OSTEOPATHIC MANAGEMENT OF MILD LEG LENGTH INEQUALITY WITH HEEL LIFT THERAPY: A PILOT STUDY ANALYZING ALTERED GAIT KINETICS AND KINEMATICS

THESIS

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INTRODUCTION

1) What is Leg Length inequality (LLI)?

Leg length inequality (LLI), also known as leg length discrepancy or short leg syndrome, is a clinical condition in which the lower extremities are noticeably unequal.[1] It is a mechanical issue leading to abnormal joint loading and symptomatology in the lower extremities and spine.[2] It has been postulated that LLI is a potential cause and/or aggravator of low back pain (LBP). LBP is itself a general term that includes pain derived from the axial skeleton, lumbosacral joints, and sacroiliac joints.[1] Investigation of this correlation is valuable because 15-20% of US population experiences LBP annually.[3] Of those who develop chronic LBP, one third will become permanently disabled.[4] Giles and Taylor found that in review of 1,806 LBP participants, 13-22% had a LLI greater than 10mm.[5] Since heel lift therapy has been shown to decrease pain scores in LBP patients with a LLI[6,7], it is believed that a connection exists between the two.[1] Symptoms of LLI include pain in the low back, knees, or hips; decreased range of motion; and altered gait.[1,2]

Conservative treatment for symptomatic LLI consists of physical therapy, osteopathic manipulative treatment (OMT), and the use of heel lifts to replace some or all of the measured leg length discrepancy. OMT is beneficial during LLI correction as it helps the patient's body adapt to postural changes induced by the heel lift.[7,8] Osteopathic physicians assert that lifting the shortened limb relieves pain symptoms by leveling the sacral base, which improves posture and equalizes joint loading in stance and walking. This claim is supported by subjective data relying on pain scores and questionnaires[6], and objective data demonstrating structural pelvic and sacral alignment changes.[9,10]

a. *Classification*

LLI can be divided into two categories: structural and functional.[1] Structural LLI implies a shortening of one or more of the osseous structures of the lower extremities. This osseous shortening can itself be an effect of various etiologies such as, but not limited to, fractures and/or soft tissue trauma, infections such as poliomyelitis, or pediatric disorders such as Legg-Calve-Perthes Disease, congenital hypoplasia, and Slipped Capital Femoral Epiphysis.[1,7,11] Knee and hip osteoarthritis has also been described as a cause in the aging population, as the loss of cartilage within the joint decreases the joint space and shortens the extremity.[12] Functional LLI stems from multiple etiologies which results in altered mechanics of the lower extremities. For example, excessive foot pronation leads to ankle instability and pes planus, shortening the lower extremity on the affected side.[13] Suprapelvic muscle hypertonicity can lead to sagittal plane rotation of an innominate.[14] LLI etiologies can be divided by acuity as well. Cases in which acute shortening of the lower extremity occurred were excluded from the present study. Acute leg length changes may occur after trauma or surgery. Such patients can be immediately lifted to the measured discrepancy because their body has not had time to compensate. This study defined LLI as chronic if it had existed greater than three months.

b. *Prevalence*

Considering the wide range of etiologies, it has been postulated that the prevalence in the general population would be high. Previous research has proved inconclusive, placing the percentage as low as 4% to as high as 95% of the general population.[1,13,15] Whatever the prevalence, it is thought the average across the population is a 5mm difference in leg length.[15] This value is not considered clinically significant by some.[16] The threshold level of LLI considered clinically significant to necessitate treatment has also ranged tremendously from 5mm[15] to 20mm.[15,17] One review found a recommendation that LLI be quantified under three labels: mild (<30mm), moderate (30-60mm), and severe (>60mm).[13] It is not surprising then that there are so many reported values of prevalence when there is still a lack of agreement on what value constitutes a significant LLI.

Symptom severity does not correlate with the degree of LLI.[6] Activity level and age are both confounders. Active individuals showed a larger preponderance for pain with smaller amounts of LLI.[1] Other studies found that LLI studied in older populations showed the same pattern as was found in the active, younger population.[13] Therefore it has been recommended that a LLI patient's activity and age should be factored in when deciding whether or not to clinically intervene, not simply the amount of LLI measured radiographically.[13]

c. Natural Compensation

Many studies have looked into the static, mechanical changes that occur to posture as a result of LLI. Studies have found postural compensations occur throughout the body from the foot up to the shoulders. Foot supination on, and a lumbar spinal curve away from, the short leg side are two of the more commonly seen compensations for LLI.[1,13] The foot excessively supinates to artificially lengthen the limb, while the contralateral foot pronates to artificially shorten the long limb. Innominate rotation or torsion is often mentioned in the literature as well. The innominate rotation is typically anterior on the side of the short leg with a contralateral posterior innominate rotation.[8,14,16] Pelvic obliquity has been reported to be the most common compensation for a LLI up to 22mm.[18]

d. Biomechanical Consequences of Postural Decompensation

Oftentimes a patient's lower extremity, pelvic, or lumbar compensations for LLI are inadequate. If so, pelvic obliquity, a lateral tilt of the pelvis, occurs towards the short leg resulting in sacral declination and scoliosis with secondary pathological loading of the spine.[1,11] This declination causes increased stress at the sacroiliac joints. In fact, a 10mm discrepancy has been found to cause a fivefold increase in force across the sacroiliac joint.[18] Sacral declination can originate from LLI as well as from muscular imbalance, and has been associated with thoracolumbar scoliosis.[19] The scoliotic curve is apparent in standing but diminishes when sitting or lying flat. This indicates the scoliotic curve is secondary to the leg length discrepancy, i.e. functional in nature.[13] The curve itself is typically convex to the side of the short leg.[8,9] A study that analyzed the effect of a simulated LLI on spinal motion found that two compensatory curves developed, one in the thoracic spine and one in the lumbar spine, just like the double or "S" curve in scoliosis.[20] It is postulated that the long term effect of this curvature is exaggerated degenerative change to the spine.[7]

The knee and hip joints of both lower extremities have been studied to ascertain the risk of osteoarthritis in LLI. Studies conflict as to which lower extremity's joints receive more force on ground impact during walking. One study found an increased risk of osteoarthritis in the knee of the shorter leg, possibly because the shorter leg has a longer distance to reach the ground and hence a slightly higher impact force with each step.[12] Hip osteoarthritis was identified in a review to be found more often in the longer limb.[21] One study concluded LLI correlates with both knee pain and hip pain, regardless of which knee or hip it occurs in.[2]

e. Diagnosis and Treatment

LLI is often suspected clinically when unequal iliac crest heights or asymmetric medial malleoli are palpated on physical exam. For quantification of a suspected leg length discrepancy, multiple assessment modalities are available. Radiography has been found to be accurate within 3mm for both functional and structural LLI.[13] Postural x-ray measurement using the interalar line between the sacral alae is one particular method of LLI quantification and will be used in this study to determine LLI in participants.[8] The interalar line has been validated as an appropriate method of measuring sacral declination.[4] External quantification using tape measures have multiple sources of error including iliac asymmetries, lateral deviations at the knee, joint contractures, and difficulty in properly palpating bony landmarks.[13]

Conservative treatment for symptomatic LLI consists of using heel lifts or full length foot orthotics.[8] They have been shown to be of benefit in lowering pain scores among individuals suffering from chronic low back pain secondary to LLI.[1,7] They have also been used in treating pain related to knee osteoarthritis.[12] Not only do they decrease pain scores, they improve posture as well as axial skeleton mobility.[22] A potential factor influencing the intensity of chronic low back and/or knee and hip pain could be the mere presence of LLI and not the exact degree of inequality.[6] This implication could lead to the widespread use of heel lifts in disease prevention.[2] Sometimes patients will only tolerate lifting a fraction of their discrepancy before symptoms shift contralaterally, as if the lifted leg was now the long leg.[23]

The decision to stop increasing the size of a heel lift is a difficult task as well. Current thinking asserts it is not always necessary to correct a discrepancy millimeter for millimeter to a perfectly level sacrum.[5,8] Because of this possibility the current recommendation is that the heel lift treatment level is considered maximized when the patient becomes asymptomatic[13], usually 50-75% of the measured discrepancy.[8]

2) Why Investigate Heel Lift Therapy Improvements to Gait?

Current understanding of the structural and biomechanical effects of mild LLI derives from studies with varying conclusions. Many studies were often conducted with the participants immobile, focusing on structural appearance in quiet standing.[24-26] In part, the recommendation not to treat LLI less than 20 mm was based on structural measurements and pain scores, excluding gait alterations. Studies objectively examining dynamic motion looked at artificial, acutely induced LLI in healthy participants.[14,17,20,22,27] The body can naturally compensate for LLI up to 20 mm acutely[1], but it is inexact to conclude that LLI less than 20 mm does not affect gait based on results from a population of healthy participants with an artificially induced LLI. Two studies have examined gait in pediatric LLI patients. Kaufman et al. and Liu et al. determined gait asymmetry does not occur until 20 mm and 23.3 mm, respectively.[23,28] It has been shown that children have greater compensatory ability than adults for LLI.[1] However, this study investigated chronic LLI in an adult population, so it would be inaccurate to accept the aforementioned pediatric conclusions to the population we studied. Consequently our focus was on LLI between the estimated population average of 5 mm[15] and 20 mm, the minimum LLI considered clinically significant by some.[16,17,28]

The latest research exploring heel lift therapy and gait in LLI has confirmed 3D motion capture as an effective method of measuring small alterations in multiple variables.[29] There exists the critical need for continued examination of the sustained effects of heel lift therapy on gait in LLI. Studies in heel lift therapy have helped formulate treatment recommendations for LLI. They have not, however, conclusively defined when to begin treating LLI, nor to what percentage of the inequality to treat with a heel lift. Accomplishing the specific aims will provide objective data on the functional improvements that OMT and heel lift therapy confers to gait. Furthermore, it will provide information, from a functional standpoint, if treating to symptom resolution is superior to treating to complete sacral leveling.

STUDY AIM

The hypothesis of this research is leg length inequality (LLI) of 5-20 mm has deleterious effects on musculoskeletal function and gait, which can be minimized with heel lift therapy and Osteopathic Manipulative Treatment (OMT) adjunctively to correct somatic dysfunction. This is supported by the following observations in the literature: LLI gait is characterized by increased cadence and decreased walking velocity on the short side[27], LLI creates asymmetrical ground reaction forces (GRFs)[11,14], and the addition of a heel lift decreases gait energy expenditure in LLI.[1] Based on these observations, our specific aim is designed to provide a comprehensive assessment on the kinetic and kinematic improvements of mild LLI patients treated with OMT and heel lift therapy. Study hypotheses are further divided under our specific aim.

Specific Aim: Investigate the effects of heel lift therapy and osteopathic manipulative treatment (OMT) on various functional gait parameters. Patients with mild leg length inequality (LLI) of 5-20mm, measured as sacral declination on standing postural x-ray, will undergo an estimated 4-6 months of intervention. Therapy will be considered complete upon resolution of chief complaint as measured by a visual analog pain scale. Pre and post treatment measures will be analyzed.

Static Measure Hypotheses:

H1. The difference between Long and Short Leg Center of Pressure ground reaction force in quiet standing will decrease post OMT + heel lift therapy compared to initial measures. This corresponds to equal weight distribution over the lower extremities.

H2. The difference between Long and Short Leg Center of Pressure Sway in quiet standing will decrease post OMT + heel lift therapy compared to initial measures. This corresponds to a decrease in the anteroposterior and Mediolateral sway in quiet standing.

Dynamic Measure Hypotheses:

H3. The Center of Mass (CoM) displacement in the sagittal plane will decrease in amplitude during the gait cycle post OMT + heel lift treatment compared to initial measures. This corresponds to a more energetically efficient cycle.

H4. The CoM displacement in the coronal plane will decrease in amplitude during the gait cycle post OMT + heel lift treatment compared to initial measures. This corresponds to a decrease in lateral sway.

H5. Lower extremity joint angular ranges of motion will become more symmetrical between the Long and Short legs post OMT + heel lift therapy compared to initial measures. This corresponds to symmetrical ranges of motion at each major joint of the Long and Short legs.

RESEARCH DESIGN AND METHODOLOGY

1) <u>Participant Recruitment</u>

Participants were recruited through the Osteopathic Manipulative Medicine / Neuromuscular Medicine Clinic at the UNTHealth Patient Care Center in Fort Worth, Texas. Research participants for this study were excluded from the study if they met any of the following criteria: 1) were pregnant, 2) had a body weight greater than 400 lbs. (the limit of the safety harness of our system), 3) visual deficits not corrected by eyeglasses or contact lenses, 4) history of motion sickness/dizziness, vestibular diseases or vertigo (due to potential triggering by the virtual reality display screen), 5) self-report of inability to stand independently for 1 minute or walk 100 yards independently, 6) had previous back surgeries or trauma, 7) had any systemic disease or condition that had a direct pathological effect on the musculoskeletal system. Prior to participation, informed consent was obtained in accordance to the specifications of the IRB office of the UNT Health Science Center (UNTHSC IRB # 2012-084). Participants were brought to the gait lab for data collection in two visits.

2) <u>Leg Length Inequality Measurement Technique</u>

Sacral base declination, a lateral tilt of the sacral base, was measured before heel lift therapy. Standing anterior posterior radiographs of the lumbar spine and pelvis was obtained. The amount of sacral base unleveling was measured thusly:

1. Two vertical lines were drawn perpendicular to the base of the film, parallel to a plumb line through the apexes of each femoral head.
2. One line was drawn parallel to the sacral base through the sacral alae. This line represented the sacral declination.
3. Two individual horizontal lines were drawn parallel to the base of the film, across the apexes of each femoral head. These lines accounted for discrepancy between femur heights.
4. The relative height of each vertical line was measured from the contact point on the horizontal femoral apex line to their corresponding contact point with the sacral declination line.
5. The level of sacral declination was the measured difference of these two heights in millimeters. A difference of zero indicated a level sacrum.

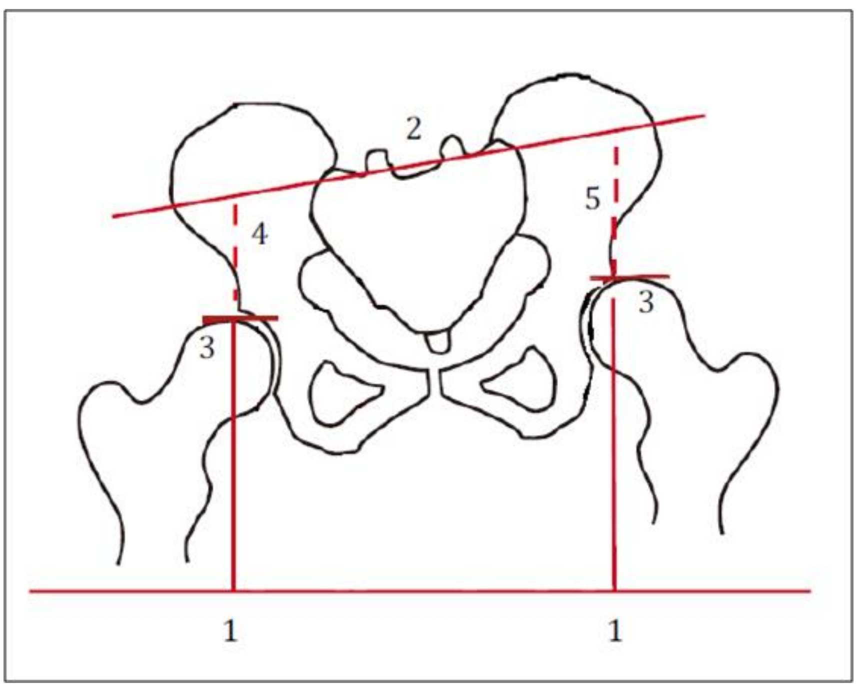


Figure 1. Sketched example of a standing anteroposterior pelvic x-ray. Numbers 1-5 reflect steps 1-5 of measuring sacral declination denoted above.

It has been shown that lateral pelvic tilt increases linearly with heel lifts.[1] Therefore, an unleveled sacrum should become leveled with a heel lift equal to the amount of declination. To accomplish this, heel lift treatment was instrumented in 1/8" increments for chronic leg length inequalities until their maximum therapeutic level was reached as determined by the PI. If symptoms worsened or shifted contralaterally at maximum lift, the heel lift was decreased in 1/16" increments until the patient became asymptomatic. An Osteopathic Manipulative Medicine/Family Medicine board certified physician continued to treat participants with osteopathic manipulation when deemed clinically necessary during follow up visits between research encounters. OMT was individualized to each patient at each follow up visit instead of using a treatment protocol.

3) Study Schedule

This study took place over one year with four subjects tested before heel lift therapy and after reduction in pain. The amount of time varied between subjects but clinically happened within 6 months. There were two research study visits each (8 subject visits) and weekly to bimonthly visits to the OMM clinic for OMT and reevaluation of treatment.

Clinic Visit 1: At the first visit, each participant was evaluated for suspected leg length inequality. If the clinician suspected inequality he provided OMT and sent the patient to a local radiology service for postural radiographs. Each participant returned to clinic where the clinician reviewed the radiographs with the patient to determine if there was a leg length inequality. When sacral declination was found, the subject was asked to enroll in the study. The clinical research coordinator (CRC) screened all subjects for the inclusion criteria mentioned previously. Next, the CRC collected the demographic data for each participant on a demographic sheet that included age, gender, weight, height, race/ethnicity, current treatment and medications, and medical history. At this point baseline gait function testing was scheduled. Once baseline measurements (see tesing protocol below) were made, the participants were able to begin with heel lift therapy. It was expected that the participants would utilize the heel lift at all times of the day, except during sleep and showering.

Clinic Visit 2+: Patients followed up in the OMM clinic every week to two weeks for regularly scheduled OMT and heel lift size progression (standard of care). Manipulative treatments were not standardized but were at the discretion of the attending physician.

Last Clinic Visit: When the attending physician determined that the heel lift requirement had stabilized based on decreased pain level, functional gait parameters were once again collected.

At each scheduled treatment session, information was collected from each participant and recorded on the Data Record Sheet to document changes in level of activity between visits that could potentially impact the signs and symptoms of their pathology, such as physical chores, lifting or other exercise, and work or hobby related repetitive tasks.

4) Testing Protocol

As mentioned above, the baseline gait measurement visit occurred shortly after confirmation of a leg length inequality, but before treatment with a heel lift commenced. This was known as the Pre Treatment visit (Pre). Once the physician determined the heel lift treatment was maximized based on subjective reports of the patient being pain free, the second visit occurred, known as the Post Treatment visit (Post). During both visits the participants were asked to wear comfortable walking shoes. They were reminded to appear to both visits with the same walking shoes. Forty-nine reflective markers were placed on the head, arms, legs and torso. A fitted spandex shirt and fitted shorts were provided to ensure the reflective markers were as close to the body as possible with minimal shearing motion over the bony landmark. A non-allergic double-sided adhesive tape, designed for use on human skin, was used to secure the reflective markers to the arms, legs, and torso. Reflective markers were attached to the following anatomic landmarks: 8 on each leg, toe, heel, lateral and medial malleolus, shank, medial and lateral femoral condyle, thigh, 9 on each arm, second and fifth metacarpal head, radial and ulnar styloid, forearm, medial and lateral epicondyle, upper arm and acromium, right and left anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS), 7th cervical and 8th thoracic vertebrae, sternal notch, xiphoid, sacrum, right hamstring and right scapula, and 4 on the head. Bone segments were defined in a 3-dimensional model using the reflective markers. The three dimensional motion data was collected using a 12 camera system (Motion Analysis Corp., Santa Rosa, CA) that tracked the reflective markers placed on the body, allowing precise calculation of kinematics, gait parameters, and joint range of motion during movements. This is not a video based system as there are no images of the participants, but rather kinematic models from which the data is extracted.

Each participant served as their own control so two visits at least one month apart was required. The initial visit was composed of baseline balance and gait data collection prior to initiation of heel lift treatment. A V-Gait, computer-assisted rehabilitation environment network system, consisting of a dual belt instrumented treadmill with a force plate mounted under each belt, provided balance data. This system is further described under Data Acquisition.

To determine baseline balance data, participants stood on the treadmill and maintained balance without moving for 4 periods of 60 seconds; 2 periods with their eyes opened and 2 periods with their eyes closed. The participants placed their feet in two different positions for each trial within a set (eyes open or eyes closed): feet side-by-side, and feet shoulder-width apart. Center of Pressure (COP) sway was collected from force plate data.

To determine baseline gait data, participants walked on the treadmill for two periods of one minute. The treadmill was set to the walking speed each participant averaged when walking on flat ground in the lab. This average was calculated over three trials of comfortable walking over a 20 foot distance. This speed was measured and used for the treadmill at both the Pre and Post visit. If the participants were uncomfortable with the treadmill speed, it was adjusted accordingly. A counter lever safety harness was employed during the walking trials for participant safety. The 12-camera motion analysis system tracked the set of 49 reflective markers placed on selected anatomical areas. Gait dynamic measures included the rotation and tilt of the pelvis, step length, step height, pelvic lateral sway, lower extremity internal and external rotation, as well as center of mass displacement.

5) Data Acquisition Systems

Previously mentioned data acquisition systems are expounded herein:

a. A 12-camera Motion Analysis System (Motion Analysis Corp., Santa Rosa, CA) tracked reflective markers placed on the body, which allowed for precise (within 0.25mm) calculation of kinematics, gait parameters, and joint range of motion during movements. This is not a video based system as there are no images of the subjects, but rather kinematic models from which the data was extracted.

b. A V-Gait CAREN (Computer Assisted Rehabilitation Environment Network) System (Motek Medical, Amsterdam, The Netherlands), consisting of a dual belt instrumented treadmill with force plates mounted underneath each treadmill belt, recorded force data.

When the treadmill belts were not rolling, the V-gait served as a flat stationary surface. Refer to Appendix A to see a picture of the system in use.

c. A 180-degree cylindrical screen enveloping the participants' field of vision delivered a virtual reality environment for cognitive loading. Cognitive load testing via the virtual display was done in order to mentally task the participant as an attempt to minimize the Hawthorne Effect. During the normal walking trials, the screen displayed a flat, virtual path in a park through which the participant moved. As a cognitive load, the participants walked down the same virtual path again, but had to use their arms to interact with birds flying through the scene. However, results of cognitive load testing were not analyzed nor reported herein.

Participants returned to the research center for repeat balance and gait data collections after a period of at least a minimum of 2 weeks after revision of their heel lift treatment. Two weeks is considered the minimum return time as previous studies have shown the body to require two weeks to adjust to any changes in heel lift therapy.[8] The data collected from the force plates, motion capture system, and postural x-rays were analyzed and compared. Due to an expected variability in individual postural adaptations to the use of a heel lift, each participant acted as his or her own control to reflect individual changes.

6) Analysis Technique

Data was collected from force plates and motion capture through Cortex Software (Motion Analysis Corp, Santa Rosa, CA). The software places the origin of the coordinate system in the center of the treadmill. The x-axis is mediolateral motion, the y-axis is superior/inferior motion, and the z-axis is anteroposterior motion. An image of the coordinate system can be found in Appendix A.

a. Static Measures

Static sway was measured using COP data from the V-Gait forceplates. These three dimensional vectors were recorded in Cortex and ran through D-Flow (Motek Medical, Amsterdam, The Netherlands) for net Center of Pressure (COP) dimensions. The net COP vector is calculated as the sum of the COP vectors from each limb.

b. Dynamic Measures

Each one minute walking trial was trimmed to remove the initial acceleration and ending deceleration of the treadmill. The data was then averaged to 100 points for each gait cycle and then "cleaned" in the Gait Offline Analysis Tool software (GOAT, Gait off Analysis tool, Motek Medical, The Netherlands). This software allowed for manual deletion of individual missteps from each trial to remove outliers. Once visible outliers were removed, all left and right steps from each trial were then averaged within the software to create kinematic diagrams that were compared to Motek's normal population dataset. Depending on the participants' walking speed, fifteen to forty steps with each extremity were available for data analysis. Univariate statistics were calculated on each measure for each condition to determine the frequency distributions and the suitability of using analysis of variance (ANOVA).

The range of motion (ROM) of each joint in the lower extremities was measured in degrees and compared in order to investigate the interpersonal variability among participants. The ROM was compared between the long and short leg Pre and Post, as well as each leg independently Pre and Post.

Vertical displacement measurements of Center of Mass (COM) have been validated using a sacral marker.[30] In order to recreate a true COM point within the pelvis, however, a virtual pelvic marker was created at the intersecting point of two lines between each of the Posterior

Superior Iliac Spines and their contralateral Anterior Superior Iliac Spines. Superior/inferior and mediolateral displacement graphs were created using kinematic data from this virtual pelvic marker.

c. Statistical Analysis

Statistical analysis was performed on the data again using PC-SAS. An ANOVA using the Proc GLM (General Linear Model) in PC-SAS was used to test for differences in gait parameters pre and post heel lift therapy. Unless explicitly stated otherwise, a *p* value of 0.05 was considered statistically significant.

RESULTS

For this pilot study, nine patients were recruited from the Osteopathic Manipulative Medicine / Neuromuscular Medicine Clinic at the UNT Health Science Center. Five failed to return to the lab for the Post Visit for reasons including a knee injury, moved cities, and noncompliance with medical care. The four participants completing the study were found to have structural LLI due to osteoarthritis of the knee and hip or mild scoliosis, neither of which were being treated with assistive devices. Table 1 outlines the participant demographics, as well as the side of the short leg, the participant's chief complaint at the initial clinic visit, and pertinent diagnoses that were felt to be contributing to the leg length inequality.

Table 1. Participant Demographics and quantity of LLI.

Demographics	Participant 1	Participant 2	Participant 3	Participant 4
Sex	M	F	F	F
Age	53	64	23	24
Ht (m)	1.80	1.63	1.69	1.68
Wt (kg)	95.25	83.50	71.80	71.00
BMI	29.29	31.60	25.10	25.20
LLI (mm)	13	8	10	6
Short Leg	Right	Left	Right	Left
Chief Complaint	Low Back Pain	Low Back Pain	Low Back Pain	Low Back Pain
Associated Diagnoses	Knee Arthritis	Knee Arthritis	Scoliosis	Scoliosis

The age range was substantial, 23-64. The range of inequality, 6-13mm, spanned the lower portion of the range which was studied. Two participants had a left short leg and two had a right short leg. To avoid confusion, the results describe differences seen between Long and Short

Leg rather than left and right. Table 2 illustrates their level of inequality, average stride length, average stride time, and walking speed.

Table 2 A & B. Gait speed and stride data before (A) and after (B) heel lift therapy. Speed = meters/second, length = meters, time = seconds.

A PRE HLT	Participant				AVERAGE	STDEV
	1	2	3	4		
Mean walking speed	0.85	1.01	1.1	1.12	1.02	0.12
Mean stride length	1.46	1.26	1.49	1.59	1.45	0.14
Mean stride time	1.42	1.09	1.14	1.14	1.20	0.15
LONG Leg:						
# of Cycles Reported	24	29	57	30	35.00	14.90
Mean Stance Time	0.98	0.73	0.77	0.76	0.81	0.11
Mean Swing Time	0.44	0.35	0.37	0.38	0.39	0.04
Mean Stance %	69.2	67.53	67.7	66.79	67.81	1.01
Mean Swing %	30.8	32.47	32.3	33.21	32.20	1.01
SHORT Leg:						
# of Cycles Reported	22	28	51	32	33.25	12.53
Mean Stance Time	0.98	0.74	0.76	0.77	0.81	0.11
Mean Swing Time	0.44	0.35	0.38	0.37	0.39	0.04
Mean Stance %	69.26	67.93	66.58	67.27	67.76	1.14
Mean Swing %	30.74	32.07	33.42	32.73	32.24	1.14

B POST HLT	Participant				AVERAGE	STDEV
	1	2	3	4		
Mean walking speed	0.82	1.01	1.09	1.08	1.00	0.13
Mean stride length	1.43	1.23	1.55	1.54	1.44	0.15
Mean stride time	1.39	1.09	1.17	1.08	1.18	0.14
LONG Leg:						
# of Cycles Reported	16	19	44	21	25.00	12.83
Mean Stance Time	0.98	0.73	0.78	0.76	0.81	0.11
Mean Swing Time	0.41	0.36	0.39	0.38	0.39	0.02
Mean Stance %	70.39	67.16	66.99	66.83	67.84	1.70
Mean Swing %	29.61	32.84	33.01	33.17	32.16	1.70
SHORT Leg:						
# of Cycles Reported	16	19	42	19	24.00	12.08
Mean Stance Time	0.97	0.74	0.77	0.67	0.79	0.13
Mean Swing Time	0.43	0.35	0.39	0.31	0.37	0.05
Mean Stance %	69.39	67.72	66.44	63.08	66.66	2.67
Mean Swing %	30.61	32.28	33.56	36.92	33.34	2.67

No significant difference was found between Pre and Post visits for mean walking speed, mean stride length, or mean stride time (Table 3). Furthermore, no significant difference was found in mean stance and swing times, or mean stance and swing percentages for the short leg when compared Pre vs Post.

Table 3 A & B. A – *p* values from Gait Offline Analysis Tool (GOAT) software gait analysis of 2D data displayed in Table 2. B - *p* values between extremities before and after treatment, as well as for each limb independently, between visits.

A.

p Values	Pre vs Post
Walking Speed	0.12
Stride Length	0.65
Stride Time	0.50

B.

p Values	Mean Stance Time	Mean Swing Time	Mean Stance %	Mean Swing %
PRE: Short vs Long	0.64	1.00	0.91	0.91
POST: Short vs Long	0.34	0.50	0.29	0.29
SHORT: Pre vs Post	0.40	0.41	0.36	0.36
LONG: Pre vs Post	0.39	1.00	0.93	0.93

1) Static Measures

a. Center of Pressure – Force

The location of the Center of Pressure (COP) under each foot was measured on the force plates during quiet standing with eyes open and again with eyes closed. This was done in two stances, feet shoulder-width apart and feet side by side. A ratio of the ground reaction force of the long leg to the force of the short leg in quiet standing in each condition was measured and compared Pre vs Post. A ratio equaling one denotes symmetry in the ground reaction forces between feet. A ratio larger than one denotes a force asymmetry in favor of the short limb (less force), while a ratio less than one denotes a force asymmetry in favor of the longer limb. As can be seen from Table 4, no significant change in the ratio of forces was found before and after heel lift treatment.

Table 4. The Long:Short leg ratios of GRF in each standing trial, with *p* values. (key: SA = Shoulder-width Apart, SS = Side by Side, EO = Eyes Open, EC = Eyes Closed)

	SS, EO		**SS, EC**		**SA, EO**		**SA, EC**	
Participant	Pre Ratio	Post Ratio	Pre Ratio	Post Ratio	Pre Ratio	Post Ratio	Pre Ratio	Post Ratio
1	1.06	1.04	1.05	1.05	1.08	1.04	1.15	1.04
2	0.87	0.83	0.88	0.77	1.05	0.94	1.04	0.91
3	0.83	0.94	0.86	0.90	0.99	0.99	0.99	1.01
4	1.02	1.02	1.04	0.88	1.14	1.11	1.08	0.98
Average	0.94	0.96	0.96	0.90	1.07	1.02	1.07	0.99
St Dev	0.11	0.10	0.10	0.12	0.06	0.08	0.07	0.05
	p = 0.76		*p = 0.32*		*p = 0.18*		*p = 0.09*	

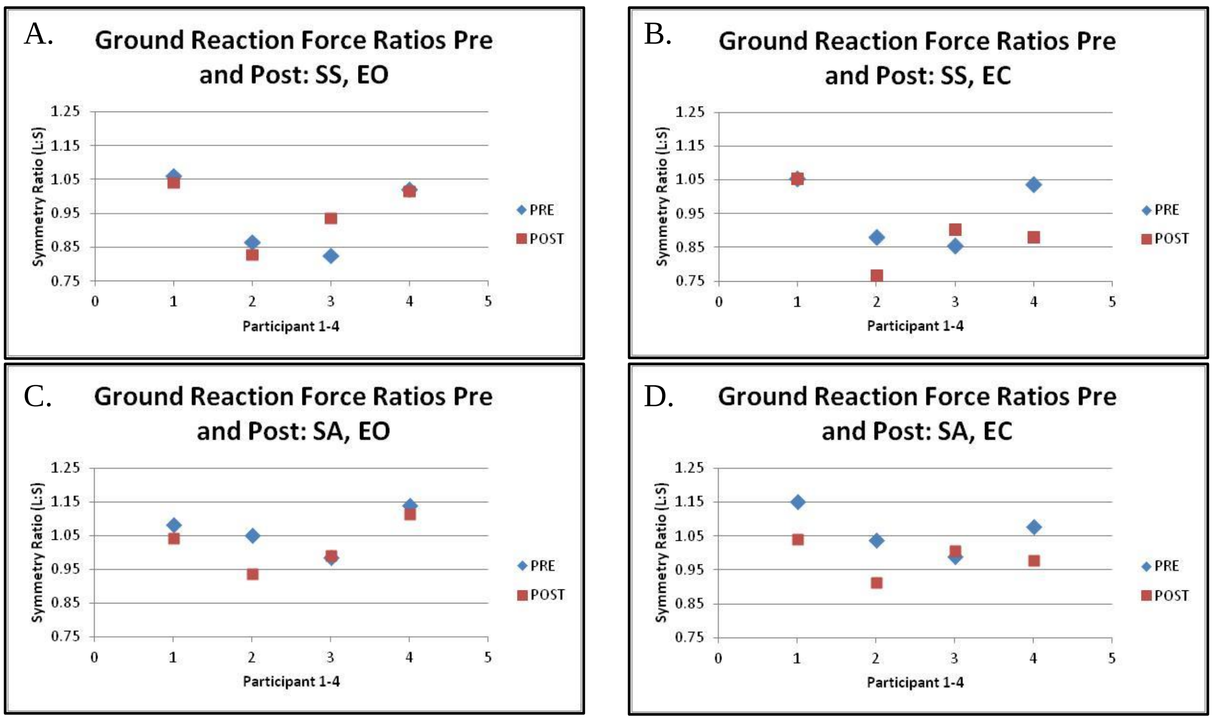


Figure 2, A-D. The ratio of Long and Short leg ground reaction force before and after heel lift therapy in the four static motion scenarios. A ratio of 1.0 denotes ground reaction force symmetry between lower extremities. (key: SA = Shoulder-width Apart, SS = Side by Side, EO = Eyes Open, EC = Eyes Closed)

Figure 2 shows the change in GRF ratios for each participant. Refer to Appendix B for an expanded table of individual forces. In the feet side-by-side eyes open trial, participant 3 showed improved symmetry. When eyes were closed, both participants 2 and 4 worsened their symmetry by increasing force on the short leg side. In the feet shoulder-width apart eyes open trial, participant 2 worsened their symmetry and switched force distribution from placing more force through the long leg in the Pre visit to placing more force on the short leg in the Post visit. When repeated with eyes closed, participant 2 once again worsened their symmetry and switched force distribution. In the same trial, however, one can see improvements in symmetry in participants 1 and 4.

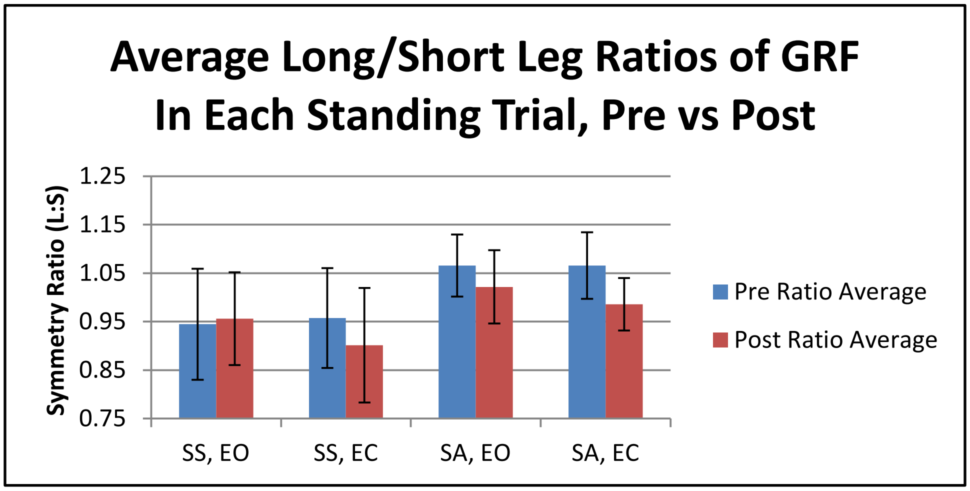


Figure 3. Average Long/Short Leg GRF ratios for each standing trial.

Figure 3 depicts the average Long/Short leg GRF ratios for each trial. There are improvements in symmetry in the SS, EO; SA, EO; and SA, EC trials, as per the average values reported earlier in Table 4. The largest improvement is in the SA, EC trial in which symmetry improved by 8% (GRF ratio 1.07 → 0.99).

b. *Center of Pressure - Sway*

Net Center of Pressure (nCOP) was used as an indirect indicator of sway during quiet standing. This value is the sum of the Center of Pressure vector from each limb's contact point on the force plates. The nCOP data points were averaged during one minute of quiet standing. Four trials were conducted: feet shoulder-width apart with eyes open and eyes closed, feet side-by-side with eyes open and eyes closed. The nCOP vector was split into its x axis (mediolateral) and z axis (anteroposterior) components to assess sway. The feet shoulder-width apart with eyes closed trial was chosen for this analysis as it most accurately depicts normal quiet standing in an individual.

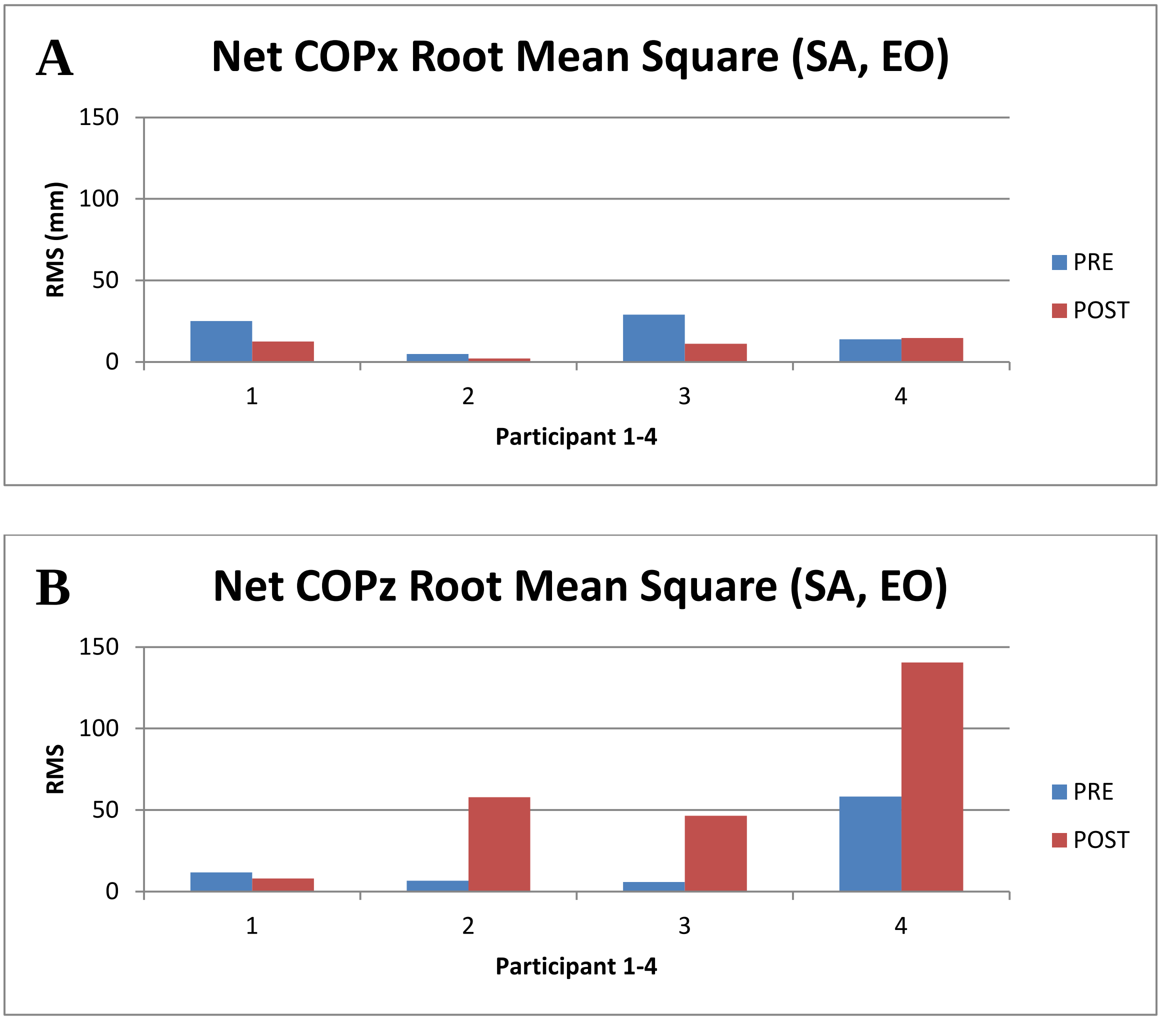
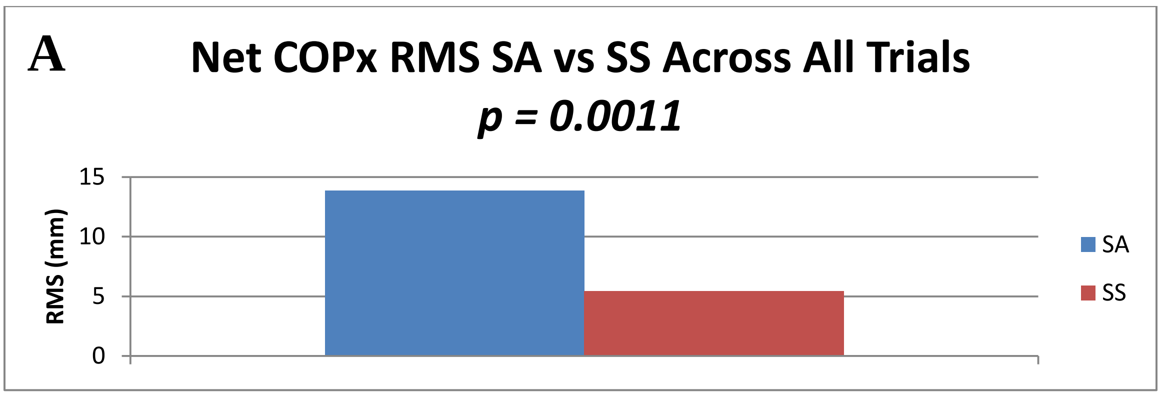


Figure 4 A&B. Net COPx and net COPz root mean squares Pre and Post. The SA, EO trial was used as it most accurately represents typical stance, as opposed to feet side-by-side or eyes closed.

The Root Mean Square was analyzed to compare the amount of residual sway occurring about the mean for each participant. The RMS was calculated as follows:

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

Where n is the number of data points, and x equals the difference between COPx (or COPz) and the mean for all points 1 to n. In Figure 4, the RMS decreased by more than one half in Participants 1, 2, and 3 in mediolateral nCOP measures. Anteroposterior nCOP RMS increased substantially in Participants 2, 3, and 4. When analyzed in SAS by ANOVA, there was no significant difference in nCOPx RMS (ML sway) between visits. As seen in Figure 5, however, a significant increase in nCOPz RMS (AP sway) between visits, with $p = 0.0056$. Furthermore, a significant decrease was found between nCOPx RMS between modes of stance, shoulder-width apart vs side-by-side, with $p = 0.0011$.



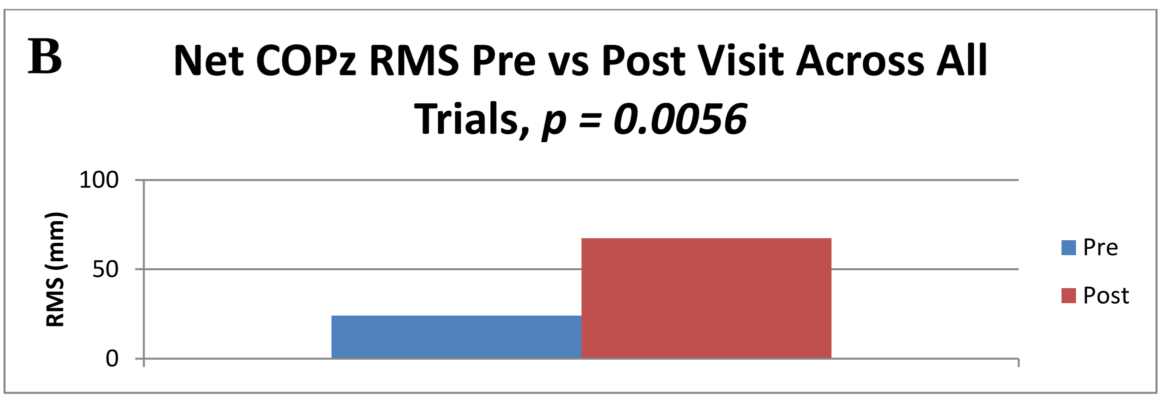


Figure 5 A&B. A – Net COPx RMS feet shoulder-width apart vs feet side-by-side across all trials. B – Net COPz RMS Pre vs Post across all trials.

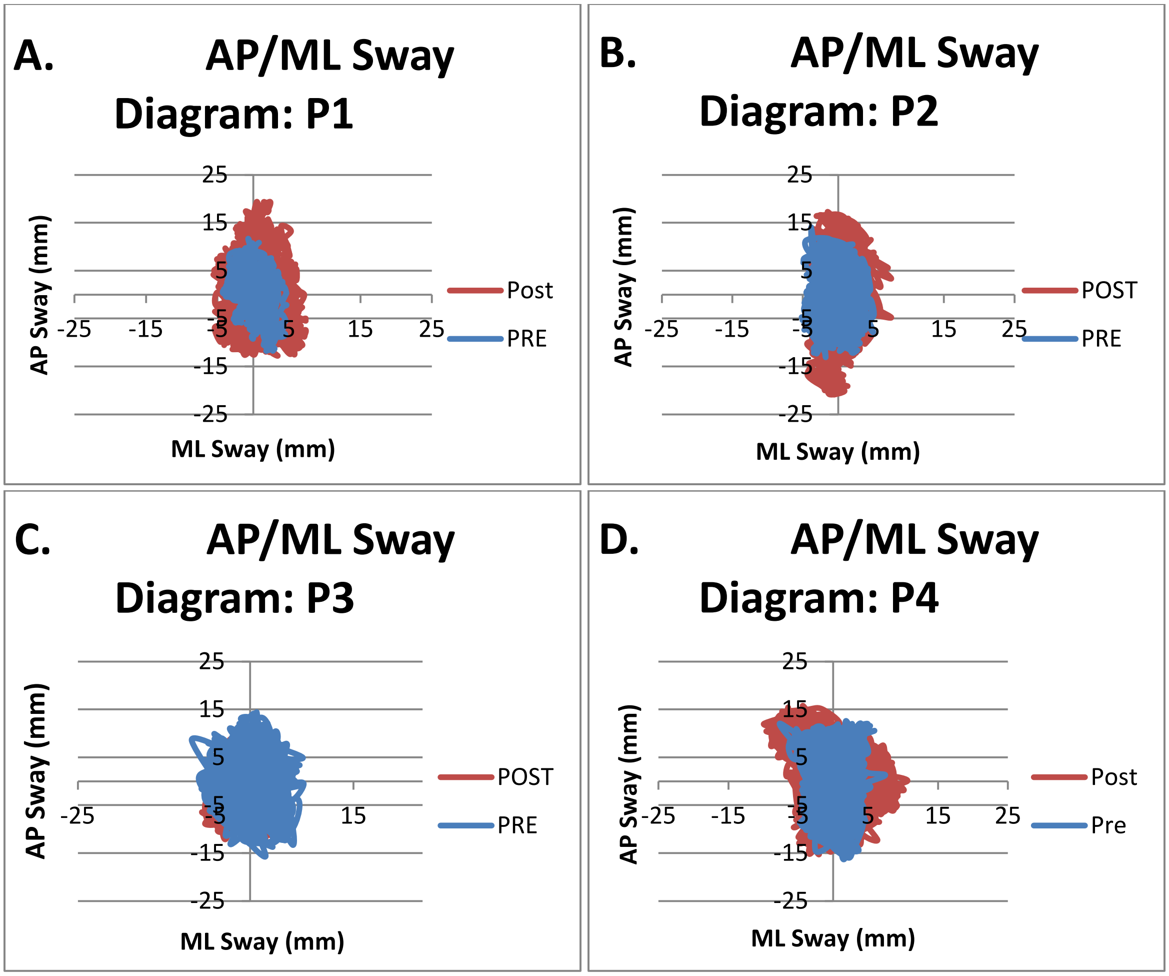


Figure 6 A-D. Center of Pressure Sway in quiet standing, feet shoulder-width apart and eyes open. A positive value in AP Sway denotes anterior motion, while a positive value in ML Sway denotes motion to the participant's right. NOTE – Post visit data set not visible for P3 as it's smaller than Pre diagram.

The x and z axes components of nCOP were plotted against each other for each participant in Figure 6 A-D. The y axis on the graphs depicts net COPz (anteroposterior motion), while the x axis on the graphs depicts net COPx (mediolateral motion). Participants 1, 2, and 4 show a visibly larger Post scatter plot, which corresponds to a larger sway range of motion during the "SA, EO" trial. The nCOP sway area was calculated in D-Flow based on the below equation and graphed in Figure 7.

nCOP Area = (3*StDev of nCOPx)*(3*StDev of nCOPz)

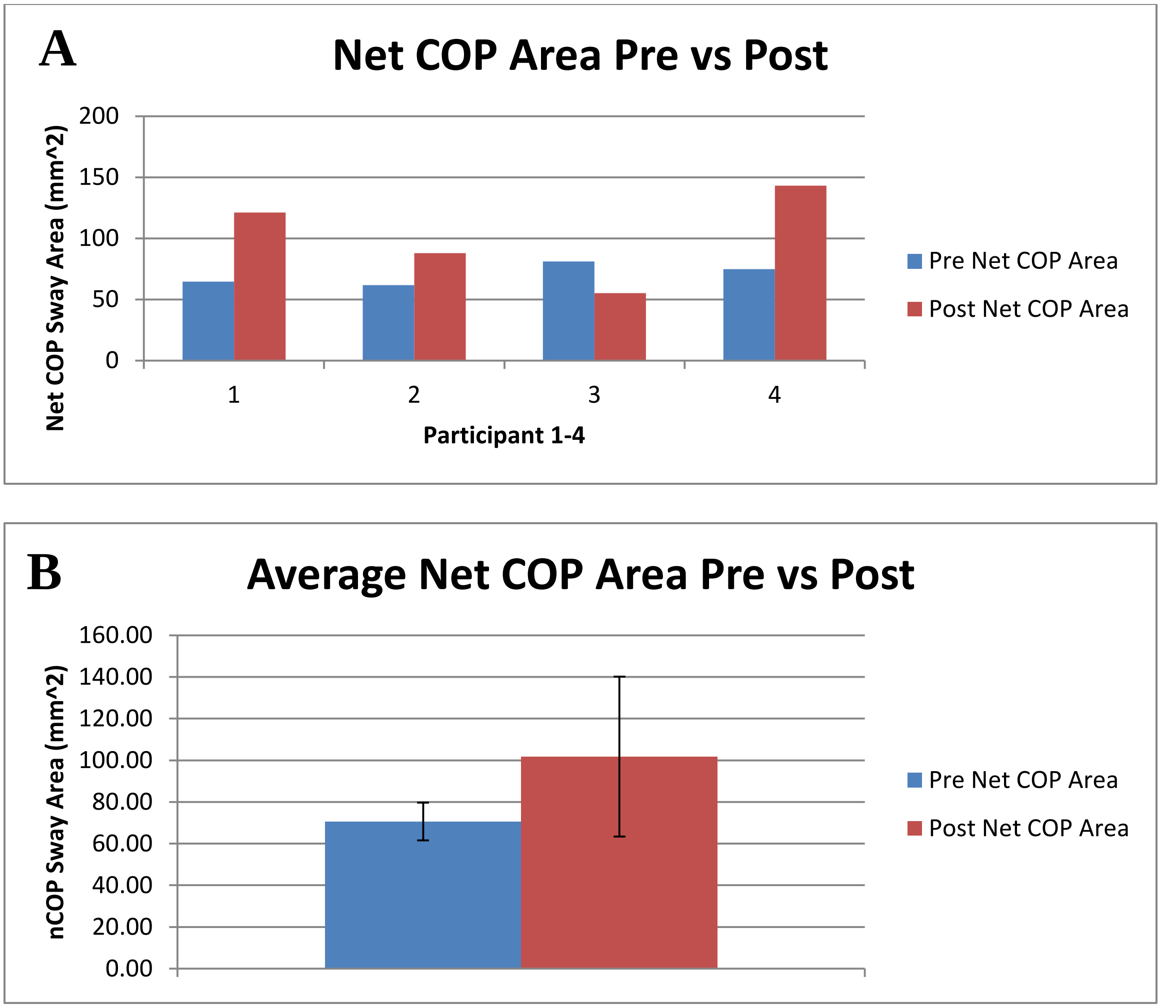


Figure 7 A & B. Net COP sway area Pre vs Post. Taken from the SA, EO Trial. A. Sway areas for each participant. B. Average nCOP sway area.

Total sway area decreased in Participant 3, while it increased in Participants 1, 2 and 4. The average nCOP for all participants in the SA, EO Trial increased, but not significantly, from 7.1cm^2 to 10.2 cm^2.

2) Dynamic Measures – Walking Trial

   a. Center of Mass

Figure 8 shows the virtual pelvis marker for each participant tracked over the walking trial and graphed in the mediolateral and superior/inferior planes (x and y axes, respectively), with the Pre visit in blue and the Post visit in red. As mentioned previously, the walking trials with the added cognitive load were excluded from analysis.

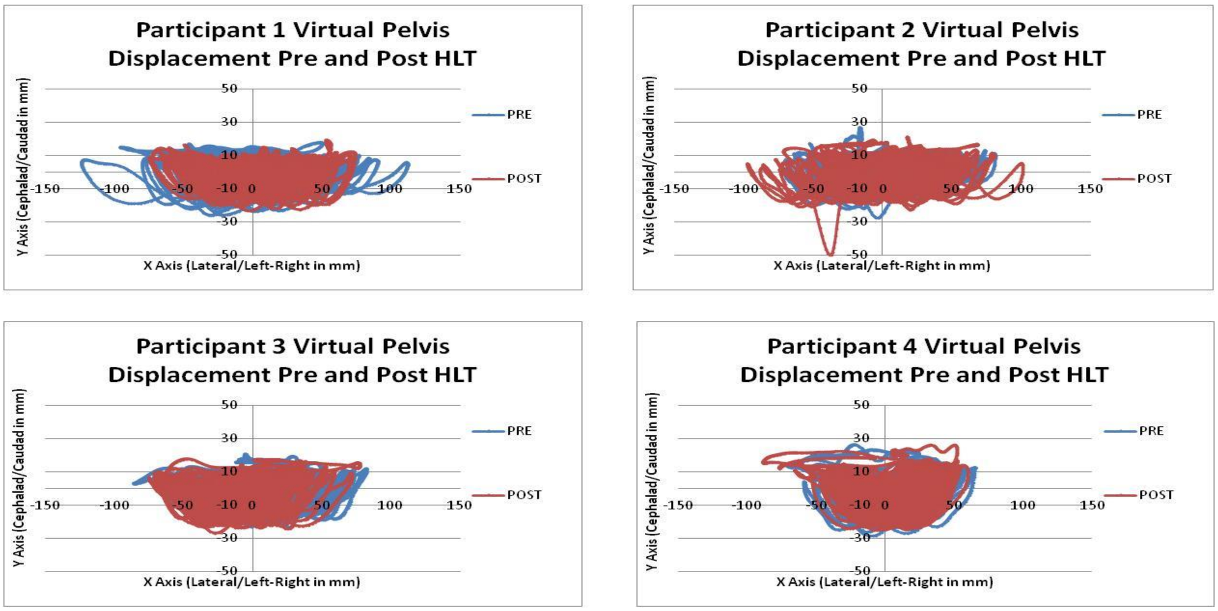


Figure 8. Mediolateral (M/L) and superior/inferior (S/I) displacement of the Center of Mass during the walking trial, pre and post heel lift therapy. X axis = M/L motion, Y axis = S/I motion, unit of measure = mm.

The virtual pelvis marker position in the mediolateral and superior/inferior directions were plotted over several gait cycles. The displacement in each axis was then averaged over at least 15 steps. This displacement was measured as the difference between the peak and valley of each gait cycle when the x and y axes coordinates were separately plotted against time, as seen in Figure 9.

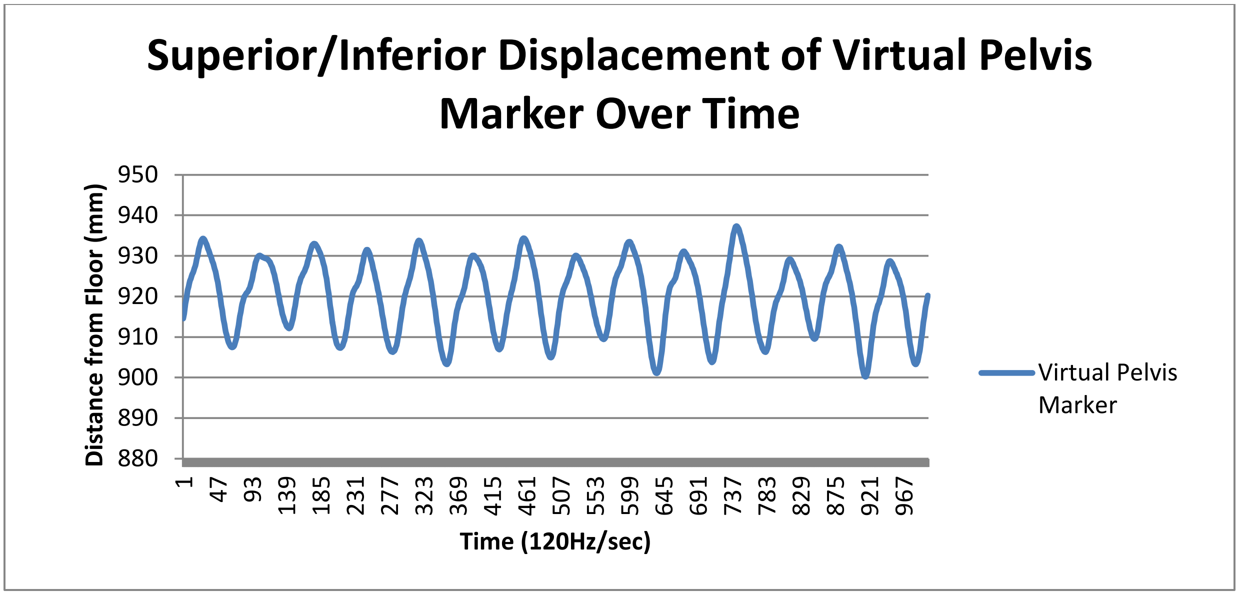


Figure 9. Superior/Inferior displacement (y axis) of the virtual pelvis marker when plotted against time. This is the S/I displacement portion of the composite M/L vs S/I displacement graph depicted in Figure 8 A-D. Note the sinusoidal pattern over time. When plotted along with M/L displacement, the motion takes on a figure-of-eight pattern. Each peak and valley corresponds to a single stride.

Table 5 lists the displacement differences Pre and Post heel lift therapy. “Delta” refers to the difference in values (Post – Pre). The average value of mediolateral displacement Post heel lift therapy was significantly larger than the Pre, with $p = 0.046$. No significant difference in superior/inferior displacement between Pre and Post walking trials was found.

Table 5. Displacement (in mm) in the Mediolateral (transverse) and Superior/Inferior (sagittal) planes before and after heel lift therapy, with averages and *p* values.

Mediolateral Displacement (mm)				Superior/Inferior Displacement (mm)			
Participant	Pre	Post	Delta	Participant	Pre	Post	Delta
1	73.17	78.48	5.31	1	24.53	23.97	-0.57
2	49.93	51.69	1.76	2	23.97	20.91	-3.06
3	53.77	56.70	2.92	3	20.82	27.08	6.26
4	60.85	62.33	1.48	4	30.45	29.83	-0.63
Average	59.43	62.30	2.87	Average	24.94	25.45	0.50
$p = 0.046$				$p = 0.82$			

b. Joint Angular Range of Motion

Tables 6 & 7 list the average range of motion for the pelvis, hip, knee, and ankle joints of each lower extremity Pre and Post heel lift treatment over at least 15 gait cycles. The range of motion differences (Post – Pre) for the Long and Short legs are shown as well for all participants. Knee and ankle AB/ADduction, as well as knee and ankle rotation, were not calculated and are therefore not listed.

Table 6. Joint ranges of motion of the Long Leg Pre and Post heel lift treatment, with averages.

LONG LEG											
ANGLE	Participant 1		Participant 2		Participant 3		Participant 4		AVERAGE		
	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	POST-PRE
Pelvic Obliquity (Z)	7.56	8.36	19.09	11.43	22.09	13.64	8.61	12.47	14.34	11.47	-2.86
Pelvic Rotation (Y)	10.63	7.42	5.39	4.40	8.50	8.86	9.78	7.33	8.58	7.00	-1.57
Pelvic Tilt (X)	4.09	4.83	4.82	3.98	3.03	2.63	3.58	3.46	3.88	3.73	-0.15
Hip Flex/Ext (X)	45.06	45.04	41.39	40.01	46.33	41.23	40.68	41.70	43.37	42.00	-1.37
Hip Rotation (Y)	17.26	15.84	8.53	15.07	12.79	7.44	6.83	3.54	11.35	10.47	-0.88
Hip AB/AD (Z)	20.62	20.76	27.11	18.13	24.92	18.04	11.16	16.45	20.95	18.34	-2.61
Knee Flex/Ext (X)	63.18	65.12	63.44	59.65	72.22	57.82	58.94	57.30	64.45	59.97	-4.47
Ankle Plant/Dorsi (X)	24.85	25.51	23.03	21.27	26.28	32.08	31.22	33.59	26.34	28.11	1.77

Table 7. Joint ranges of motion of the Short Leg Pre and Post heel lift treatment, with averages.

SHORT LEG											
ANGLE	Participant 1		Participant 2		Participant 3		Participant 4		AVERAGE		
	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	PRE ROM	POST ROM	POST-PRE
Pelvic Obliquity (Z)	7.51	8.31	19.18	11.39	22.09	13.69	8.68	12.34	14.36	11.43	-2.93
Pelvic Rotation (Y)	10.49	7.56	5.40	4.31	8.54	8.90	10.19	7.36	8.66	7.03	-1.62
Pelvic Tilt (X)	4.09	4.70	4.76	3.81	2.97	2.49	3.51	3.28	3.83	3.57	-0.27
Hip Flex/Ext (X)	44.08	45.26	43.11	39.08	41.34	41.09	45.58	44.05	43.53	42.37	-1.16
Hip Rotation (Y)	16.65	22.08	19.76	8.13	20.04	6.84	9.23	6.37	16.42	10.86	-5.56
Hip AB/AD (Z)	18.98	19.54	21.69	16.83	25.20	19.48	10.75	16.12	19.15	17.99	-1.16
Knee Flex/Ext (X)	66.63	69.19	77.30	58.28	67.48	62.79	66.54	68.66	69.49	64.73	-4.76
Ankle Plant/Dorsi (X)	24.16	25.46	25.49	22.36	26.39	23.82	28.33	26.81	26.09	24.61	-1.48

Paired Two Sample for Means t-Tests were conducted for each joint range of motion tabulated above. No significant differences were found between Short and Long leg, or Pre and Post trials, at each joint across all participants ($p > 0.05$ at all joints).

DISCUSSION

As would be expected with such a small sample size, there were multiple variables whose influences could not be accounted for, such as sex, age, and BMI. The variation in number of gait cycles reported for each participant is secondary to the "cleaning" process in GOAT software. Those with a lower number of reported gait cycles had more missteps during their walking trial, which were then removed from the data set using GOAT. Those with a high number of gait cycles had fewer missteps.

1) Static Measures

   a. *Center of Pressure – Force*

The static ground reaction forces (GRFs) unfortunately did not reveal any significant improvement in the weight balance between the long and short legs after treatment with a heel lift. Ratios between the GRFs of the long and short legs were used to account for the differences in weight between participants. Figure 2 A & B show participants 1 and 4 having a Pre treatment ratio greater than 1.0, indicating more force applied through the long leg. Participants 2 and 3 began with more force applied through the short leg. This same event does not hold true in the shoulder-width apart trials. Participants 1,2, and 4 had more force on the long leg, as seen in Figure 2 C & D. It is not frankly evident why Participant 3 applied more force through the Long leg with feet side by side, and applied more force through the short leg when feet were shoulder-width apart. It may be that because of a narrow stance, the Participant is unable to shift her center of mass to a favorable point, thereby causing more force to enter the long leg. In contrast, when feet are shoulder-width apart, the center of mass theoretically shifts lateral towards the short leg.

This explanation is supported by the finding that the participant's GRFs became more symmetrical after the LLI was treated with the heel lift. In Figure 2 B, Participant 4 showed an increased asymmetry with larger force on the short leg during the feet side-by-side eyes closed trial, but GRF symmetry improved in the feet shoulder-width apart eyes closed trial (Figure 2 D). Participant 4's eyes open trials showed either no change, or slight improvement post heel lift therapy. Therefore, no trend was found in regards to Participant 4 having a vestibular issue. Interestingly, Participant 2 showed a trend of worsening symmetry across all four scenarios, while the other participants, except as noted earlier, showed an improvement by moving towards 1.0. With more participants, it is theorized that a significant improvement in the symmetry of ground reaction forces in quiet standing will be observed.

b. Center of Pressure - Sway

The goal of static sway measurement in this study was to observe if treatment of LLI with heel lift therapy would cause significant changes in the amount of anteroposterior and mediolateral sway that occurs with quiet standing. Our hypothesis was based on the idea of shifting each extremity's center of pressure to a more symmetrical position, creating less AP and ML sway of the net COP during standing. Gurney stated a study conducted by Mahar et al. detected an increase in mediolateral sway after inducing an artificial LLI of 10mm.[1] The amount of sway seen with each participant fell within the normal range of sway in healthy adults measured in a previous study on sway using similar body marker set and software.[31] The average nCOP sway area, although not significantly, increased by roughly 44%. The area itself, however, was smaller than that reported in two studies investigating COP sway area in young, healthy adults. Lin et al. found a COP sway area of 41.7 +/- 23.2cm, while Santos et al. reported 20.9 +/- 8.2cm.[32,33] Figure 7B shows a Pre value of 7.01 +/- 0.9cm, and a Post value of 10.1 +/- 3.8cm.

On the other hand, one control group from a neurological study investigating early Parkinson's Disease reported a COP sway area of 10.70 with an SEM of 1.58.[34] Therefore it is difficult to conclude whether or not the sway area calculated herein is different from normal values.

2) Dynamic Measures – Walking Trial

No significant difference in 2D stride variables (mean walking speed, mean stride length, mean stride time) was found. This may be due in part of the analysis software averaging the short and long legs together to create a single average speed and stride value for each participant. There was substantial variability in the number of cycles analyzed between participants. This was due to the "cleaning" process, in which many steps were visually deemed inappropriate for analysis secondary to different factors: misstepped onto the contralateral tread/force plate, dragged their toe on the treadmill, or dragged their heel on the treadmill.

a. Center of Mass

The virtual pelvis marker created as the point between the ASISes and PSISes worked well as a means of tracking each individual in three dimensions during the walking trial. The values within Table 5 fall within a similar range of normal values of COM displacement in the mediolateral and superior/inferior direction.[35] The mediolateral displacement of the COM was significantly increased across all four participants. We believe that through equalizing leg lengths with a heel lift and providing osteopathic manipulative treatment to increase mobility of the lumbar spine and sacroiliac joints, the pelvis becomes less hindered to motion, and therefore increases its mediolateral displacement. This claim, however, has not yet been validated to my knowledge. Vertical displacement has been found to increase with increased pelvic rotation.[36] In this study, vertical displacement did not significantly decrease, which may be due in part to the insignificant decrease in pelvic rotation range of motion.

b. Joint Angular Range of Motion

The total range of motion encountered at each joint was measured by averaging the difference in peak and nadir of each major joint's kinematic dataset over 16-40 gait cycles, depending on how many cycles were purged from the dataset due to faulty measurement as previously described. The ranges calculated would not necessarily reflect the actual total range of motion possible at the joint, nor does the degree value calculated equate to the position of a joint in space. Walsh et al found that pelvic obliquity was the most common compensation in persons with a LLI less than 23mm. In the same study, they concluded that the hip and knee of the long leg have increased flexion compared to the short leg.[17] In Gurney's review of LLI, it was noted that the long leg would also have increased hip circumduction, with an ipsilateral upward pelvic obliquity to compensate.[1] It was therefore postulated in this study that there would be an improvement of lower extremity joints' ROM symmetry after heel lift therapy, specifically a compensatory decrease in knee and hip flexion of the long leg, as well as decreased circumduction on the long side.

Analyzed as a group, Pre visits versus Post visits, there was no significant difference in range of motion at the pelvis, both hips, both knees, or both ankles. Every joint range of motion decreased after heel lift therapy. This finding, when coupled with the identical stride lengths Pre and Post, suggests decreased requirement for extremity movement for the same amount of distance coverage. This may reflect decreased energy expenditure.

There was much variability within participants' visits, none of which however, proved significant. Ratios that were asymmetric by >10% (> 1.1 or < 0.9) were further probed for trends. Hip flexion symmetry improved in the participants with scoliosis (participants 3 and 4), and hip rotation symmetry worsened in participants with knee osteoarthritis (participants 1 and 2). These and other individual improvements are tabulated in Appendix C. The improved hip flexion symmetry in the scoliotic patients may be secondary to lumbar spine mobilization from osteopathic manipulative treatments received throughout the study period. It may also be due to improved flexion capability secondary to decreased varus positioning of the hip joint, which itself is a result of improved pelvic tilt.[25]

The decline in hip rotation symmetry in the arthritic participants may be due to increased hip circumduction to avoid heel drag. The rotation ROM increased on the Short leg in Participant 1, but on the Long leg in Participant 2. It may be due to external rotation at the ankle, which is a compensation mechanism in LLI during gait. Ankle external and internal rotation was not measured in this study; therefore no clear explanation can be given for this finding. Participant 4 had the most interesting changes to their joint ranges of motion in that three planes of motion at three different joints worsened after treatment. Worth noting was during their post visit, Participant 4 complained of moderate fatigue from lack of sleep the night before data collection. This may have contributed to their worsening ranges of motion. No participant had a significant change to their physical activity level post treatment, except for the stretching exercises each participant was given as part of their osteopathic manipulative treatment.

LIMITATIONS

1) Recruitment/Retention

The most evident limitation to our study was the low level of participants completing the required length of treatment. With only four participants completing the pre and post visits, we were unable to account for variations in gender, age, or chronicity of LLI. Due to conflicts, two of the four participants found it difficult to visit the OMM Clinic at their scheduled times. As this study was a pilot study, it can be said that certain aspects of the protocol used herein were beneficial while other portions will require changes prior to reevaluating gait in patients with LLI. For instance, due to long wait times at the patient clinic secondary to limited faculty, it was difficult for our participants to obtain their routine follow up visits within a two week period as per the protocol. Increased face time between the gait lab faculty and clinicians is imperative to maintain adequate recruitment and ensure proper follow up of active participants. Furthermore, there has been a recent increase in the number of available qualified physicians in the recruitment clinic which will help increase participant numbers. The attrition rate was high in this pilot for multiple reasons, the most common being participants did not feel they had adequate time to devote to the study. To aid in proper recruitment, a sample recruitment algorithm has been created to be used in UNTHealth clinics (Appendix D).

Timely rescheduling for Post visits were difficult due to participant schedules. Optimally, each participant would come into the gait lab for the Post visit soon after their last clinic visit at which their treatment culminated. In two participants, one month passed between their final clinic visit and their Post gait lab visit. This puts an unacceptable amount of time between the Post visit and the participant's last manipulative treatment.

2) Body Marker Set

Body marker placement was hindered by the style of safety harness used during the initial walking trial of Participant 1. This was remedied partially by implementing a different safety harness that did not obscure as many posterior body markers as the original harness. However, future researchers should find an alternative safety harness that may fit better (and not obscure body markers) and therefore incur fewer changes to participant's gait patterns. It may be possible to withhold the safety harness and instead use hand rails during the quiet standing trials in future studies, since the participants meeting inclusion criteria are able to stand and walk independently, and because the treadmill is not in motion. This recommendation is contrary to findings by Freitas et al. who found no significant difference in sway in individuals with and without a safety harness.[31] This is because participants vocalized tightness of fit and weight of the harness, which lead us to speculate it may in fact be interfering with standing. Some markers in close proximity to each other may have caused the participants to inadvertently change their gait patterns to avoid rubbing them together. For example, the medial femoral condyle reflective markers on each leg would sometimes rub together during walking and would loosen during the trial. These and other such markers should be independently evaluated for necessity based on the goals of future studies using the same marker set.

3) Data Analysis Software

The GOAT software at this time averages the stride length of both limbs into a single value. This made it temporarily impossible to calculate independent limb values of stride length, standing phase, and swing phase. In addition, software macros will be needed to help sift through the copious amounts of data during each trial in order to maximize efficiency in the lab, as the current time requirement for data analysis is not cost-effective. This will especially be the case when expanding the next trial to 50+ participants.

4) Effect of OMT, HLT, or Both?

The purpose of this study was not to find evidence suggesting OMT improves gait kinetics and kinematics alone. The utilization of OMT was based on standard of care practices for conservative treatment of musculoskeletal pain and somatic dysfunction in conjunction with other measures. It was a treatment to improve the patients' ability to quickly compensate to increases in their heel lifts.

5) Objective Outcomes from the Clinic

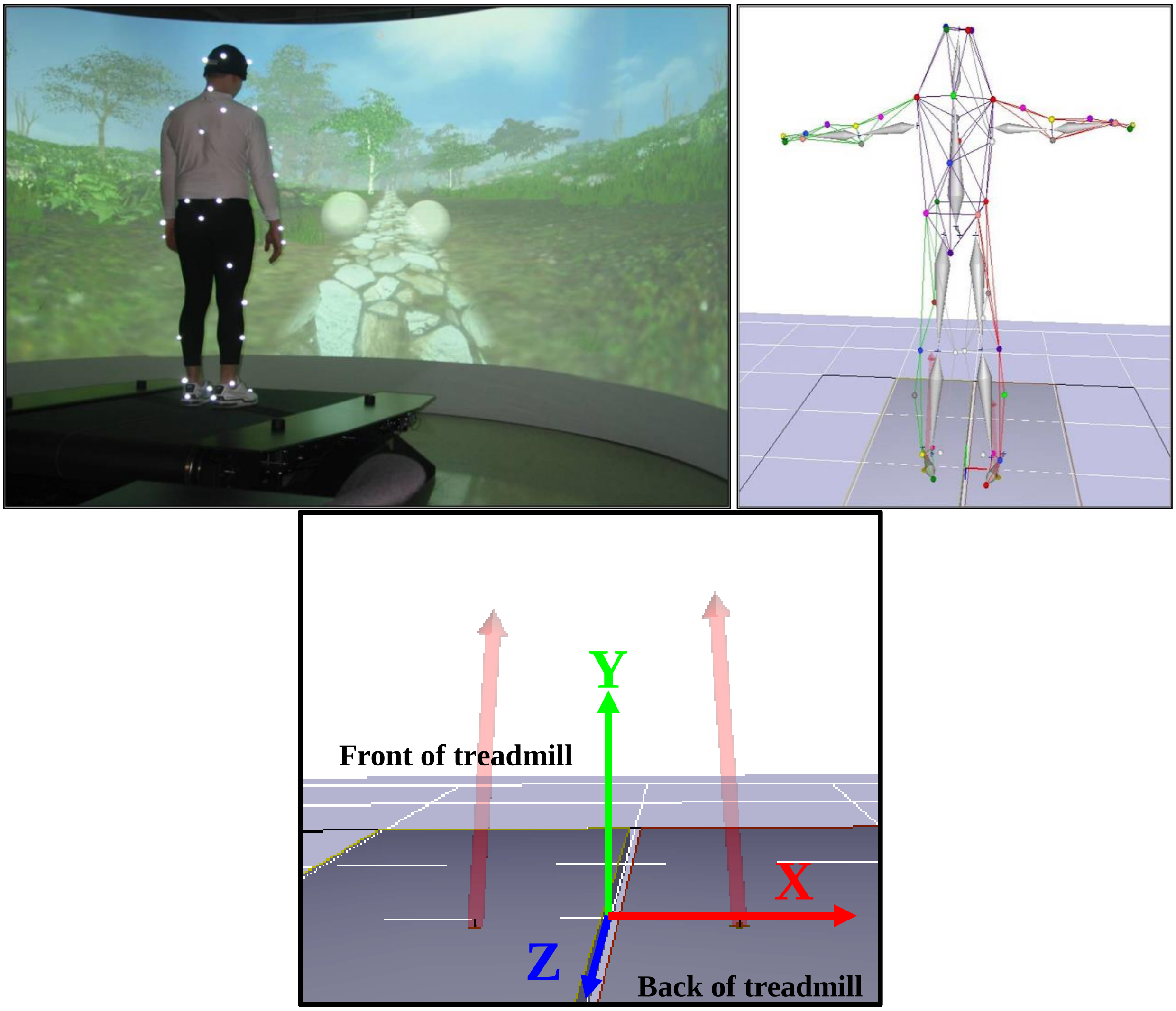
The major question regarding whether or not patients achieve optimal gait and pain relief with complete sacral leveling could not be assessed in this study due to the inability to obtain repeat standing postural x-rays. This was simply due to cost. With funding, a repeat standing AP Pelvic x-ray can be obtained to see if there is a correlation between the degree of sacral leveling and balance/gait improvement.

The collection of physical activity levels from the participants while in the clinic setting was not standardized with the use of a questionnaire. It is recommended that future studies incorporate the use of the International Physical Activity Questionnaire (iPAQ), as it has been validated in twelve countries, and can even be administered over the phone.[37]

CONCLUSIONS & RECOMMENDATIONS

This study provided pilot evidence of significant changes to mediolateral displacement in individuals treated for mild LLI with osteopathic manipulative treatment and a heel lift. No significant change in joint angle ranges of motion or static sway was found, but there is evidence of some underlying trends that may become significant with larger numbers of participants. Although our results show some promise in answering questions regarding limb kinetic and kinematic behavior during correction of LLI, more testing is necessary with a greater number of subjects before any clinical recommendation can be made regarding whether or not heel lift therapy significantly improves lower extremity kinetic and kinematic symmetry. Repeat postural x-rays linked with gait evaluation would be necessary to recognize if stopping heel lift progression at symptom resolution matches objective results of improved gait symmetry. We advocate the continued investigation of treating mild, structural leg length inequality with heel lifts in otherwise healthy persons to expand our understanding of the body’s compensatory patterns to the inequality as well as the heel lift therapy undertaken.

APPENDIX A



On the top left, a lab member demonstrates the interaction with the CAREN system. Note the treadmill, in which lie two force plates, as well as the large virtual display environment with which the participant can interact. On the top right, an interlinked body model shows the "Skeleton View" in the Cortex program. These interlinked markers correspond to the body markers on the subject seen in the left image. Bottom center is an example showing the 3D coordinate system placed at the center point in the middle of the treadmill. The two faint, upward red arrows are GRF vectors from the contact of both feet on the treadmill.

APPENDIX B

Ground Reaction Forces for each of the four quiet standing trials. Key: SA = feet shoulder-width apart, SS = feet side-by-side, EO = eyes open, EC = eyes closed, FP1 = force plate under left foot, FP2 = force plate under right foot. *p* Values are listed below.

SA, EO	PRE			POST			
	FP1	FP2	Ratio L/S	FP1	FP2	Ratio L/S	L/S =
1	439.90	476.71	1.08	459.26	479.54	1.04	FP2/FP1
2	421.10	400.52	1.05	389.31	415.30	0.94	FP1/FP2
3	356.86	352.43	0.99	353.96	350.77	0.99	FP2/FP1
4	374.22	328.15	1.14	372.04	333.94	1.11	FP1/FP2

SA, EC	PRE			POST			
	FP1	FP2	Ratio L/S	FP1	FP2	Ratio L/S	L/S =
1	425.09	490.40	1.15	459.48	479.03	1.04	FP2/FP1
2	418.86	403.30	1.04	384.75	421.01	0.91	FP1/FP2
3	356.12	353.05	0.99	351.16	353.61	1.01	FP2/FP1
4	364.30	337.73	1.08	349.04	356.27	0.98	FP1/FP2

SS, EO	PRE			POST			
	FP1	FP2	Ratio L/S	FP1	FP2	Ratio L/S	L/S =
1	449.73	477.21	1.06	461.83	481.05	1.04	FP2/FP1
2	382.32	440.94	0.87	366.03	441.42	0.83	FP1/FP2
3	389.83	322.69	0.83	365.37	342.09	0.94	FP2/FP1
4	357.88	349.82	1.02	356.27	350.36	1.02	FP1/FP2

SS, EC	PRE			POST			
	FP1	FP2	Ratio L/S	FP1	FP2	Ratio L/S	L/S =
1	450.83	475.56	1.05	458.61	483.56	1.05	FP2/FP1
2	385.85	437.79	0.88	350.51	457.40	0.77	FP1/FP2
3	383.67	328.41	0.86	371.54	335.58	0.90	FP2/FP1
4	360.31	347.57	1.04	385.85	437.79	0.88	FP1/FP2

Condition	p Value
SS, EO	0.756
SS, EC	0.324
SA, EO	0.175
SA, EC	0.090

APPENDIX C

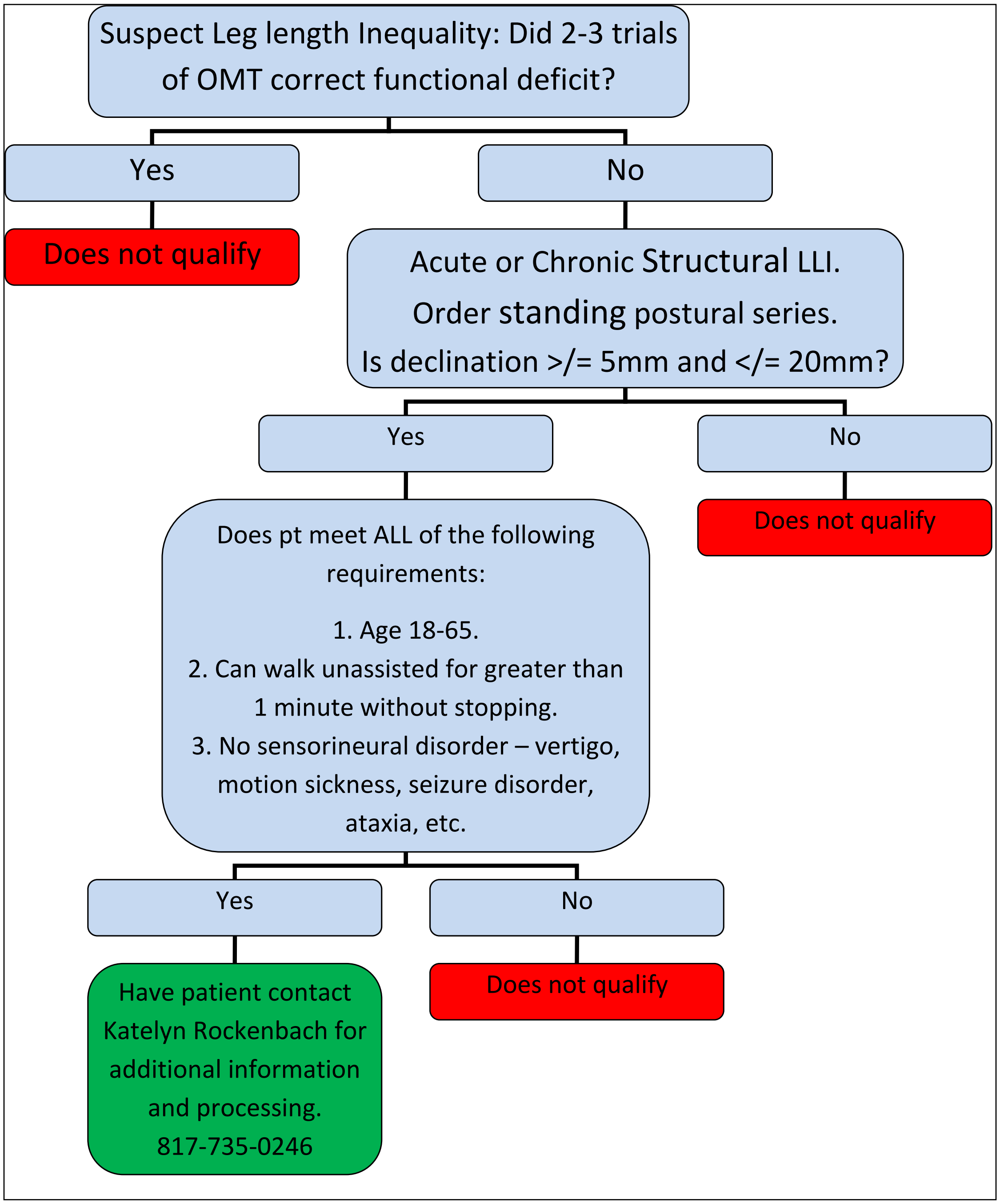
Joint ranges of motion (in degrees) reorganized from Tables 6 & 7 into individual participant sections. Key: orange = worsened symmetry Post compared to Pre, green = improved symmetry Post compared to Pre, * symbol = ratio falls greater than 10% away from 1.0.

Participant 1					Participant 2				
PRE	Long	Short	Ratio L:S		**PRE**	Long	Short	Ratio L:S	
Pelvic Obliquity (Z)	7.56	7.51	1.01		Pelvic Obliquity (Z)	19.09	19.18	1.00	
Pelvic Rotation (Y)	10.63	10.49	1.01		Pelvic Rotation (Y)	5.39	5.40	1.00	
Pelvic Tilt (X)	4.09	4.09	1.00		Pelvic Tilt (X)	4.82	4.76	1.01	
Hip Flex/Ext (X)	45.06	44.08	1.02		Hip Flex/Ext (X)	41.39	43.11	0.96	
Hip Rotation (Y)	17.26	16.65	1.04		Hip Rotation (Y)	8.53	19.76	0.43	*
Hip AB/AD (Z)	20.62	18.98	1.09		Hip AB/AD (Z)	27.11	21.69	1.25	*
Knee Flex/Ext (X)	63.18	66.63	0.95		Knee Flex/Ext (X)	63.44	77.30	0.82	*
Ankle Plant/Dorsi (X)	24.85	24.16	1.03		Ankle Plant/Dorsi (X)	23.03	25.49	0.90	
POST	Long	Short	Ratio L:S		**POST**	Long	Short	Ratio L:S	
Pelvic Obliquity (Z)	8.36	8.31	1.01		Pelvic Obliquity (Z)	11.43	11.39	1.00	
Pelvic Rotation (Y)	7.42	7.56	0.98		Pelvic Rotation (Y)	4.40	4.31	1.02	
Pelvic Tilt (X)	4.83	4.70	1.03		Pelvic Tilt (X)	3.98	3.81	1.05	
Hip Flex/Ext (X)	45.04	45.26	1.00		Hip Flex/Ext (X)	40.01	39.08	1.02	
Hip Rotation (Y)	15.84	22.08	0.72	*	Hip Rotation (Y)	15.07	8.13	1.85	*
Hip AB/AD (Z)	20.76	19.54	1.06		Hip AB/AD (Z)	18.13	16.83	1.08	
Knee Flex/Ext (X)	65.12	69.19	0.94		Knee Flex/Ext (X)	59.65	58.28	1.02	
Ankle Plant/Dorsi (X)	25.51	25.46	1.00		Ankle Plant/Dorsi (X)	21.27	22.36	0.95	
	p = 0.23					*p = 0.29*			

Participant 3					Participant 4				
PRE	Long	Short	Ratio L:S		**PRE**	Long	Short	Ratio L:S	
Pelvic Obliquity (Z)	22.09	22.09	1.00		Pelvic Obliquity (Z)	8.61	8.68	0.99	
Pelvic Rotation (Y)	8.50	8.54	1.00		Pelvic Rotation (Y)	9.78	10.19	0.96	
Pelvic Tilt (X)	3.03	2.97	1.02		Pelvic Tilt (X)	3.58	3.51	1.02	
Hip Flex/Ext (X)	46.33	41.34	1.12	*	Hip Flex/Ext (X)	40.68	45.58	0.89	*
Hip Rotation (Y)	12.79	20.04	0.64	*	Hip Rotation (Y)	6.83	9.23	0.74	*
Hip AB/AD (Z)	24.92	25.20	0.99		Hip AB/AD (Z)	11.16	10.75	1.04	
Knee Flex/Ext (X)	72.22	67.48	1.07		Knee Flex/Ext (X)	58.94	66.54	0.89	*
Ankle Plant/Dorsi (X)	26.28	26.39	1.00		Ankle Plant/Dorsi (X)	31.22	28.33	1.10	*
POST	Long	Short	Ratio L:S		**POST**	Long	Short	Ratio L:S	
Pelvic Obliquity (Z)	13.64	13.69	1.00		Pelvic Obliquity (Z)	12.47	12.34	1.01	
Pelvic Rotation (Y)	8.86	8.90	1.00		Pelvic Rotation (Y)	7.33	7.36	1.00	
Pelvic Tilt (X)	2.63	2.49	1.06		Pelvic Tilt (X)	3.46	3.28	1.05	
Hip Flex/Ext (X)	41.23	41.09	1.00		Hip Flex/Ext (X)	41.70	44.05	0.95	
Hip Rotation (Y)	7.44	6.84	1.09		Hip Rotation (Y)	3.54	6.37	0.56	*
Hip AB/AD (Z)	18.04	19.48	0.93		Hip AB/AD (Z)	16.45	16.12	1.02	
Knee Flex/Ext (X)	57.82	62.79	0.92		Knee Flex/Ext (X)	57.30	68.66	0.83	*
Ankle Plant/Dorsi (X)	32.08	23.82	1.35	*	Ankle Plant/Dorsi (X)	33.59	26.81	1.25	*
	p = 0.44					*p = 0.88*			

APPENDIX D

Sample algorithm for participant recruitment from clinic.



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