†Significant group by initial Dynamic Arch Drop interaction ($p = .005$)



Figure 1. Dropouts from control and foot strengthening groups



Figure 2. Vicon Oxford Foot Model marker placement

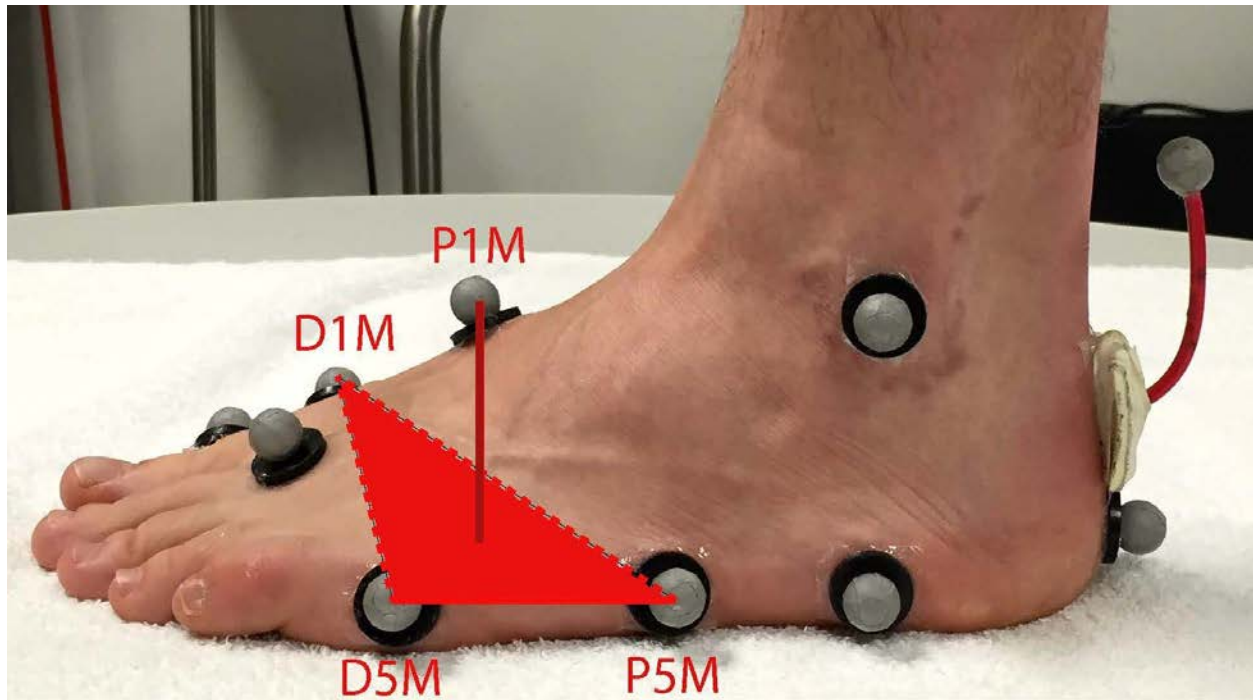


Figure 3. Markers used for calculation of arch height. Arch height was defined as the vertical difference between the plane created by the 3 markers placed at the proximal 5th metatarsal (P5M), distal 5th metatarsal (D5M), and the distal 1st metatarsal (D1M) and the single marker at the dorsal surface of the proximal 1st metatarsal (P1M).

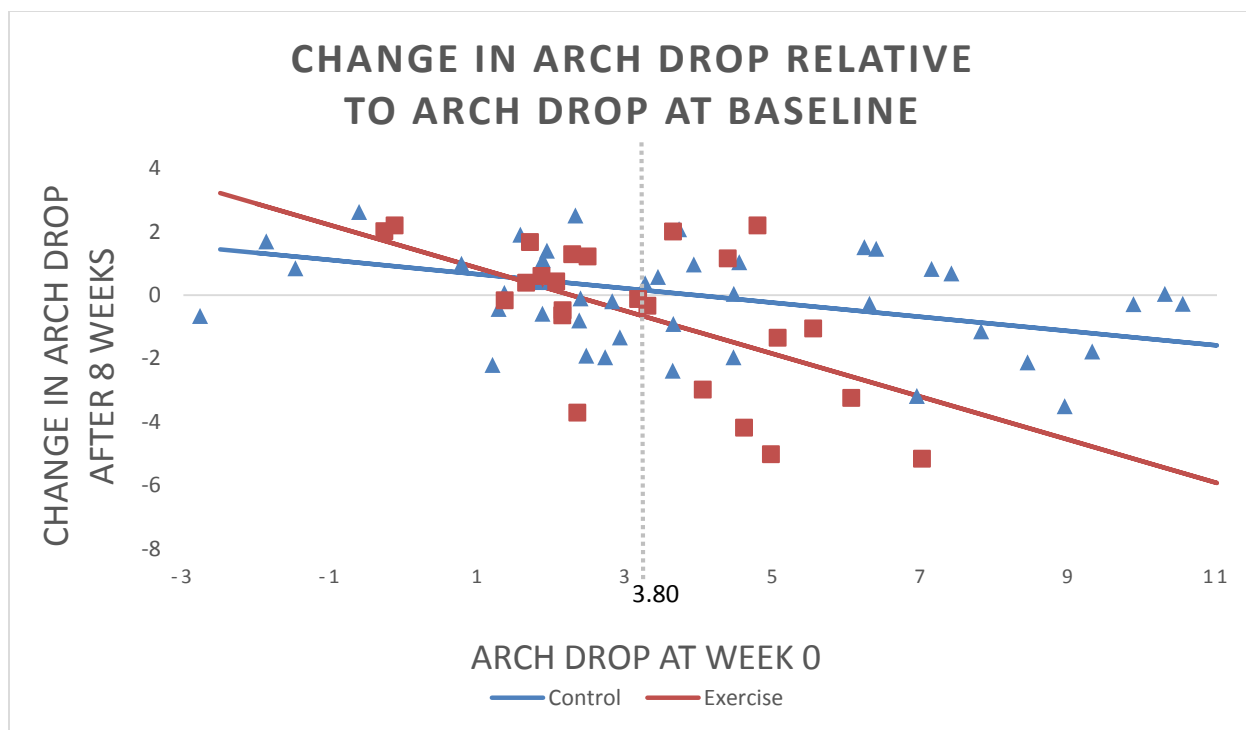


Figure 4. Change in arch drop relative to baseline arch drop

| | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 |
|---|------------------------------|------------------------------|-------------------------------|-------------------------------|------------------------------|------------------------------|--------------------------------|--------------------------------|
| Double leg heel raises on flat surface | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | | | | | | |
| Double leg heel raises off edge of step | | | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | | | | |
| Single leg heel raises on flat surface | | | | | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | | |
| Single leg heel raises off edge of step | | | | | | | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 to 3 sets of 30 |
| Towel curls | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 |
| Toe Spread | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 |
| Toe Squeeze | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 |
| Doming | 3 sets of 10 to 3 sets of 20 | 3 sets of 20 | 3 sets of 20 to 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 | 3 sets of 30 |
| Doming Hopping in place | | 3 sets of 10 | 3 sets of 20 | | | | | |
| Doming Hopping Square | | | 3 sets of 10 forward and back | 3 sets of 20 forward and back | 3 sets of 10 side to side | 3 sets of 20 side to side | 3 sets of 10 diagonal and back | 3 sets of 20 diagonal and back |

Stretch feet before & after each session. Sitting with one leg crossed over the other, point your foot & stretch toes into flexion. Hold 5 secs and repeat 5 times. Then pull your ankle back and toes back stretching your arch. Hold 5 secs and repeat 5 times. Move each of your 5 long foot bones with respect to each other.