

Asymmetry in Clinical and Running Gait  
Measures in Injured and Healthy Runners

By

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## **An Abstract of the Thesis of**

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This study assessed kinematic asymmetry clinically and during running gait for both injured and healthy runners at the hip, knee, and ankle. This study consists of two parts: 1) a primary evaluation of correlations between extent of range of motion (ROM) asymmetry measured clinically and during running in a healthy population and 2) an assessment of differences between asymmetry in injured runners with Achilles tendinopathy (AT) and medial tibial stress syndrome (MTSS), and their matched controls.

Asymmetry during running gait was collected while subjects ran continuous loops in the laboratory. A trained clinician assessed for measures of clinical asymmetry using a goniometer. The extent of asymmetry at each joint was quantified through the symmetry index (SI).

A significant moderate correlation was noted in the internal hip rotations between clinical asymmetry and during running gait ( $r = 0.443$ ;  $p = 0.01$ ). While these results do show potential correlations between clinical and running joint kinematic asymmetries, further investigation is required to determine any causal conclusions as to

whether or not modifications in static asymmetry may translate to better symmetry in running. No other significant correlations were noted.

A significant difference between the SIs of injured runners and matched controls was detected in the ankle dorsiflexion ( $p=0.037$ ) ROM of clinical assessment. During running gait, significant differences in SIs between groups were detected in the peak ankle dorsiflexion ( $p = 0.012$ ) and dorsiflexion ROM ( $p = 0.004$ ). These results indicate that lower extremity injuries, such as AT and MTSS, present with significantly increased amounts of asymmetry with ankle dorsiflexion and ROM during running. Clinically, similar differences are observed with the peak dorsiflexion with the knee extended. Given healthy runners were noted to have a correlation between the asymmetry present clinically and during running gait, these results may have relevant implications clinically.

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# INTRODUCTION

## Health Benefits Associated with Running

With the increasing prevalence of chronic metabolic diseases such as obesity, type 2 diabetes, coronary artery disease, and cancer, clinical and research efforts have shifted towards preventative measures for such illnesses. Aerobic exercise, particularly running, is a popular approach which is associated with reduced risk for development of chronic conditions (Thompson, 2003). The benefits of aerobic exercises expand beyond metabolic disease prevention. Previous studies have shown that aerobic exercise may be involved in the modification of gene expression through modulation of histone acetylation, which essentially delays the deleterious effects of aging (Denham et al, 2014). Running is recognized as one of the most iconic forms of aerobic exercise. Given the plentiful benefits associated with running, the activity has grown in popularity, regardless of age. Per USA Track and Field, it is estimated that 35.9 million Americans engage in the activity of running with roughly 10.5 million individuals running a minimum of 100 days per year (Willson et al, 2011). As health awareness becomes more widespread, it can be predicted that the popularity of running will continue to grow, increasing the population of running Americans.

## Running Injuries: Prevalence and Consequences

Despite its many benefits, there are drawbacks to running. Although reported rates of injury vary due to differing criteria of injury among institutions, the rate of running related injuries has been found to be between 19%-79% (Teng et al, 2014). Even at the lower estimated range for injury occurrence, running injuries affect a massive population. Moreover, these unacceptably high rates of injury have been

persistent through the years despite significant efforts to reduce injury through advancements in shoe technology, training style, and research (Van Gent et al, 2007).

In a systematic review conducted on evaluating the incidence and prevalence of the most common running-related musculoskeletal injuries, it was found that medial tibial stress syndrome (MTSS) has both the highest prevalence and incidence, followed by Achilles tendinopathy, and plantar fasciitis in the total population, but that Achilles tendinopathy and patellofemoral pain syndrome were the most common injuries in ultramarathon runners (Lopes et al, 2012). Unfortunately, these ailments are not only common, they also tend to be notoriously chronic and may persist for extended periods of time. Prevention for such injuries has classically been categorized into those involving equipment or training (McBain et al, 2012). For running, the focus is on injury prevention through training intervention, especially of range of motion. The implications of these astoundingly high injury rates on medical costs and life style establishes an urgent need to address this issue.

### *Achilles Tendinopathy*

Although the Achilles tendon is the largest tendon in the body, it is also most disposed to injury during running. Of all Achilles tendon related injuries including Achilles tendonitis and Achilles rupture, Achilles tendinopathy is the most common, accounting for 55-65% of all Achilles overuse injuries (Järvinen et al., 2005). Despite the high prevalence of Achilles tendinopathy in the general population, very little is known of the mechanism of injury. Achilles tendinopathy is characterized by decreased stability of the tendon due to an increase in degeneration of collagen fibers and tendon tissue, with an associated decrease in recovery of these same tissues (Longo et al,

2009). Many predisposing risk factors have been identified, including mechanically induced strain (Constantinos et al, 2008).

### *Medial Tibial Stress Syndrome*

Medial tibial stress syndrome (MTSS), which is commonly referred to as shin splints, is characterized by pain localized to the posteromedial tibial border, and arises as a product of increased bone resorption, and decreased bone formation (Moen et al, 2009). Predisposing factors for this injury include prior history of MTSS, female sex, and excessive pronation of the foot (Moen et al, 2009). Although some amount of pronation helps to absorb external ground forces through absorption of the impact by soft tissues, prolonged pronation can lead to injury of these absorptive structures (Becker and Chou, 2013).

Physicians will often examine musculoskeletal injuries through the mnemonic “TART” which addresses Tenderness, Asymmetry, Restricted motion, and Tissue Texture abnormality (Galbraith and Lavallee, 2009). This study will focus on the measures of asymmetry and motion in attempt to identify possible preventative efforts.

### Significance of Stretching and Joint ROM in Injury and Performance

It is commonly believed that stretching, by an increase in flexibility, may help to reduce the risk of injury. However, previous studies on this topic have found the relationship between flexibility and injury risk to be inconclusive, especially in terms of dynamic flexibility (Weerapong et al, 2004). Flexibility is essentially a measure of the elasticity of ones’ muscle, connective tissue, and surrounding ligaments which is typically assessed through range of motion (ROM), but the exact approaches differ from institute to institute. The argument in support of flexibility in injury prevention has

traditionally been based around the notion that lower flexibility translates to stiff muscles which increases stress on joints, leading to compensation and poor mechanics (Hreljac et al, 2000). Despite this, stretching muscles, be it pre- or post-activity, has not shown significant evidence of being effective in reducing risk of injury (Hreljac et al, 2000). This contradicts the common view of stretching as an effective modality for increasing flexibility and decreasing injury. What limits these studies is the lack of attention to measures of both static and dynamic flexibility. Static flexibility is evaluated by examining the ROM present when the subject is at rest, and is the typical clinical approach to assessing flexibility. Dynamic flexibility on the other hand, measures ROM during an active task. Although both approaches attempt to measure flexibility, a relationship between the two cannot be adequately assessed through prior studies (Thacker et al, 2004). Discerning a relationship between static and dynamic flexibilities may be helpful for clinicians to form effective, personalized treatment plans for patients.

#### Significance of Clinically Assessed Measures of ROM

Clinically assessed measures of ROM were selected for their relevance to running injuries, particularly AT and MTSS. Although ankle dorsiflexion has not been identified to be a significant risk factor for medial tibial stress syndrome (Hamstra et al, 2015), a limited dorsiflexion ROM has been found to increase the risk for developing Achilles tendinopathy (Rabin et al, 2014). Muscles involved in plantar flexion have been identified to absorb some impact during running (Rabin et al, 2014), and increase plantarflexion has been noted to be a risk factor for developing MTSS (Hamstra et al, 2015). It has further been noted that increased activation of muscles involved in

plantarflexion may increase loading and contribute to Achilles tendinopathy (Muneanu and Barton, 2011).

Decreased range of motion with hip internal rotation statically and increased excursion during running gait, have also been found to be linked to a greater risk for MTSS development (Becker and Chou, 2013). Additionally, increased external hip rotation has been found increase risk of developing MTSS in males (Newman et al, 2013). Distally, subtalar joint inversion and eversion have been found to be increased in patients with MTSS (Akiyama et al, 2015).

This study also inspected hamstring, quadriceps, and gastrocnemius flexibility, as well as 1<sup>st</sup> metatarsophalangeal joints and arch height ratio to assess for any novel differences.

#### Significance of Asymmetries in Running

Etiologies of running injuries are highly specific to an individual and the nature of their training. It has been postulated that running injuries stem from both intrinsic factors, such as an individual's past medical history, running experience and technique, body mass index, physical strength, and flexibility and extrinsic factors such as shoe selection, and training intensity (Daoud et al, 2012). Although extensive investigations of running injuries have been conducted to determine why common injuries occur, research on why a particular limb and the other sustains an injury is lacking. Previous studies have revealed that within the injured population of runners, there is a 50% higher chance of recurring an injury to the previously effected limb (Zifchock and Davis, 2005). This suggests there may be underlying factors which predispose one limb to a greater risk of injury and the other. The asymmetric development of injuries is

particularly interesting because running is a very symmetric activity, in that forces are exerted by and to both limbs at similar to equal rates.

Asymmetries in strength, structure, and one's running mechanics have been found to play a role in increasing the risk of one developing an injury (Zifchock et al, 2008). While asymmetries in strength and structure have thoroughly been investigated in the past, but there seems to be a gap of knowledge when it comes to asymmetries in flexibility.

### Purposes and Hypotheses of the Study

The purpose of this research was to investigate the implications of asymmetry in joint range of motion obtained during clinical assessment and running, in regards to injury risk and prevention. This was accomplished by identifying any correlations between clinical and running gait asymmetries at the hip, knee, and ankle, and by comparing the extent of asymmetry in injured and healthy runners. It has been well established that joint strength asymmetries, as well as asymmetries in anthropometric measures, may predispose an individual to developing an overuse injury (Zifchock and Davis, 2005). However, the extent of asymmetry and relationship between clinical and running gait measures of range of motion has not been well studied. Establishing a relationship between these two types of measurements may assist in determining how clinically assessed asymmetries may translate into an individual's running mechanisms. Further, comparison of asymmetries between injured and healthy runners may help to identify select areas for therapists and physicians to focus on during treatment.

I hypothesize that clinical and running asymmetries at the hip and ankle, but not knee will be correlated, and that in injured runners, there will be significant difference in asymmetry with motions at the ankle.

## **METHODS**

### Subjects Inclusion Criteria

Subjects for this study were identified retrospectively from a prior study performed on running biomechanics and injury at the University of Oregon. Two subject groups were formed: an injured and healthy population. All subjects were between 18-60 years old. Injured subjects were included if they were currently symptomatic for either AT or MTSS as diagnosed by a clinician and were averaging greater than 20 miles per week before injury. 21 subjects met these criteria, 13 of which were symptomatic for AT and 8 of which were symptomatic for MTSS. Healthy controls reported no injuries for at least 6 months prior to testing and were matched with injured individuals based on sex, weekly mileage, age, and foot strike pattern.

### Experimental Equipment

#### *Data Collection*

A ten-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz was used to record the three-dimensional marker trajectories. A modified Helen Hayes marker set (Kadaba et al., 1990) and multi-segmented foot model (Carson et al., 2001) of 39 reflective markers was used to track body segments. These segments included the forefoot, rearfoot, shank, thigh, pelvis, trunk, arm, forearm, hand, and head.

The protocol was completed in shoes which subjects normally wore for their training. Forefoot markers were placed on subjects' shoes between the 1<sup>st</sup> and 2<sup>nd</sup> metatarsal heads, the base of the 5<sup>th</sup> metatarsal, and the navicular tuberosity. For the rearfoot, three total markers were used. Two were placed on the vertical bisection of the

heel counter and one was placed over the lateral aspect of the heel (Carson et. al, 2001, McClay & Manal, 1998; Noehren et. al., 2007). The shank was identified through placement of markers at the medial and lateral malleoli, as well as at the medial tibia. The thigh was defined by marker placement at medial and lateral femoral condyles, and also midline to the lateral femoral epicondyle and greater trochanter. Markers were placed at the left and right anterior superior iliac spines and between the posterior the iliac spines to define the pelvic segment. Upper extremity markers were placed at the lateral epicondyles of the humerus, between the ulnar and radial styloid processes, and on the hands. The head segment was identified by placement of two markers superior to the subjects' ears.

Following a static calibration trial, subjects ran continuous laps at a self-selected easy pace in the Motion Analysis Laboratory. Each lap was approximately 40-meters long.

#### *Clinical Assessment of Range of Motion*

Static flexibility and ROM were assessed by a trained clinician using a goniometer at the hip, knee, ankle, and foot with the subject seated on a treatment table. Specific measurements included hamstring flexibility, quadriceps flexibility, gastrocnemius flexibility, leg varus to floor, extremity length, ankle dorsiflexion, ankle plantarflexion, hip internal rotation, hip external rotation, subtalar joint inversion, subtalar joint eversion, 1st MPJ joint ROM, and arch height ratio. Measurements of flexibility were performed as follows. Quadriceps flexibility was measured with subjects prone. Subjects placed one leg straight while flexing their contralateral knee to its furthest capacity. A goniometer was used to measure the angle between the table and

their lower leg. Hamstring flexibility was measured with subjects supine. The hip and knee of one leg were bent to 90° while the opposite leg lay straight. Subjects then attempted to straighten their leg. A goniometer was used to measure the angle between their lower leg and vertical. Gastrocnemius flexibility was assessed through having the subject dorsiflex their ankle while lying supine with their knee fully extended. A goniometer was used to measure the degrees lacking from vertical. Leg varus to floor was evaluated by measuring the angle of deviation of the talocrural joint in neutral from vertical.

At the hip, extremity length was found using the location of the subject's superior anterior iliac spine and medial malleolus, and measuring the distance between the two. Internal and external rotation of the hip were measured with the subject lying prone and knee flexed to 90 degrees. The clinician was then able to internally and externally rotate the hip and measure the angle of deviation by placing the axis of the goniometer at the patella and stationary arm perpendicular to the floor.

Ankle dorsiflexion was assessed by having the subject lie prone on the examination table with their knee flexed to 90 degrees in order to mitigate the impact of gastrocnemius tightness on ROM. Plantarflexion was measured with the subject lying supine and maximally plantarflex. With the subject prone and the ankle dorsiflexed, subtalar joint inversion and eversion were evaluated. Range of motion at the 1<sup>st</sup> metatarsal phalangeal joint was measured by passively bringing the 1st toe into dorsiflexion. Arch height ratio was calculated by measuring the arch height at half the foot length and dividing it by the truncated foot length.

*Hamstring Flexibility*



*Quadriceps Flexibility*



*Subtalar Inversion/Eversion*



*Hip Internal Rotation*



*Hip External Rotation*



*Ankle Dorsiflexion*



*Ankle Plantar Flexion*



*Ankle Dorsiflexion*



*Leg Varus to Floor*

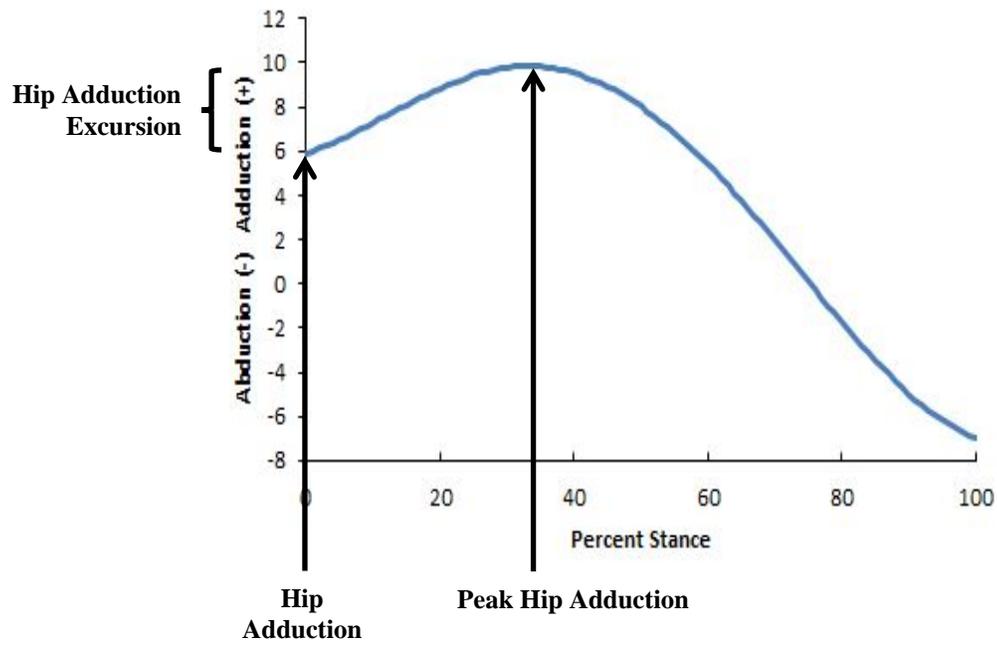


## Data Analysis

### *Kinematic Data during Overground Running*

Cortex 4.0 motion capture software (Motion Analysis Corp., Santa Rosa, CA) was used to identify marker trajectories for running gait. Analysis was focused on the stance phase of gait, with the period starting at heel strike and ending at toe-off.

Joint and segment angles were calculated using a custom LabView program (National Instruments, Austin, TX). Average joint angles in each cardinal plane of motion were measured. The peak angle of motion was found by identifying the maximal degree of motion achieved. Joint excursion was defined by the difference between the angle at initial contact and the peak angle.



**Figure 1: Angle at initial contact and peak hip adduction**

### *Symmetry Index*

Asymmetry between limbs of static clinical assessment or dynamic running was calculated using the symmetry index (SI) (Zifchock et al, 2008), as defined by the equation below, where  $X_R$  is the amount of joint excursion in the right limb, and  $X_L$  is the amount of joint excursion in the left limb:

$$SI = \frac{|X_R - X_L|}{0.5 (X_R + X_L)} \times 100$$

### Statistical Analysis

Pearson correlation coefficients were used to test the strength of the relationship between clinical SIs and running gait SIs at the hip, knee, and ankle in healthy runners. Specifically, asymmetry in peak hip adduction and peak internal rotation during running were correlated with external hip rotation and internal hip rotation clinically. At the knee, peak knee flexion and adduction during running were compared to hamstring and quadriceps flexibility, assessed clinically. At the ankle, peak ankle dorsiflexion during running was correlated to static dorsiflexion ROM with the knee both flexed and extended. Peak ankle dorsiflexion during running was also correlated to static plantarflexion ROM. Because clinical tests will evaluate for maximal joint motion, peak motion rather than ROM was selected as a measure for correlation. Correlation coefficients ( $r$ ) between  $\pm 0.10$  and  $\pm 0.30$  were identified as weak relationships, correlation coefficients between  $\pm 0.3$  and  $\pm 0.7$  were considered moderate, and correlation coefficients greater than  $\pm 0.7$  were considered strong. The alpha-level was set to 0.05 for all statistical tests.

Independent sample t-tests were then performed to ascertain any significant differences between the injured and healthy populations both for clinical and running

gait measures. A significance level of  $p < 0.05$  was used. The alpha-level was set to 0.05 for all statistical tests.

## RESULTS

### Correlation Analysis Between Clinical and Running Gait SIs

A moderate, significant relationship was found in the dorsiflexion joint excursion SIs between running gait and clinical assessment ( $r = 0.44$ ;  $p = 0.01$ ). No other significant correlations were identified, as summarized in Tables 1-3. Despite this moderate correlation, it appears that an outlier is driving this correlation (see Figure 1).

**Table 1.** Pearson correlation coefficients for running and clinical measures at the hip

<b>Measure</b>	<b>Correlation</b>
Peak Hip Adduction (running) to Static External Hip Rotation	-0.11
Peak Hip Adduction (running) to Static Internal Hip Rotation	0.09
Peak Internal Hip Rotation (running) to Static External Hip Rotation	-0.02
Peak Internal Hip Rotation (running) to Static Internal Hip Rotation	0.22

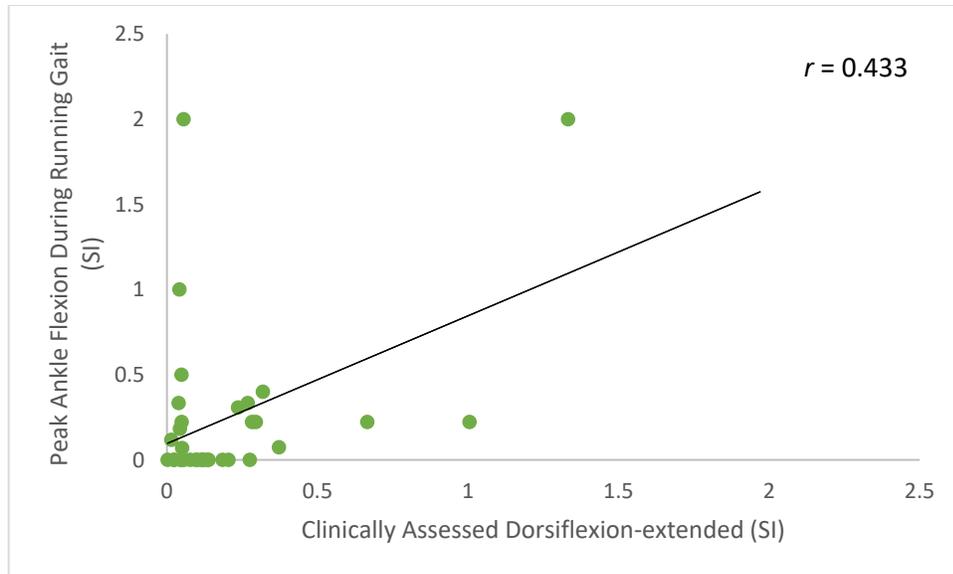
**Table 2.** Pearson correlation coefficients for running and clinical measures at the knee

Measure	Correlation
Peak Knee Flexion (running) to Quadriceps Flexibility	0.00
Peak Knee Flexion (running) to Quadriceps Flexibility	0.12
Peak Knee Adduction (running) to Hamstring Flexibility	0.03
Peak Knee Adduction (running) to Quadriceps Flexibility	0.02

**Table 3.** Pearson correlation coefficients for running and clinical measures at the ankle

	Correlation
Peak Dorsiflexion (running) to Dorsiflexion (knee flexed)	0.43*
Peak Dorsiflexion (running) to Dorsiflexion (knee extended)	0.25
Peak Dorsiflexion (running) to Plantar flexion (knee extended)	-0.11

\*Indicates a significant correlation,  $p < .05$



**Figure 2: Correlation between clinical ankle flexion and dorsiflexion during running gait**

Group Comparisons: Clinical Measures

Mean symmetry for anthropometric and flexibility measures are summarized in Table 4, and mean symmetry values from clinical assessments are shown in Table 5. A significant difference between average symmetry values in healthy and injured runners was observed during ankle dorsiflexion with the knee extended ( $p = 0.037$ ). These differences in average symmetry are displayed in Figure 2.

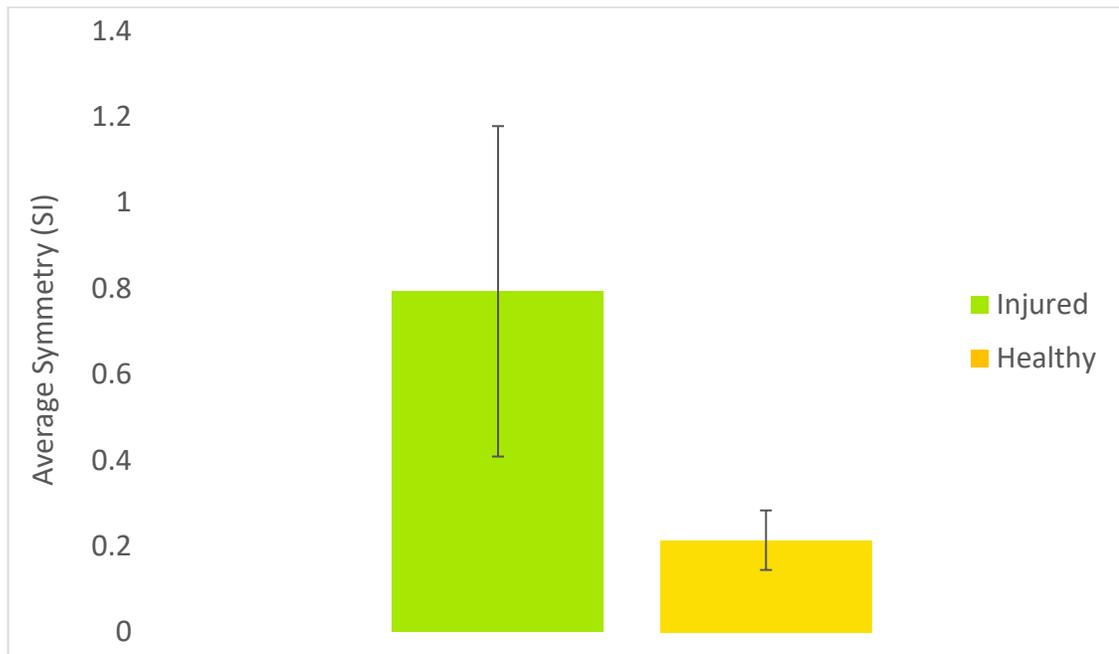
**Table 4.** Differences in SI of anthropometric and flexibility measures

Measure	Injured Average Asymmetry (SI)	Healthy Average Asymmetry (SI)	<i>p</i> -value
Leg Varus to Floor	0.163 ± 0.5	0.103 ± 0.16	0.629
Extremity Length	0.002 ± 0.004	0.004 ± 0.004	0.233
Quadriceps Flexibility	0.016 ± 0.021	0.029 ± 0.03	0.814
Hamstring Flexibility	0.167 ± 0.237	0.364 ± 0.57/	0.205
Arch Height Ratio	0.047 ± 0.06	0.051 ± 0.042	0.138

**Table 5:** Differences in SI of clinically assessed ROMs

Measure	Injured Average Asymmetry (SI)	Healthy Average Asymmetry (SI)	p-Value
Ankle Dorsiflexion (extended)	0.794 ± 0.942	0.214 ± 0.269	0.037*
Ankle Dorsiflexion (flexed)	0.118 ± 0.167	0.2 ± 0.248	0.431
Ankle Plantarflexion (flexed)	0.064 ± 0.063	0.062 ± 0.064	0.910
Internal Hip Rotation	0.097 ± 0.102	0.147 ± 0.21	0.393
External Hip Rotation	0.126 ± 0.154	0.199 ± 0.269	0.339
Subtalar Joint Inversion	0.188 ± 0.257	0.286 ± 0.23	0.241
Subtalar Joint Eversion	0.294 ± 0.279	0.202 ± 0.3	0.354
1 <sup>st</sup> MPJ ROM	0.117 ± 0.093	0.124 ± 0.114	0.860

\*Indicates a significant correlation,  $p < .05$



**Figure 3:** Differences in clinically assessed ankle flexion asymmetry between healthy and injured runners

### Group Comparisons: Running Measures

Mean symmetry for kinematic differences during running gait are summarized in Table 7. A significant difference between average symmetry in healthy and injured runners was observed during peak dorsiflexion ( $p = 0.012$ ) and dorsiflexion ROM ( $p = 0.004$ ). These differences are presented in Figures 3-6, along with differences in peak and ankle ROM in the frontal plane. Group demographics are summarized in Table 6.

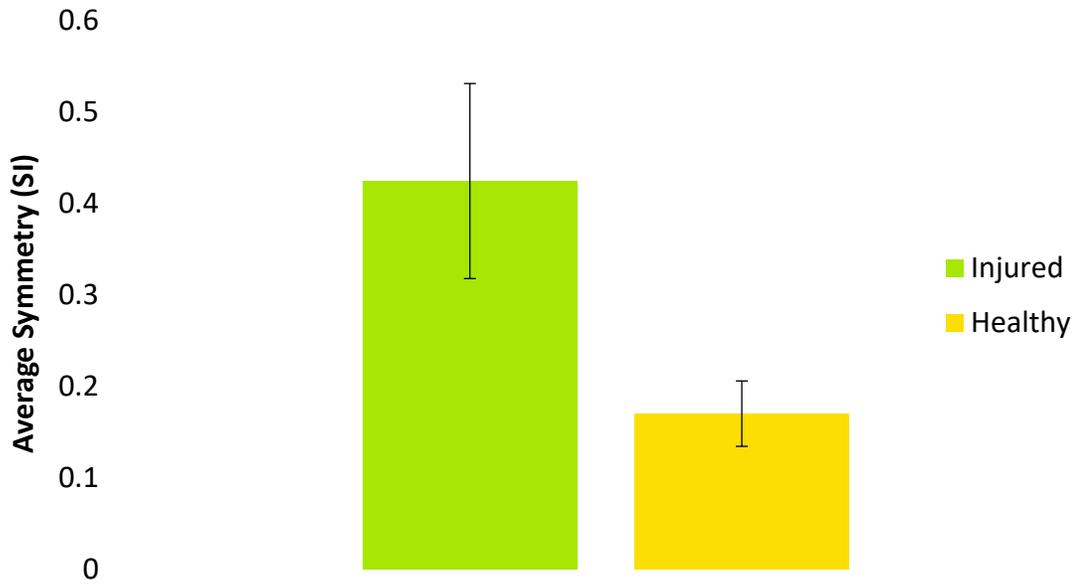
**Table 6.** Injured and healthy subject demographics

	<b>Injured</b>	<b>Healthy</b>	<b><i>p</i>-value</b>
Average Age	36.2 ± 14.0	34.0 ± 11.3	0.47
Average Height	175.2 ± 10.1	177.6 ± 10.0	0.44
Average Weight	69.2 ± 13.1	73.6 ± 16.4	0.35
Average Speed	3.5 ± 0.4	3.4 ± 0.6	0.71

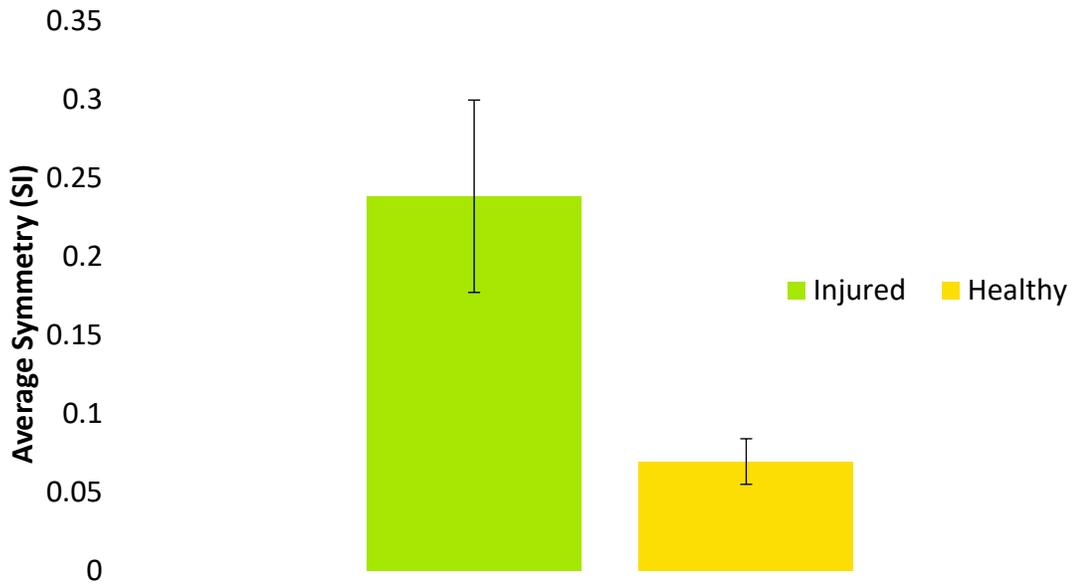
**Table 7.** Kinematic differences during running gait

<b>Measure</b>	<b>Injured Average Asymmetry (SI)</b>	<b>Healthy Average Asymmetry (SI)</b>	<b><i>p</i>-value</b>
Peak Hip Flexion	0.212 ± 0.557	0.094 ± 0.173	0.278
Hip Flexion ROM	0.087 ± 0.065	0.066 ± 0.097	0.445
Peak Hip Adduction	0.253 ± 0.21	0.257 ± 0.22	0.945
Hip Adduction ROM	0.192 ± 0.184	0.299 ± 0.321	0.164
Peak Hip Rotation	1.47 ± 4.25	0.478 ± 0.409	0.234
Hip Rotation ROM	0.306 ± 0.30	0.36 ± 0.28	0.549
Peak Knee Flexion	0.118 ± 0.124	0.072 ± 0.056	0.094
Knee Flexion ROM	0.095 ± 0.092	0.101 ± 0.123	0.825
Peak Knee Adduction	0.461 ± 0.472	0.649 ± 0.47	0.224
Knee Adduction ROM	0.392 ± 0.226	0.487 ± 0.277	0.217
Peak Dorsiflexion	0.425 ± 0.44	0.171 ± 0.16	0.012*
Dorsiflexion ROM	0.238 ± 0.267	0.069 ± 0.065	0.004*
Peak Ankle Inversion	0.813 ± 0.553	0.656 ± 0.558	0.484
Peak Ankle Eversion	0.631 ± 0.527	0.521 ± 0.432	0.445
Ankle Adduction ROM	0.358 ± 0.346	0.217 ± 0.131	0.062

\*Indicates a significant correlation,  $p < .05$



**Figure 4: Differences in running gait dorsiflexion asymmetry between healthy and injured runners**



**Figure 5: Differences in running gait dorsiflexion joint excursion asymmetry between healthy and injured runners**

## DISCUSSION

The primary focus of this study was the investigation of clinical and running gait asymmetries. This investigation was carried out through a two-part study concerning: 1) a correlative study between running gait asymmetry at the hip, knee, and ankle, and asymmetry in the respective clinical measures 2) evaluation of significant differences between both clinical and running gait measures in healthy and injured runners.

### Correlation Testing Results

Correlations between running gait and clinical asymmetries at the hip, knee, and ankle were assessed in healthy runners to determine how asymmetries may translate from clinical assessment to running gait. Strong, significant correlations were thought to serve as possible predictors for running injury when assessed by a clinician, or serve as indicators for improved treatment of injuries. Correction of these asymmetries may help prevent injury setbacks for both recreational and competitive runners.

#### *Correlations at the Hip*

Although it was hypothesized that there may be a correlation between clinical assessment of asymmetry at the hip and asymmetry at the hip during running gait, no such correlation was found. Results of this study showed insignificant correlations between the amount of asymmetry in present clinical measures of external and internal hip rotation, and hip adduction during gait. No significant correlations were observed between the amount of asymmetry with static internal and external hip rotation, and internal hip rotation during running as well. The lack of correlative results may be attributable to differences in limb stability and motion during the testing of these measures. While in running, movement at the hip is highly unstable, during clinical

assessment, both the examination table and clinician stabilize the joint. Further, clinical tests aim to reach maximal limits of range of motion, while during running, similar excursion at the hip does not occur.

#### *Correlations at the Knee*

Given the inconclusive significance of flexibility, no correlation between asymmetry at the knee and asymmetry with either hamstring or quadriceps flexibility was hypothesized. Upon statistical analysis of these measures, no significant correlations were noted. As noted with correlations at the hip, this lack of relationship may be owed to the difference in mechanics during clinical assessment and running. While during running gait, the knee moves mostly in the sagittal plan, with minimal frontal plane motion, during clinical assessment of knee adduction, the joint is moved maximally in the frontal plane.

#### *Correlations at the Ankle*

At the ankle, it was hypothesized that correlations would exist between clinically assessed asymmetries and asymmetries present during running gait. This hypothesis was derived from noting the highly mobile nature of the ankle, and similarities in mechanical motion during both clinical assessment and running. A moderate, significant correlation was noted between the asymmetry present with peak sagittal ankle motion and static dorsiflexion range of motion with the knee extended ( $r = 0.433$ ). This position of dorsiflexion with the knee extended, can be likened to joint positioning at heel strike. During this phase of the running cycle, high impact forces are felt and absorbed by soft tissues over the course of the first half of stance phase (Novacheck et al, 1998). The tissues recognized primarily in dissipating this force are

the Achilles tendon, plantar fascia, quadriceps, and hip abductors (Novacheck et al, 1998). Asymmetries in dorsiflexion range of motion with the knee in extension can then be expected to result in unequal distribution of absorptive force. This would exert excessive stress to the soft tissues involved in force dissipation.

#### *Clinical Application and Conclusions*

Correlations between asymmetry in clinical and running gait measures might provide clinicians with predictive information as to how their clinical observations may translate to running gait. Future studies may wish to use clinical tests which better mimic motion present during running gait. It may also be helpful to investigate how observed asymmetry during rehabilitation tasks correlates with asymmetry in running gait motion.

Correlative hypotheses were formed considering that movements during running occur predominately in the sagittal plane, whereas many of the clinical measurements were focused on measuring ROM even in planes which typically do not reach the full limits of joint excursion during running. In other words, runners often do not display mechanical patterns which mimic the tests which are conducted in the clinic at the hip or knee. For example, during the clinical assessment for internal and external hip rotation, the joint has greater stabilization as compared to during running due to support from both the examination table and clinician. This relative lack of stability during running was predicted to present as increased asymmetry between limbs as compared to respective movements during clinical assessment.

### Group Comparisons

Significant differences between the asymmetry present in injured and healthy runners at the hip, knee, and ankle were assessed. Deviations between groups were thought to indicate the possible relevance of asymmetry in contributing to AT and MTSS injuries. Identifying these differences might emphasize areas of focus during treatment.

#### *Group Comparisons in Clinical Assessments*

In clinically assessed group differences, it was hypothesized that there would be greater asymmetry displayed by injured runners at the ankle. This hypothesis was formed with consideration of the close association between AT injuries and the ankle. Results of this study supported this hypothesis, showing a significant difference between the clinically present asymmetry in injured and healthy runners at peak dorsiflexion with the knee extended ( $p = 0.0373$ ). Evaluation of motion with dorsiflexion is commonly used by clinicians to assess for and manage several injuries of the lower extremity, including Achilles tendinopathy, plantar fasciitis, and navicular stress fractures (Munteanu et al, 2009). These injuries typically present with limited ankle dorsiflexion, which is thought to be attributable to soleus and gastrocnemius tightness (Munteanu et al, 2009). Our results supported this, as the average angle of dorsiflexion in healthy runners was  $8.43 \pm 3.9^\circ$ , whereas in injured runners, the average angle of dorsiflexion was  $8 \pm 56^\circ$ . While these results did not indicate a significant difference between the angle of dorsiflexion between groups, there was a difference noted in the amount of asymmetry displayed among the two groups. Healthy runners displayed an average asymmetry of  $0.21 \pm 0.27$  and injured runners presented with an

average asymmetry of  $0.94 \pm 0.98$ . Upon inspection within this injured population, it was seen that the injured limbs of runners presented with 36.4% less mobility when compared to their respective healthy limb. Such findings suggest that given approximately equal ROM between groups, asymmetry in dorsiflexion may be linked with lower extremity injury. The influence of pain, especially with dorsiflexion in AT subjects, should be considered when looking at potential causes of this asymmetry.

The lack of difference seen between other clinical measures may be attributable to the nature of the injuries at hand. Both AT and MTSS are closely associated with the shank and ankle rather than the hip or knee.

#### *Group Comparisons in Running Gait*

During running gait, it was hypothesized that there would be significant differences in symmetry between groups at measures of the ankle. These hypotheses were formed considering the nature of AT and MTSS injuries, and indications for altered motion at the foot and ankle in prior literature. As with the results of clinical group comparisons, the lack of deviation among injured and healthy runners at the hip and knee suggests that these joints may not be strongly associated with AT or MTSS injuries. However, significant differences between the healthy and injured populations were seen at the ankle. Significant differences in peak dorsiflexion ( $p = 0.012$ ) and dorsiflexion ROM ( $p = 0.0039$ ) were noted. Additionally, peak ankle adduction was seen to trend toward significance (0.062). Given that the Achilles tendon is formed by the gastrocnemius and soleus muscles, and that these very muscles are involved in plantarflexion, the results of this study agree with expectations for altered ankle motion in the sagittal plan for individual's with AT or MTSS injuries.

The average asymmetry in peak dorsiflexion in injured runners was found to be  $0.425 \pm 0.44$ , whereas healthy runners had a considerably lower average SI of  $0.171 \pm 0.16$ . Within the injured population, the asymmetry may be attributed to an average increase in motion of 15.9% at the injured limb. Prior studies support the association between increased plantarflexion and both MTSS (Hamstra et al, 2015) and Achilles tendinopathy (Muneanu and Barton, 2011).

Total ankle dorsiflexion ROM was also found to be varied among healthy and injured runners. Healthy runners displayed an average asymmetry of  $0.069 \pm 0.065$ , while injured runners showed an increased asymmetry of  $0.238 \pm 0.267$ . This increase in asymmetry appeared to be linked to differences between the injured and healthy limb. Specifically, a 29.2% increased range of motion in the sagittal plane was noted in the injured limb when compared to the healthy limb. Considering this data, it shows that injured runners display greater asymmetry in their running gait in sagittal ROM of the ankle than healthy runners, and that this asymmetry is due to an increase range of motion at the injured limb.

Although the amount of asymmetry in ankle adduction was not significantly different between injured and healthy runners during running gait, it appeared to be trending towards significance. Injured runners showed an average of  $11.6 \pm 3.4^\circ$  of ROM, whereas healthy runners showed an average of  $11.5 \pm 3.5^\circ$ . While these values are comparable, the average asymmetry between groups does show some difference. While healthy runners only showed an asymmetry average of  $0.22 \pm 0.13$ , injured runners displayed an increased asymmetry of  $0.36 \pm 0.35$ . Inspecting differences between the limbs of injured runners, it was noted that the healthy limb of these runners

had an average ROM of  $13.0 \pm 2.8^\circ$  and injured runners had an average ROM of  $10.2 \pm 3.5^\circ$ . This 23.7% decrease in ROM between injured and healthy limbs indicates that decreased frontal ROM may be linked to increased risk for lower extremity injury.

## CONCLUSIONS

These results show that even in populations with similar average peak joint motion and excursion, differences may still exist in the amount of asymmetry present with these measures. Specifically, it was noted that with clinically assessed dorsiflexion with the knee extended, there was greater asymmetry in the injured population, and that this arose from a decrease in the average angle of dorsiflexion in the injured and healthy limb. During running gait, an increase in asymmetry in peak dorsiflexion in the injured population was observed. This was contributed to an increased average mobility of the injured limb in comparison to the healthy limb. A significant difference was also found in the asymmetry of dorsiflexion joint excursion. Here, the injured limb showed greater range of motion here when compared to the average healthy limb.

The increase in injured limb joint excursion during running and decrease in injured limb range of motion during clinical assessment of joint excursion should be noted by clinicians during the assessment and planning of treatment plans. Given the correlation found between clinical and running gait measures with ankle dorsiflexion, clinicians might find some utility in addressing asymmetries statically. Although further research is required to confirm such a relationship, the results of this study suggest alterations made statically may be able to translate into mechanical changes during running gait.

Limitations in this study arose from use of SI in assessing asymmetry. Although the SI index provides a way to quantitatively analyze asymmetry, it is flawed in there is no determined reference value (Zifchock). In healthy individuals, this is assumed to be the average of the two limbs, but such an assumption may lead to inaccuracies. Further,

it was noted that there was a false inflammation of asymmetry when one limb presented with positive degrees of motion while the other had negative degrees of motion. To avoid such an exacerbation of asymmetry, subjects with such discrepancies were not concerned in this study. Despite these flaws in SI, the results of this study are promising for further improvements in running injury treatment and prevention.

Support for the utility of SI in clinical assessment requires further investigation. The results of this study show that clinically assessed asymmetry at ankle dorsiflexion with the knee flexed is linked to asymmetry of peak sagittal motion present during running gait. When looking at group comparisons, differences present clinically at the ankle persisted in running gait, supporting that there may be utility in using SI to approach asymmetry of dorsiflexion.

## APPENDIX A

### CONTENTS OF THE CLINICAL EVALUATION FORM

Subject:

Subject #:

Date of Collection

Subject Age:

Parameter	Shod		Barefoot	
	L	R	L	R
Height (in cm)				
Body Mass (kg.)				
ASIS Width (cm)			N/A	
Thigh Length (cm)			N/A	N/A
Mid-Thigh Circumference (cm)			N/A	N/A
Calf Length (cm)			N/A	N/A
Calf Circumference (cm)			N/A	N/A
Knee Diameter (cm)			N/A	N/A
Foot Length (cm)				
Malleolus height (cm)				
Malleolus width (cm)			N/A	N/A
Foot Width (cm)				

## APPENDIX B

### CONSENT FORM

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Louis Osternig, Stan James, and graduate student James Becker. We hope to develop a protocol for a thorough clinical and biomechanical assessment of runners, and using this protocol, track the runners over time to see if there are any changes in these parameters prior to, during, or post injury. At this point we are testing, refining, and trying to validate the protocol.

If you decide to participate, you will be tested in the Motion Analysis Laboratory at the University of Oregon.

**TESTING PROCEDURES:** The assessments in the Motion Analysis Lab will include both clinical and biomechanical evaluations. The clinical evaluation will include measures of your body alignment, joint range of motion, and muscle strength. The alignment and range of motion assessments will be made by a trained clinician while the strength measures will be tested. For the running gait analysis reflective markers will be placed on your at selected bony landmarks and muscle surfaces to record the motion of each individual body segment. You will run laps around the laboratory space and your body movement (indicated by motion of reflective makers) during running will be recorded by our optoelectronic cameras for further analysis. With your approval we may also record your running with traditional video cameras and/or take photographs of the marker set up placed on your body. We will record your running under several different conditions. In the first condition the markers for your feet will be placed directly on the outside of your shoe. For the second condition we will drill holes in your running shoe and the markers will be directly attached to your heel through the shoe. You will be asked to wear a pair of paper physical therapy shorts and sleeveless shirt (tank top) during testing. The testing session will require a maximum of 3 hours of your time.

**COMPENSATION:** You will be compensated \$75 for participating in this study as reimbursement for a new pair of running shoes. You should understand that your old shoes will no longer be usable after your participation in the study.

**RISKS AND DISCOMFORTS:** We expect that there will be no more risk for you during these tests than there normally is for you when outside of the laboratory. However, running in the laboratory is different than running outside. You will be asked to speed up then slow down over a 20 meter distance. Running laps in the laboratory will require negotiating tight corners. We will do our best to arrange the lab equipment and furniture to minimize any discomforts and provide as much room as possible. If you are not comfortable you may stop the trials at any time. You may feel fatigue during or after the testing. Our staff member will check with you frequently and provide any required assistance. You will be given frequent breaks as requested. Drilling the holes in your running shoes will require the removal of the inner lining so there is the possibility of

rubbing or discomfort on your feet. We will do our best to reduce these effects, and should they still be present you may request additional modifications or stop the trials at any time. There is also the possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the experiment.

ADDITIONAL INFORMATION: Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will not be shared without your permission. Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.

Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with the Department of Human Physiology or University of Oregon. You do not waive any liability rights for personal injury by signing this form. In spite of all precautions, you might develop medical complications from participating in this study. If such complications arise, the researchers will assist you in obtaining appropriate medical treatment. In addition, if you are physically injured because of the project, you and your insurance company will have to pay your doctor bills. If you are a University of Oregon student or employee and are covered by a University of Oregon medical plan, that plan might have terms that apply to your injury. If you have any questions about your rights as a research subject, you can contact the Office for Protection of Human Subjects, 5219 University of Oregon, Eugene, OR 97403, (541) 346-2510. This office oversees the review of the research to protect your rights and is not involved with this study.

If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty.

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Name: \_\_\_\_\_

Signature: \_\_\_\_\_

Date: \_\_\_\_\_

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