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Honors Thesis
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Department: Health and Sport Science
Advisor: Matthew Beerse, Ph.D.
April 2023

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Abstract

The foot, functioning as a lever to support our body weight during movement, can present with structural differences like a smaller arch height resulting in pes planus or flat feet, or a higher arch height which is called pes cavus. Commonly, arch height develops with age, as infants are born with flat feet and, as they grow, their arches develop until the ages of 10-13 years. Dysfunction in the foot from abnormal arches has been shown to impact foot function and ankle stabilization, which can influence sports performance and injury risk. Dynamic balance is an important aspect of many different types of sports and can be an indicator of good performance. The purpose of this study is to inform clinicians and athletes of the effects of different arch heights on dynamic balance and muscle activation, so that correct interventions can be implemented to improve performance. This study looked at 15 healthy young adults between the ages 23-25 years. We evaluated arch height index (AHI) by scanning the volume of their foot in a single leg stance of their dominant leg. Participants then performed three trials of the Star Excursion Balance Test (SEBT) to evaluate dynamic balance. A motion capture system was used to obtain reach distance, center of pressure sway on a force plate and muscle activation of muscles of the thigh and shank. This study aims to conclude how dynamic balance is impacted by arch height looking at correlations between arch height and each of the variables. Our results will demonstrate how different muscles might activate across different arch heights. Practitioners might then implement exercises to target specific muscles that are under or over utilized.

Acknowledgements

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University *of* Dayton

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Introduction

The foot is an important and complex structure that functions daily to assist in common movements like standing, walking and running. It acts as a base of support that allows the body to maintain balance through its movements. The foot is also crucial for more dynamic sports movements such as planting, cutting, lunging, leaping and pitching. If there is a difference in the structure of the foot, specifically its arch structure, there can be biomechanical differences to how the lower extremity moves[1].

Foot arches develop with age, as children start out with flat feet and their arches develop by ages 10-13 years[2]. The height of the medial longitudinal arch of the foot can categorize someone as having pes cavus, i.e., a high arched foot, or pes planus, i.e., flat feet[1]. Often if flat feet persist into adulthood it is manifested as flexible flat feet (FFF), which means that the arch of the foot will reform when the foot is not weight bearing[3]. This can easily go unnoticed, since there is commonly no pain or other symptoms associated[2]. However, atypical arches have been shown to create dysfunction in the foot which can lead to differences in hip, knee and ankle stabilization and kinematic parameters, which affect sports performance and injury risk.

The hip, knee and ankle joints are all influenced by foot arch height[1][4][5][6][7]. For the ankle, some potential positive adaptations have been found in individuals with low arch height including improved ankle strength[1] and isometric contractions of the dorsiflexor and plantarflexor muscles[4]. However, negative adaptations have also been found, specifically at the knee joint where athletes with low arches, during walking and running showed greater knee abduction moments, which is thought to be a mechanism for patellofemoral pain[5]. Similarly, during a cutting motion it was found that there was increased knee valgus angle for low arched individuals who didn’t have arch support[6]. Adaptations have even been suggested at the hip joint, where the total work of the hip muscles during abduction and adduction was greater in individuals with flat feet[7]. Since it has been shown that there are altered kinematics in each of the joints in the lower leg that manifest with flat feet, the way we actively control our balance is likely to differ as well, which can be an important aspect to cover when creating a sports training program.

Balance is vital for sports, as well as everyday activities. Balance consists of maintaining the stability and orientation of the body within a small base of support, i.e., the feet. Small changes to the foot structure can have significant impacts on balance because of how the foot moves and shifts to correct itself. An article by Dabholkar et al. can support this, as they evaluated how dynamic balance differed in people with flat feet compared to individuals with normal arch heights[8]. To test dynamic balance they used the Star Excursion Balance Test (SEBT) and found those with flat feet performed worse in all reach directions[8]. In a similar study done by Sudhakar et al. in short distance runners they found that individuals with high arches had improved scores in the SEBT and faster sprints than those with normal and low arches[9]. Balance is not always simply measured by outcome scores, so when evaluating how arch height might affect balance performance it’s important to also look into the different strategies behind dynamic balance.

Karagiannakis et al. conducted a study on healthy individuals, which looked at the activation of different muscles in the shank that contributed to ankle stability, as well as center of pressure (CoP) displacement to see if they had any effects on the outcome of the SEBT. They found that the tibialis anterior, followed by the peroneus brevis, had the most activation throughout the test[10]. For CoP displacement they found that the anteroposterior displacement was greater than the mediolateral displacements for any direction of the SEBT[10]. Another study by Jaber et al. compared people with and without chronic ankle instability (CAI). The CAI group were found to have less reach distance and CoP measures and less muscle activation of the tibialis anterior in the anterior direction and gluteus maximus in the posterolateral direction compared to normal individuals[11]. Individuals with CAI were found to have balance deficits similar to low arched individuals[12], so we might expect to see similar activation strategies for balance in low arched individuals. This study aims to evaluate the effect of arch height on dynamic balance and muscle activation strategies in young adults. We hypothesized that the balance scores and CoP area will be negatively affected by a lower arch height. We expect muscle activation in the lower leg to have higher amplitudes in low arched individuals to assist in that lower balance control.

Methods

This study evaluated 15 healthy young adults between the ages 23-25 years. Each subject first came into the lab to have their dominant foot scanned using a volume scanner to obtain arch height index (AHI), which is the measure of their dorsum height at 50% of their foot length divided by their truncated foot length (Figure 1). The scans were taken both in a seated position and in a single leg stance. For the single leg stance, they stood on their dominant foot, with the opposite foot held off the ground. Balance support was provided, but subjects were instructed to not unload their dominant foot during the test. Using the Human Body 3D Measurement Software (MSoft, Bellevue, WA), the images were oriented and clipped in order to get the most accurate foot measurements.

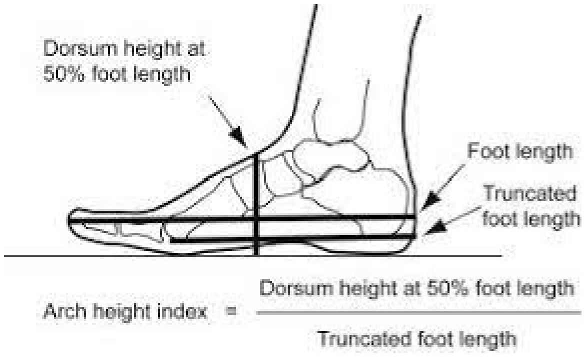

Figure 1: Values indicating how arch height index is measured and calculated.

On a different day, subjects visited the lab for balance testing. First, EMG sensors were placed on 7 different muscles of the thigh and shank on the dominant leg: rectus femoris, semitendinosus, gluteus medius, tibialis anterior, peroneus longus, gastrocnemius and soleus. The EMG sensors were placed according to SENIAM guidelines. Then reflective markers were attached to the lower body in accordance with Figure 2. A 3D motion capture system (Vicon, Denver, CO, USA) captured motion of their body and force plate (Bertec, Columbus, OH, USA) captured their CoP sway. Static standing and dynamic movement of the dominant leg were first collected in order to determine normalized values of muscle activation and movement strategies, as well as to obtain the leg length. The subjects were asked to perform the SEBT a total of three times. For the SEBT, there were

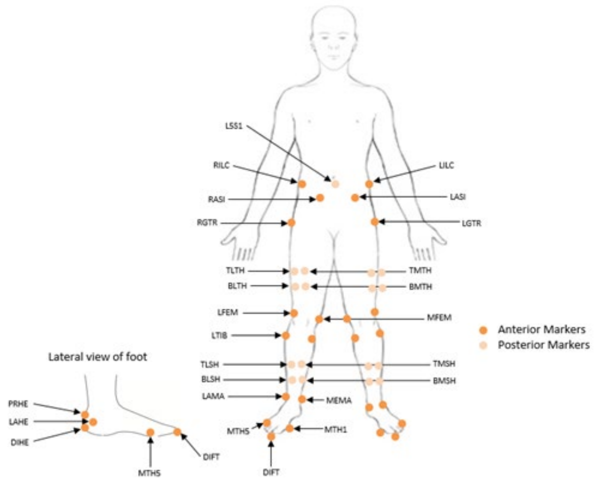

Figure 2: Motion analysis reflector marker locations.

four strips of tape placed in a star pattern with the middle being centered on a force plate (Figure 3). The subjects were instructed to stand with their dominant leg on the force plate in the center of the star and reach with their non-dominant leg in each direction as far as they could along each direction. Since all of the subjects were right leg dominant, they started with the anterior direction and then went in a counter clockwise direction ending in the anterior lateral direction. It was emphasized that during the test the subjects should come back to the center before reaching out in the next direction and avoid the foot touching the ground. est was provided in between each trial according to the subject's preference.

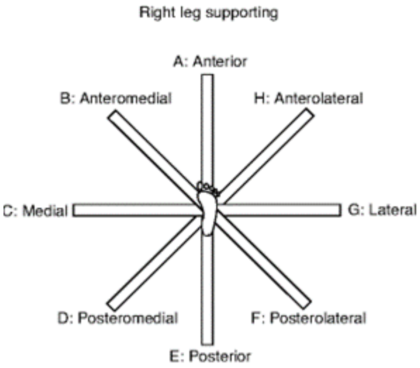

Figure 3: Star Excursion Balance Test directions for right leg stance.

Data Analysis

To calculate the AHI we added the instep height to the arc height in order to get the dorsum height at 50% of the foot's length. We then divided by the given arc length, which is the truncated foot length. The SEBT reach scores were determined by a reflective marker placed on the left big toe. The trajectory of the toe marker for each direction was used to determine the farthest reach point from the middle of the right foot, in each direction. Reach distances were normalized by subject leg length, measured as the height of the greater trochanter from the ground. An overall score was calculated as the sum of all eight reach distances. For each reach direction, we evaluated the CoP sway area and peak muscle amplitude during the reach out portion only. The 90% confidence ellipse area was determined for each reach direction. The peak muscle amplitude for each muscle was identified for each reach direction and normalized by the peak muscle amplitude during the static standing calibration trial.

Statistical Analysis

The JASP (Amsterdam, The Netherlands) software was used to conduct all of our statistical analyses. To determine if there was any difference between the sitting and single leg stance AHI a T-test was used. Correlation analyses were conducted to determine if there were any significant associations between AHI and reach scores, CoP sway area, and peak muscle amplitude. Significance was set at alpha = 0.05.

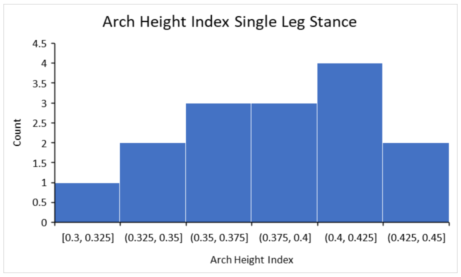

Figure 4: Histogram of single leg stance AHI data

Results

Measured AHI in a seated position compared to the single leg stance position was not significantly different (t(8)=0.966, p=0.181). Therefore, we conducted the remaining statistical analyses in the single leg stance position only. The AHI of our subjects did not cover the possible range of observations and no subjects could be classified as having flat feet. However, the AHI data did demonstrate normal distribution (Fig 4).

Table 1: Correlation statistics for AHI compared to reach distance in each direction of the SEBT.

	AHI Compared to Reach Distance								
	A	AM	M	PM	P	PL	L	AL	Total
r	-0.100	-0.024	0.109	0.299	0.202	**0.312**	**0.330**	-0.086	0.191
R^2	0.010	0.001	0.012	0.089	0.041	0.0973	0.109	0.007	0.036
p	0.722	0.933	0.699	0.279	0.471	0.258	0.230	0.760	0.496

Table 1 shows the correlation statistics for AHI compared to reach distance. AHI was not significantly correlated with any of the reach directions for the SEBT. Moderate correlations were found for the lateral (L) (r=0.330) and posterolateral (PL) (r=0.312) directions, suggesting that lower AHI is associated with a smaller reach distance.

Table 2 shows the correlation statistics for AHI compared to CoP sway. Correlations were not found between AHI and the CoP area in any of the SEBT directions with the exception of the anteromedial (AM) direction (r=-0.423), which demonstrated a moderate correlation. This suggests that those with lower AHI had a greater CoP area in that direction.

Table 2: Correlation statistics for AHI compared to CoP sway area for each direction for the SEBT.

	AHI Compared to CoP Area							
	A	AM	M	PM	P	PL	L	AL
r	0.008	**-0.423**	-0.110	0.249	-0.080	0.214	0.118	-0.077
R^2	6E-05	0.179	0.012	0.062	0.006	0.046	0.014	0.006
P	0.978	0.116	0.695	0.371	0.778	0.443	0.675	0.786

Correlations between AHI and the 7 muscle amplitudes in each direction demonstrated that the rectus femoris and semitendinosus were significantly associated with AHI (Table 3). For the rectus femoris, each direction had a moderate or high negative correlation with AHI, except for the AL direction. Also, the anterior (A) (p=0.011) and anteromedial (AM) (p=0.004) were statistically significant. For the semitendinosus, all directions had moderate to high negative correlations with AHI and were statistically significant (Table 3). Therefore, during the SEBT, low arched individuals had greater peak activation of their rectus femoris and semitendinosus compared to higher arched individuals. The gluteus medius demonstrated some moderate correlations to AHI (A r=0.417, AM r=0.382, AL r=0.329), signifying that in low arched individuals the gluteus medius had a lower peak muscle activation.

Table 3: Correlation statistics for AHI compared to each of the 7 muscles for each direction of the SEBT.

		AHI compared to muscle amplitude							
		A	AM	M	PM	P	PL	L	AL
Gastrocnemius	r	0.199	0.162	0.213	0.266	0.23	0.207	0.255	0.184
	R^2	0.040	0.026	0.045	0.071	0.053	0.043	0.065	0.034
	p	0.477	0.565	0.447	0.337	0.409	0.459	0.359	0.511
Soleus	r	0.158	0.210	0.237	0.182	0.219	0.244	0.126	-0.008
	R^2	0.025	0.044	0.056	0.033	0.048	0.060	0.016	6E-05
	p	0.574	0.453	0.359	0.515	0.432	0.380	0.654	0.977
Peroneus Longus	r	0.292	0.247	0.272	0.230	0.148	**0.385**	0.223	0.210
	R^2	0.085	0.061	0.074	0.053	0.022	0.148	0.050	0.044
	p	0.290	0.375	0.327	0.410	0.598	0.157	0.425	0.452
Tibialis Anterior	r	0.121	0.103	0.025	0.047	-0.007	-0.052	-0.024	0.059
	R^2	0.015	0.011	0.001	0.002	5E-05	0.003	0.001	0.003
	p	0.668	0.715	0.929	0.868	0.981	0.855	0.932	0.836
Rectus Femoris	r	**-0.633**	**-0.692**	**-0.404**	**-0.500**	**-0.365**	**-0.424**	**-0.468**	-0.149
	r^2	0.401	0.479	0.163	0.250	0.133	0.180	0.219	0.022
	p	**0.011**	**0.004**	0.136	0.058	0.181	0.115	0.078	0.595
Semitendinosus	r	**-0.661**	**-0.632**	**-0.589**	**-0.563**	**-0.613**	**-0.616**	**-0.568**	**0.690**
	r2	0.437	0.399	0.347	0.317	0.376	0.379	0.323	0.476
	p	**0.007**	**0.011**	**0.021**	**0.029**	**0.015**	**0.017**	**0.027**	**0.004**
Gluteus Medius	r	**0.417**	**0.382**	0.146	0.130	0.149	0.202	0.245	**0.329**
	R^2	0.174	0.146	0.021	0.017	0.022	0.041	0.060	0.108
	p	0.122	0.160	0.604	0.645	0.596	0.469	0.379	0.231

Discussion

Effect of arch height on balance performance

Our study found minimal correlations between AHI and reach distance or CoP sway area which was partially supported by our hypothesis. CoP sway areas might not have shown significant correlations due to the small fluctuations of CoP during single leg stance[13]. Our results are slightly inconsistent with other studies that have shown that those with flat feet have worse SEBT reach scores[8][9]. This is likely due to none of our subjects meeting the criteria for flat feet. However, it is interesting to note that the subjects with the lower arches in our sample demonstrated some indication of worse balance performance in specific directions. Only the PL and L directions were moderately associated with AHI, indicating worse performance for the individuals with lower arches. This could be due to the increased knee valgus that has been shown to happen with more everted feet[6][14] which might have caused limited movement in the lateral directions. The increased knee valgus might reduce hip mobility limiting how well the leg can reach laterally. Correction of the low arches with things like arch support in shoes may be able to lessen the knee valgus and allow for greater reach in the lateral directions.

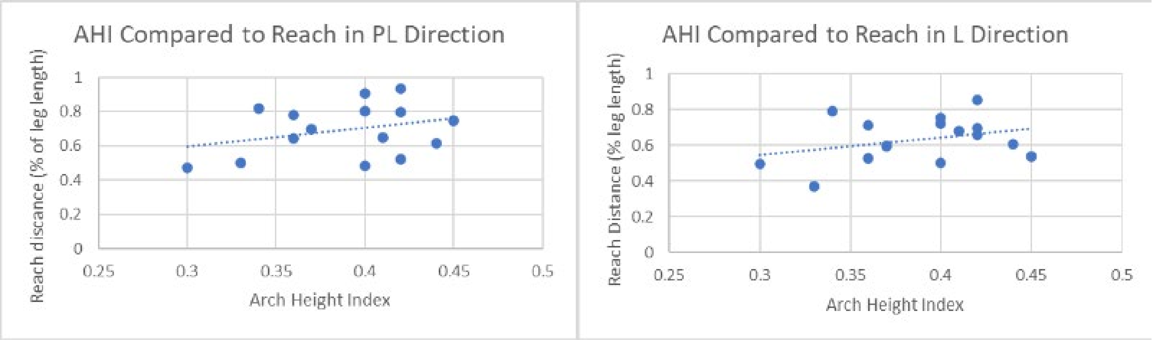

Figure 5: Linear regression plot for AHI compared to PL and L reach distance.

Arch height on muscle control strategies

We found no significant correlations between AHI and shank muscle amplitudes in any of the directions. This is slightly inconsistent with other studies that found ankle muscles to have greater muscle torques[1] and contractions of the plantarflexors and dorsiflexors in those with flat feet[4]. This could simply be due to the fact that no subjects were able to be classified as having flat feet, so the muscle amplitude may not be as affected as studies with flat feet have shown.

Both the rectus femoris and the semitendinosus showed higher peak muscle amplitudes in individuals with lower arches in most or all of the directions of the SEBT, which partially supported our hypothesis. This increased hip muscle activation seen with low arches likely occurs in order to help stabilize the knee and ankle through slightly atypical balance movements. Also, the extra contractions seen in the hip muscles for people with flat feet may signify that they have a tendency to fatigue easier[7]. Little literature was found surrounding the rectus femoris and semitendinosus during balance relating to arch height.

In various directions the gluteus medius exhibited less peak muscle amplitude in low arched individuals. Many studies have found that hip abductors, like the gluteus medius, seem to have a significant impact on balance[12][14][15]. It has been found that in people with flat feet the abductors have been seen to have less strength compared to those with normal or higher arches[14]. Similarly to what has been found for those with low arches, individuals with chronic ankle instability (CAI) were found to have less abductor muscle torque[12], of which the gluteus medius is a primary contributor. It is likely then that the rectus femoris and semitendinosus have bigger muscle contractions to compensate for the decreased gluteus medius contractions in lower arched individuals. To combat this, lower arched individuals might add gluteus medius and other ankle stability exercises into a training program. Similarly, because the hip muscles may fatigue quicker it is recommended that hip endurance exercises also be incorporated.

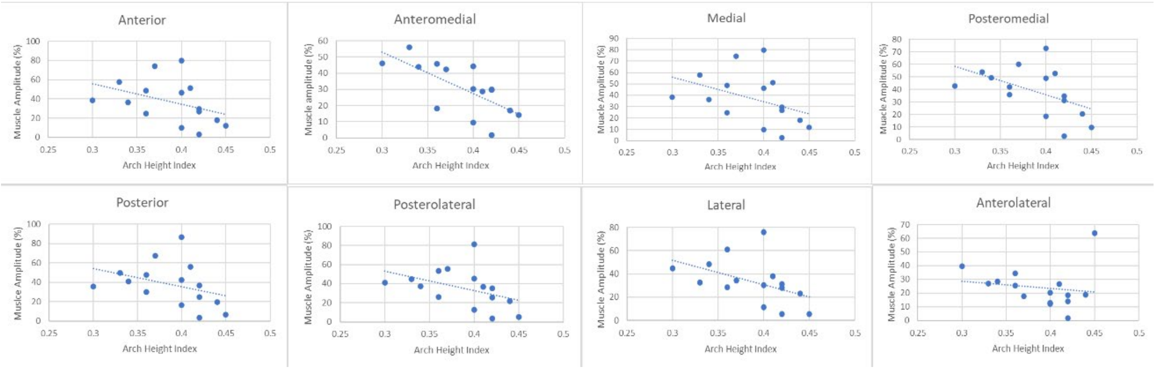

Figure 6: Linear regression plots of the AHI compared to rectus femoris peak muscle amplitude for each direction of the SEBT.

Further Research

Suggestions for further research include examining the same variables, but with inclusion criteria that allow the researchers to separate the subjects into high arches and low arches to compare between groups. Since dynamic balance isn't as standard as the SEBT, future studies may use the same variables to look into sport specific balance movements and evaluate any performance deficits or differences with differing arch heights. Other studies might focus only on hip muscles, covering all of the actions at the hip, to see if arch height impacts any of the muscle activations differently or if there is a difference in a certain hip action involvement from the muscles.

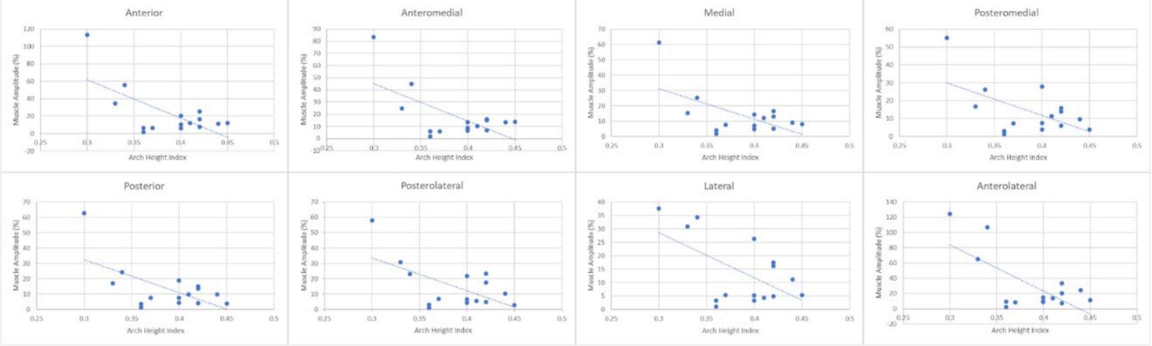

Figure 7: Linear regression plots of the AHI with the semitendinosus peak muscle amplitude for each direction of the SEBT.

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