# COMPARING ANKLE RANGE OF MOTION, ARTHROKINEMATIC POSTERIOR GLIDE MOTION, AND MUSCULAR STIFFNESS OF THE TRICEPS SURAE IN DIVISION 1 FEMALE GYMNASTS TO DIVISION 1 FEMALE NON-JUMPING ATHLETES

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**ABSTRACT**

Morgan Langton: Comparing ankle range of motion, arthrokinematic posterior glide motion, and muscular stiffness of the triceps surae in Division 1 female gymnasts to Division 1 female non-jumping athletes
(Under the direction of Meredith Petschauer)

As gymnasts experience greater ankle injury than other female athletes, we investigated injury risk factors in this population. Decreased dorsiflexion range of motion (ROM) has been shown to increase injury risk with jump landing because of the decrease time of landing, thus increasing ground reaction forces. Factors that affect the amount of ROM in the ankle include arthrokinematic restrictions of the joint capsule which will be measured by an arthrometer and a talar glide, as well as tenomuscular restrictions in the form of increased muscle stiffness. These measurements, along with weight bearing and non-weight bearing ROM were assessed for differences across the two groups of athletes. It was found there was a significantly lesser dorsiflexion ROM in gymnasts (15.19 ± 4.59 vs 19.47 ± 5.93 degrees, P =0.015). We also found a significantly greater amount of plantar flexion ROM (68.43 ± 6.36 vs 55.1 ± 9.53 degrees, P <0.001) and arthrokinematic motion (9.31±3.6 vs 5.22±3.61 mm, P=0.045) in gymnasts. No differences were seen in weight bearing lunge, muscle stiffness, or talar glide measurements.

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| | |
|---|---|
| ACL | Anterior cruciate ligament |
| AP | Anterior to posterior |
| DFROM | Dorsiflexion range of motion |
| GRF | Ground reaction force |
| ICC | Intraclass correlation coefficient |
| MVIC | Maximal voluntary isometric contraction |
| NCAA | National Collegiate Athletic Association |
| ROM | Range of motion |
| SEM | Standard error of measurement |
| SPSS | Statistical package for the social sciences |
| WBL | Weight bearing lunge |

# CHAPTER 1 INTRODUCTION

Ankle and foot injuries are among the most common in physically active individuals. Collegiate female gymnasts sustain ankle and foot injuries at a rate of 4.41 injuries per 1000 competition athlete exposures and 1.18 injuries per 1000 practice athlete exposures.[1] These rates are higher than in other female collegiate sports such as lacrosse, volleyball, softball, and field hockey which occur at 1.8, 1.51, 0.44, and 0.92 injuries per 1000 athlete exposures respectively during competition.[2-5] Why these numbers are higher for gymnasts than in individuals who participate in sports that do not routinely involve jumping and landing (i.e. non-jumping athletes) is not understood.

Though ankle injury risk is increased with gymnasts, the underlying causes are unkown. External risk factors influencing ankle injury include greater height and velocity of a fall or jump and the associated greater ground reaction force (GRF).[6,7] Internal injury risk factors include plantar flexor strength and ankle range of motion (ROM) influenced by a combination of passive and active characteristics including muscle stiffness and talocrural posterior glide motion.[8-11] These factors may be particularly influential in gymnasts, as a take-off or 'punch' requires a large amount of concentric plantar flexor strength, while the height of landing requires a large amount of dorsiflexion ROM[12] and eccentric plantar flexor strength to dissipate forces.[13-16] The less stiff/more compliant a muscle is, the more the joint can move into a position where the ligaments will be at risk for injury. These risk factors all play a role in the injury rates of all female collegiate athletes, but with the increased injury prevalence in gymnasts these factors will be compared across gymnasts and non-jumping athletes to assess possible differences.

This study will measure dorsiflexion range of motion (ROM) in weight bearing and non-weight bearing positions as well as the factors affecting ROM such as triceps surae muscle stiffness and talocrural joint glide. There is a lack of research in the gymnastics population to assess these factors which have been shown in both the general and athletic population to increase ankle injury risk.[9-11,17] Gymnasts are a unique athletic population as they require extreme flexibility along with strong and powerful muscles to compete in their sport. Comparing these factors together in gymnasts and non-jumping athletes who do not have those same muscle requirements may elucidate contributions to the greater risk of ankle injury in gymnasts. This may then inform preseason screenings and lead to the development of preventative intervention as range of motion can be altered depending on the cause of the motion limitation. A lack of dorsiflexion ROM has been seen empirically in female college gymnasts by athletic trainers who work with them, but the cause of this decrease in motion is yet to be determined. Restrictions in ankle mobility coming from arthrokinematic factors could be due to the nature of the sport and the repetitive pounding of the ankle during landing causing scar tissue build up in the joint capsule.[13,15] This could cause bony changes in the ankle similar to that which occurs with humeral torsion in the shoulder as the repetitive pounding occurs during the formative years. This will then decrease the amount of motion at the joint due to capsular restrictions.[14,18] Greater muscular stiffness can decrease ROM at the ankle due to a higher resistance to change in motion.[19] This is expected in gymnasts because they are constantly landing and using their triceps surae eccentrically to control the landing. Greater injury risk has been reported in individuals with restricted dorsiflexion ROM. [8-11] With less dorsiflexion ROM, there is less time for the forces of a landing to be absorbed following impact during landing, thus creating greater stress on the foot and ankle.[14,20] Because of the frequency of landing during gymnastics, restricted dorsiflexion ROM may be present, thus contributing to the heightened risk of ankle injury.

While external injury risk factors cannot easily be modified, internal risk factors are potentially targets for rehabilitation interventions designed to reduce injury risk. If gymnasts have a decreased ROM due to decreased arthrokinematic motion, joint mobilizations could be utilized to normalize the motion.[21] Muscle stiffness can be increased by performing isometric or eccentric exercises.[22] In a sport plagued with ankle injury there is a need to establish preventative measures and manage the high injury risk which can only be done once targets for intervention are identified.

This study will compare dorsiflexion ROM in a weight bearing lunge, non-weight bearing dorsiflexion ROM, non-weight bearing plantarflexion ROM, and a ratio of dorsiflexion ROM compared to total ankle ROM in non-weight bearing between Division 1 female gymnasts and non-jumping athletes. These measurements will assess possible differences in ROM and the underlying contributors to these differences. Restricted dorsiflexion ROM has been shown to increase injury risk in other populations and if seen in gymnasts as compared to a control group of division 1 athletes this information could be used to provide opportunities for future research in this area. Identifying difference between these groups could lead to development of preventative methods to alter ROM, muscle stiffness, and arthrokinematic motion in efforts to reduce injury risk. Correlations will be used to assess how one factor influences each other. Do those with decreased joint glide have increased stiffness? Do those with decreased dorsiflexion ROM have decreased joint glide? Do those with decreased dorsiflexion ROM have increased muscle stiffness? These correlations will help to describe how each measurement is related to the others. The final factor to be assessed is a clinical measure of posterior talocrural joint motion as compared to an ankle arthrometer. Not many athletic trainers have access to an ankle arthrometer due to the expense and training needed to use it, therefore if the talar glide method is comparable to the ankle arthrometer, it will be a useful clinical measurement. These assessments will hopefully lead to future research in both the gymnastics and physically active population to help decrease the risk of injury.

**Research Questions:**

1. Do ankle non weight bearing dorsiflexion ROM, weight bearing lunge dorsiflexion ROM, arthrokinematic posterior glide, and triceps surae muscle stiffness differ between collegiate gymnasts and female collegiate field non-jumping athletes?
    a. Gymnasts will have less weight bearing lunge dorsiflexion ROM compared to non-jumping athletes.
    b. Gymnasts will have a less non-weight bearing dorsiflexion ROM as compared to non-jumping athletes.
    c. Gymnasts will have a smaller ratio of non-weight bearing dorsiflexion ROM to total ankle ROM as compared to non-jumping athletes.
    d. Gymnasts will have greater triceps surae muscle stiffness compared to non-jumping athletes.
    e. Gymnasts will have less talocrural joint posterior glide compared to non-jumping athletes.
2. Are there significant positive or negative correlations between the talar glide motion, normalized triceps surae muscle stiffness, and ratio of dorsiflexion ROM to total ankle non-weight bearing ROM?

a. There will be a negative correlation between talar glide motion and normalized triceps surae muscle stiffness.

b. There will be a positive correlation between talar glide motion and ratio of dorsiflexion ROM to total ankle non-weight bearing ROM.

c. There will be a negative correlation between triceps surae muscle stiffness and ratio of dorsiflexion ROM to total ankle non-weight bearing ROM.

3. Is the talar glide method of measuring posterior glide restriction a valid clinical test in comparison to the ankle arthrometer measurement of posterior glide?

   a. The talar glide method will have moderate positive correlation with the ankle arthrometer posterior glide measurements.

**Research Variables:**

1. Independent variables
   a. Group:
      i. Gymnasts
      ii. Softball, Tennis, and Field Hockey Athletes
2. Dependent Variables
   a. Ankle ROM
   b. Triceps Surae Stiffness
   c. Arthrokinematic posterior glide

**Assumptions:**

1. The participants will accurately report if they have current lower extremity injuries that would change their measurements.

2. The participants will perform a maximum contraction for the maximal voluntary isometric contraction (MVIC) measures.
3. The participants accurately relay previous injury history and history of stress fractures to their lower extremity.
4. The participants will go through full ROM in a weight bearing lunge (WBL).
5. The participants will relax lower extremity musculature on the tested leg during the talar glide assessment to allow adequate assessment of motion.
6. The participants will relax lower extremity musculature on the tested leg during the arthrometer measurement allowing for full motion analysis.

# CHAPTER 2 LITERATURE REVIEW

## Epidemiology

According to NCAA surveillance survey data, which measures injury rate per 1000 athlete exposures, collegiate gymnasts are injured at an overall rate of 15.19 injuries per 1000 athlete exposures in competition and 6.07 injuries per 1000 athlete exposures in practice.[1] This was twice the rate of injury that occurred in collegiate women's lacrosse, 7.15 and 3.30 injuries per 1000 athlete exposures in competition and practice respectively.[5] Collegiate field hockey had similar injury rates to lacrosse with 7.87 and 3.70 injuries per 1000 athlete exposures in competition and practice respectively.[2] Collegiate women's softball athletes had an injury rate of 2.64 and 1.63 injuries per 1000 athlete exposures in competition and practice respectively.[4] Another study showed that elite gymnasts were injured at a rate of 6.29 injuries per 18 month period per gymnast.[23] A third study showed that 109 injuries occurred in 87 gymnasts with 62% of athletes injured at least once[24]. Based on this evidence, ankle injuries in gymnasts occur at a higher rate than other women's collegiate sports.

Ankle and foot injuries are the most common injuries in gymnastics ranging from 31.2% to 45.7% of all types of injuries[23-34]. These injuries are defined as fractures, contusions, muscle strains, tendinitis, or joint sprains to any structures that insert or are fully located distal to the distal tibiofibular syndesmosis joint. Ankle and foot injuries to collegiate gymnasts are high occurring at a rate of 4.41 during competition and 1.18 during practice sessions.[1] Similar studies have shown the same trend that injury incidence is higher during competition when athlete exposures are taken into account.[31] In contrast collegiate women's lacrosse injury rates were 1.8

in competition and 0.70 during practice.[5] In collegiate women's field hockey there was a rate of 0.92 in competition and 0.50 during practice.[2] Collegiate women's softball teams are injured at a rate of 0.58 in competition and 0.33 during practice.[4] In comparison to the injury rates of non-jumping sports such as field hockey or softball, even a jumping sport like women's volleyball had an injury rate of 1.51 in competition and 0.94 during practice which was still lower than women's gymnastics.[3] Although injury rates differ among the types of female collegiate athletes described above, for this study gymnasts will be compared to female collegiate softball, tennis, and field hockey athletes who all participate in a sport where jumping does not regularly occur. Comparisons will be made between women gymnasts, field hockey, softball, and tennis athletes as they participate in non-jumping sports. Differences in height and weight will be present between these athletes, but controls for height and weight will be taken into account in stiffness measurements where differences have been shown to create different measurements.

Injury rates for gymnasts across different events and the duration of a routine vary between studies, but similarities are present. [24-29,35,36] Though routines on the beam provide the hardest, most dense surface for landing,[13] it is not the event causing the most injury. [24-29,35,36] Multiple studies showed that ankle and foot injuries are most prevalent in floor routines.[24-29,35,36] The floor surface is constructed of springs covered by fiberglass or wooden panels, with a carpeted 5cm foam padding on top. This creates a floor surface providing the least amount of cushioning to absorb landing forces leading to increased injury risk. [13,24-29,35,36] Kirialanis' study of the occurrence of acute injuries in gymnasts indicated half the injuries during all events in gymnastics occur during the landing of each tumbling pass or dismount. [26] Another study indicated 49% of injuries occur in the landing phase of the floor routine.[27] That study also showed that 84% of injuries occurred during practices even though they occurred at a rate of 1.0 injury per 1000 exposure hours in practice compared to 196.1 injuries per 1000 exposure hours during competition.[27] This is important because the landing surface used in practice often consists of a 4 or 8 inch landing mat which provides additional cushioning.[13] Even with the use of additional mats and padding, injuries still occur at rates anywhere from 1 to 26 injuries per 1000 hours of gymnastics training.[24,27,31] These mats are utilized when learning new techniques to decrease injury risk and increase safety measures.[13] While gymnasts have higher injury rates than non-jumping athletes despite altered training techniques to lower the external risks, this study aims to determine any possible internal injury risk factors that could be altered to decrease injury risk.

## Anatomy and Biomechanics

Gymnasts are typically injured during the landing aspect of the sport. Therefore, it is important to understand what is happening to the body when this occurs.[20,24,26,27,37] The foot and ankle complex serves a dual purpose to absorb the forces and to propel the body to the next motion during walking or jumping.[14] The foot and ankle complex combines for a total of 28 bones, 25 joints, 23 muscle tendon units, and ligaments that provide the stability and mobility needed to walk.[14] The foot is broken up into sections (rearfoot, midfoot, and forefoot) depending on the bony anatomy of each structure. The tarsals are split between the rearfoot (calcaneus and talus) and midfoot (cuneiforms, navicular, and cuboid) but each section is connected during closed chain movement. Therefore, when pathology occurs in one part of the chain, it affects the entire complex as dissipation of forces cannot occur as seamlessly.[14]

Weight is distributed through the medial longitudinal arch while in standing. The bones that make up this arch are the calcaneus, talus, navicular, cuneiforms, and the three medial metatarsals.[14] These bones, therefore, absorb a large amount of the force as stress is consistently placed on them, even when doing simple tasks.[14] For example during gait, the height of the medial longitudinal arch decreases by 15% of its tallest height as the foot moves from heel strike to the stance phase.[14] The arch decreases in height due to calcaneal eversion with adduction and plantar flexion of the talus joint during what is known as pronation of the foot in a closed kinetic chain.[14] During this motion, much of the force of the body is distributed through the deformation of the arch.[14] As this occurs, the tibialis anterior, extensor digitorum longus, and extensor hallucis longus move eccentrically to lower the foot to the ground and move from neutral foot position to 15 degrees of plantar flexion to also aid in the distribution of forces through the leg and foot.[18] Force distribution continues as the foot moves into the stance phase and pronation and eccentric loading of the gastroc soleus complex occurs.[18] After midstance, the foot and ankle complex move into supination during the push off phase of gait.[14,18] During this phase the soleus and flexor hallucis longus and brevis all initially continue to move eccentrically and then switch to a concentric contraction.[18] This concentric contraction causes the foot to become a rigid lever which is used to then propel the body forward.[18] Then the foot continues to move from heel off to toe off as the plantar flexors including the gastrocnemius, soleus, peroneals, and toe flexors, all concentrically contract to force the foot into plantar flexion.[18] Then as the foot moves through the swing phase the tibialis anterior, extensor digitorum longus, and extensor hallicus longus all work concentrically to dorsiflex the foot and then work isometrically to hold the foot in that position through heel contact.[18] The multitude of parts which have to work together seamlessly create many opportunities for imbalances if one part is not working properly.

As briefly mentioned, the tibialis anterior and posterior muscles are critical for the deceleration of the speed at which the foot pronates in walking and landing.[14] This pronation helps to transfer the loads more effectively and with the best distribution patterns of stress on the structures of the foot.[14] The intrinsic muscles and ligaments on the medial side of the foot, including the deltoid ligament, tibialis anterior, tibialis posterior, flexor digitorum longus, flexor hallucis longus, and spring ligament, also aid in the distribution of forces.[14] The availability of movement in each structure of the foot is important, because an overly rigid structure does not allow for force distribution. However, a foot that is too mobile also puts additional stress on the bony structures of the foot and other structures higher in the chain.[14] This occurs when excessive pronation occurs which causes the force to be distributed through the second metatarsal.[14] Pronation can also be seen with knee valgus which then puts stress on the ligamentous structures of the knee and the muscular structures responsible for stability.[14] There is no concrete definition of how much motion is ideal and how this leads to decreased injury risk. Normal dorsiflexion ROM is defined at 20 degrees according to multiple sources.[14,18] Motion at the talocrural joint is typically restricted by the posterior musculature of the leg, mainly the triceps surae, which acts as the check reign for end ROM.[18] If the triceps surae complex is flexible enough, the posterior joint capsule itself may be the check reign.[18] When that occurs, the joint capsule is more prone to injury which can then cause joint or ligamentous damage such as sprains. When the muscle is too tight and restricts motion, the injury typically occurs to the muscle itself in the form of strains.

In gymnastics, the landing and push off phases are important motions used to perform their maneuvers during routines. Therefore, the ankle experiences the greatest loads during these phases.[14] When going into a tumble pass or when going to vault, the gymnast pushes off or 'punches' to propel themselves into the air.[13,15] Punching is the act of forcefully pushing off the ground by going into plantarflexion.[13] This is a highly powerful motion that occurs using both feet to propel the gymnast into the air to then perform a tumbling pass, a beam dismount, or a vault skill.[15] A quick eccentric motion first occurs to increase the power in the take off by eliciting the stretch reflex.[15] Then the feet must become supinated to form a rigid lever to propel the gymnast into the air, the gastrocnemius soleus complex must contract concentrically to generate the force needed to propel the body into the air.[15,18] During vault this is done by increasing forward velocity by sprinting. Forward velocity is partially converted to vertical velocity with a tumbling skill like a handspring onto the springboard where the landing and concurrent punching motion transitions into the take-off.[15]

During landings, gymnasts must work to stop all momentum and force of their moving bodies.[15] Young gymnasts are taught the importance of 'sticking' a landing.[15] This is crucial to the sport, because there are point deductions for any ensuing steps or hops taken after the landing.[15] There are also point deductions for going into full flexion at any lower extremity joint.[15] In order to stick a landing in the safest way the gymnast must land with the ankle dorsiflexed, the knee slightly flexed, the hip slightly flexed, and the shoulders flexed and horizontally abducted to increase balance and decrease the amount of force in any one joint.[15] In this position the triceps surae complex, quadriceps, and erector spinae contract eccentrically to absorb part of the landing forces.[15] Without the eccentric control of these muscles, a gymnast can 'land short' or rotate too much or too little and hyper dorsiflex. This causes pinching of the anterior aspect of the ankle complex. In a backwards pass, this will occur if the gymnast does not rotate enough and once again her chest is anterior to her feet. When this occurs, the gymnast can experience anterior ankle impingement.[33] This common injury can cause a gymnast to lose training time due to inflammation, pain, and concurrent decrease in ROM at the ankle.[33] This injury has been found to create the longest lasting symptoms in gymnasts who no longer compete due to bone spurs forming on the talus.[33] This happens due to the calcification of areas where the talus is jammed into the syndesmosis between the tibia and fibula.

Proper biomechanics of punching, gait, and landing are critical to gymnasts because they perform barefoot.[13] Barefoot participation can lead to multiple problems. The main issue from a prevention standpoint is the inability to correct any naturally occurring biomechanical pathology. Gymnasts with forefoot or rearfoot varus cannot simply wear an orthotic in a shoe to correct the problem and create ideal alignment. In runners those with uncorrected forefoot or rearfoot varus are more prone to stress fractures of the 2nd metatarsal and the same is true for gymnasts due to the hours of compounded stress that occurs to the area. These biomechanics and the inability for gymnasts to use protective equipment compound to raise the question of is there anything that can then be done for gymnasts to decrease injury risk? This question can be answered by looking at measures of triceps surae stiffness, dorsiflexion ROM, and posterior talar motion. If there are differences in these measurements between female gymnasts and non-jumping athletes, then further research can be done to assess why these differences occur.[38-40]

**Stiffness**

Another factor affecting ROM and injury rates is muscular stiffness. According to Foure, stiffness is the “degree of resistance offered by tissues in response to lengthening.”[41] Stiffness is comparable to viscosity of fluids and the resistance they have to deformation. When thinking of stiffness as a rubber band, a stiffer rubber band is more prone to breaking while a less stiff rubber band cannot apply much resistance to lengthening. Translating this to joints and muscles, a stiffer muscle is more prone to tear or strain when it is lengthened. In contrast a compliant muscle will put the joint, ligamentous and bony structures alike, at risk for injury due to increased motion and lack of control provided by the compliant muscle. There is a balance that is maintained between having muscles that are stiff enough to assist with stability and function, but not so stiff that they become injured.

Hamstring stiffness, has been researched in regards to anterior cruciate ligament (ACL) injury and anterior tibial translation. The posterior attachment of the hamstring tendons on to the tibia produce posterior tibial translation and provide a protective mechanism from ACL injury. It has been seen that increased hamstring stiffness was correlated with decreased anterior tibial translation.[42] However, hamstring strength was not correlated to either measure. Clinically this is important to prevent excessive joint motion leading to injury. Another study by Blackburn showed a trend towards significance utilizing isometric interventions to increase stiffness. However, the result was likely not significant due to small sample size.[22]

As much of the research on muscle stiffness has been done in relationship to ACL injury, another common ideology is that the phase of the menstrual cycle has an effect on the likelihood of ACL injury. This has been researched in comparison to muscle stiffness at different phases of the menstrual cycle to see how the hormones of the female body affect hamstring muscle stiffness. There are inconsistent results for the correlation between hamstring stiffness and the menstrual cycle phases. Multiple studies showed that both the phase of the menstrual cycle and the differences between taking oral contraceptives and having normal hormonal changes during regular menstrual cycles did not significantly change muscle stiffness in the hamstring.[8,43] In contrast women with decreased estrogen levels from the lack of a menstrual cycle had significantly increased stiffness of the triceps surae compared to young women experiencing a menstrual cycle. However, the significant result from that study could also be contributed to the increased body mass index levels and increased age of the postmenopausal women in that study.[44] As all of our participants are at an age that they should be menstruating, there is no research indicating that there should be any concern about the part of the menstrual cycle the participants are measured during. However, for extreme caution, the participants could be measured during the same period of the menstrual cycle.

Gender differences and anatomical differences are other factors that affect stiffness measures of hamstring muscles. Foure et al. demonstrated that men had stiffer hamstrings compared to women, but after correcting for height and anatomical differences, the stiffness measures were the same.[41] Other studies showed that height and weight are factors contributing to stiffness.[44-46] This factor is very important when gymnasts are compared to athletes such as women's lacrosse and field hockey players as their heights and weights can be more variable in those sports as compared to gymnastics. Gymnasts tend to be shorter and weigh less due to the nature of the sport, whereas lacrosse and field hockey players are more varied in size.

Stiffness measures are important because data have shown that different exercise methods can effectively change the stiffness of a muscle. If there is a difference between the gymnasts and other female athletes then there are ways to increase or decrease the stiffness of a muscle.[22] Clinically, this could be a way to incorporate preventative medicine as athletic trainers and to add certain exercises to strength and conditioning programs. If a muscle has less than optimal stiffness, studies showed that isometric training increased stiffness levels.[22] There is research which supports higher hamstring muscle stiffness was strongly correlated to increased hamstring injury.[45] Increased muscle stiffness has also been shown to be a risk factor in injury due to the correlation between increased stiffness and increased vertical jump height and coincidental increased jumping velocities.[47] Knowing the magnitude of stiffness in the triceps surae could be important for creating preventative measures in gymnasts to work on decreasing the number of ankle injuries in gymnasts.

**Injury Risk Factors**

When muscular imbalance or pathology occurs, biomechanics change which can lead to injury.[10,14] More research on common risk factors for ankle and foot injuries is needed, as current research has varied findings. Risk factors evaluated include ROM measurements, strength measurements of the ankle, proprioception measures, hormone levels and part of the menstrual cycle, landing times, landing surfaces, footwear, and concentration levels. Mahieu's prospective study of risk factors for Achilles injuries showed that decreased plantar flexor strength and excessive dorsiflexion ROM were significant indicators of injury.[10] Biomechanically, decreases in dorsiflexion ROM area are associated with greater biomechanical errors in completing a double leg squat.[48] The double leg squat is also a part of jump landing mechanics for gymnasts. Carcia's literature review on Achilles pain indicated the factors that lead to injury include abnormal dorsiflexion or subtalar joint ROM, decreased plantar flexion strength, increased foot pronation, and training errors.[9] However, Baumhaue found no significant changes in risk of injury with dorsiflexion ROM differences, but increased risk with greater eversion ROM and strength.[11]

It is difficult to make clinical decisions based on these findings. The lack of consistent findings also leads to variability in prevention and treatment of such injuries. However, the deficits in dorsiflexion ROM are shown to have effects on the biomechanics of landing leading to increased injury risk and ground reaction force.[49] Bell showed that those with decreased plantar flexion strength had an increased incidence of medial knee displacement.[49] Increased medial knee displacement is linked to pronation at the foot, and excessive pronation at the foot leads to stressing soft tissue structures of the foot that are not meant to take the force of jump landings.[14,49] Ground reaction forces are reduced when joint angles are allowed to move through optimal ROM so that the muscle can also absorb a portion of the force and it is not solely being absorbed by the bones and joints.[14] Fong et al. showed that greater passive dorsiflexion ROM with drop landings lead to decreased ground reaction forces. However, it was not a significant finding due to small sample size.[17] However, another study looking at ROM compared to motor task performance indicated that while there was less dorsiflexion in walking down stairs, there was no significant difference in total net moment, joint angle, or timing of peak muscle activation.[50] As can be seen there is limited and conflicting research in risk factors for ankle injuries in gymnastics as they have a unique mechanism of injury due to landings. There is a need for research in ankle ROM and strength to allow health care professionals, strength and conditioning coaches, and coaches to create preventative systems to decrease injury rates.

Other injury risk factors to gymnasts that have been researched include landing surface, time of training, and type of landing. Little consistency has been found with these factors with some studies finding that neither a softer nor a harder landing surface alters ground reaction forces.[51] However, Zhang showed that when comparing three different heights and three different landing surfaces, the stiffer landing surfaces required more eccentric contraction from the triceps surae and caused increased loading to the ankle joint.[12] This was correlated to gymnasts who train doing landings from higher heights and practice on softer landing surfaces but then compete on stiffer surfaces which may be a cause of the increased injury rate during competition.[12] Another study compared the GRF of recreational athletes and gymnasts dropping from a height of 30, 60, and 90 cm and showed that gymnasts have higher GRFs at 60 and 90 cm than recreational athletes do with landing.[7]

Two big factors that contribute to injury risk are increased age and increased training time each week. Gymnasts become taller and weight more as they age, which contributes to more pounding on their body when they land.[52] The same can be said with an increase in training time as a gymnast progresses to higher levels of gymnastics.[52] The more a gymnast practices, the more opportunities there are for her to become injured.[52] However, there are interventions that can be taken to decrease the risk of injury. External interventions such as using softer landing surfaces or foam pits will increase the safety of training for gymnasts. Other interventions can include muscle stiffness interventions or doing joint mobilizations and soft tissue massage to increase ROM measures.

**Instrumentation**

Measurements will be taken to evaluate the dorsiflexion ROM in weight bearing, talar glide tibial angle, ankle arthrometer joint motion measurement, and the stiffness of the triceps surae muscle. All ROM measures will be taken with a digital inclinometer to decrease the amount of human error which can occur with manual goniometric measurements.[53] In weight bearing, the proper placement of the digital inclinometer is along the tibial tuberosity and lined up distally with the shaft of the tibia.[53] The intraclass correlation coefficient (ICC), a measurement of reliability, of the digital inclinometer in measuring ankle dorsiflexion ROM in a weight bearing lunge is 0.96.[53] The closer to 1 the ICC measure, the better the correlation and reliability of the technique or tool. The inclinometer also had the lowest mean detectable change meaning it was more sensitive and able to measure differences in ROM more easily than other measures including a manual goniometer.[53]

Other tools are available to measure dorsiflexion ROM, however they are not readily available to everyone in a clinical setting and that decreases the ability for the results from this study to be utilized on a broad spectrum. One study showed that a Lidcombe template apparatus was used to measure passive dorsiflexion ROM with metal plates on the metatarsals and the posterior aspect of the leg.[54] This tool had high success at measuring dorsiflexion ROM compared to camera angle measures and had an ICC of 0.97. [54] However, this tool lacks the ability to be clinically applicable because it is out dated and not readily available.[54] The Iowa ankle measure device also has an ICC of 0.95 or higher in all measurements. Like the Lidcombe template apparatus, the Iowa ankle measure is a homemade device for the lab that is not feasible for use in the clinic.[55] Another limitation of both of these measuring devices is the lack of measuring while Participants are in a weight bearing maneuver. As has been previously stated it is important to measure ROM in a weight bearing position for gymnasts because most of the injuries occur in the landing phase with weight bearing.[26] Measuring dorsiflexion ROM in a weight bearing lunge with a digital inclinometer has a high ICC rating of 0.97 and thus has high reliability and validity.[56]

The talar glide measurement and the ankle arthrometer posterior assessment will both be used to assess arthrokinematic gliding motion at the talocrural joint. The talar glide measurement has been used previously in multiple studies to determine where dorsiflexion stops due to lack of talar motion.[57] This method has been shown to have a high $ICC_{3,1} = 0.88$ which assesses the reliability when each subject is assessed by each examiner of interest and an $ICC_{3,3} = 0.99$ which assesses the reliability of an average of measurements from multiple examiners.[58] A second study using this measurement found an ICC = 0.931 with a standard error measurement of 1.2 degrees.[57] A normal measurement for this clinical measure has been stated to be anywhere from 16-24 degrees according to Mauntel and Grindstaff.[57,58] The measurement is one which can be completed in any athletic training room with either a manual goniometer or a digital inclinometer to measure the amount of posterior glide at the talocrural joint. The second measurement used for posterior talocrural glide joint motion is the ankle arthrometer. This tool has also been used throughout ankle research to demonstrate the amount of motion in an anterior and posterior direction at the talocrural joint. Reliability of this tool has been much more variable with ICC measures of 0.91 for interrater measurement with an SEM = 1.02.[59] However, these measurements were taken in a cadaveric study which brings to question the reliability in a living participant.[59] The sensitivity and specificity of measurements were measured in another cadaveric study lead by Nauck.[60] The sensitivity of the ankle arthrometer was 96.3 while the specificity was measured to be 44.4.[60] This indicates that the arthrometer helps to rule out hypermobility at the talocrural joint in the anterior and posterior directions.[60] Schwarz determined normal measurements for the ankle arthrometer in women aged 19-25, similar to the age of participants in the current study.[61] Schwarz showed that normal total anteroposterior displacement of the talocrural joint was 18.79 mm and that posterior displacement averages were 8.82 mm in females in the specific age range.[61] However, distributions showed that ‘normal’ mobility in a posterior direction is anywhere from 6.34 – 11.3 mm and for total displacement can vary from 14.67 – 22.91 mm.[61]

Stiffness measurements will be taken using a custom made device where the forefoot is propped up on a block and the participant isometrically holds the ankle at a 90 degree angle. The examiner then creates a perturbation using a load equal to 20% of the participant’s maximal voluntary isometric contraction to the knee creating a downward force and the dampened oscillatory reaction will be recorded and measured. This measurement will be of the vertical component taken of the ground reaction force which measures the dampened oscillation reaction. This set up along with other similar set ups at the knee joint have been shown to be a valid measure of muscle stiffness.[62-65] Using a fixed load has the most consistent measurement of stiffness when perturbing the ankle joint.[64] Stiffness will be measured using damped oscillatory frequencies by taking the frequency of the oscillation and mass of the leg and foot. This stiffness device has been used in previous studies and has an ICC measure of anywhere from 0.803 to 0.874 depending on the area of measure from the muscle belly to the tendon unit.[66] That same study also indicated that stiffness measures did not significantly vary between the injured and uninjured leg for participants with previous lower body injuries.[66] Stiffness has been shown to be an injury risk factor when too high or too low but the actual magnitude of what is too high or too low has not been determined. This is a limitation of measuring stiffness as there is not a set normal to compare our magnitude of stiffness. However, this will not affect the current study due to the comparison across two groups and not to a normal measure.

# CHAPTER 3 METHODS

## Participants

Gymnasts from the University of North Carolina at Chapel Hill and North Carolina State University will participate in this study. Division I collegiate female non jumping athletes will also be selected from the women's teams at the University of North Carolina at Chapel Hill and will serve as control participants. Each group will be comprised of 20 participants as determined by power analysis (P=0.80) of pilot testing data. Participants from all sports will be selected by voluntary participation. Participants will be between 18 and 23 years old. Exclusion criteria for all participants include restriction from activity within two months prior to data collection due to a lower extremity injury or bilateral ankle surgery. Control group participants will be excluded if they have a history of competitive participation (at the high school or college level) in a jumping sport including gymnastics, volleyball, basketball, field events, and hurdles in the past 3 years.

## General Description

This study will utilize a cross-sectional experimental design. Subjects will report to the Neuromuscular Research Lab for a single testing session, lasting approximately 45 minutes. The participant's will first complete a health history questionnaire (Appendix A). They will then complete ROM measurements of the ankle, including both weight-bearing lunge ankle ROM measurements and non-weight-bearing seated plantarflexion and dorsiflexion ROM measurements, a triceps surae muscle stiffness assessment, and clinical and laboratory assessments of posterior joint glide in a counter balanced manner.

**Procedures**

*Demographic Survey*

When participants arrive for their testing session they will read and sign the consent form approved by the Institutional Review Board at the University of North Carolina at Chapel Hill. Participants will complete a questionnaire about their medical history (Appendix A). The questionnaire includes questions to gain insight to previous lower extremity injury, surgical history, menstruation history (if they regularly have a period and when the last one began) and which foot will be measured. The foot measured in gymnasts will be the opposite of their lead leg. The lead leg is the leg which they hurdle with and the opposite foot is the one which is important for balance and push off on single limb events. In non-jumping athletes, the measured foot will be the stance leg when they kick a ball to mimic the stance leg in a gymnast.

*Weight Bearing Lunge ROM Measurements*

The weight bearing lunge measurement will assess the functional flexibility of the ankle joint in dorsiflexion using a digital inclinometer (Saunders Group, Inc., Chaska, MN). There is excellent intrarater reliability (ICC = 0.96-0.97) using the digital inclinometer to measure active and passive ROM while participants are in a weight bearing lunge.[53] Intrarater reliability for the weight bearing lunge ROM measurement were calculated with $ICC_{2,k}$=0.976 and SEM=0.297 degrees for the current study. The weight bearing lunge ankle dorsiflexion ROM angles have a standard error of measure of 1.4 degrees and the minimal detectable change in ROM is 3.8 degrees.[53] In the weight bearing lunge the participant will have the dominant foot in the front with the contralateral foot behind to stabilize with the foot facing forward. This measurement will always be tested first to avoid any increases in joint motion due to talocrural joint motion during arthometric measurements. The participant will be barefoot and lean as far forward on the front foot as she can without lifting the heel of the front foot off of the ground (Figure 3.1). A digital inclinometer, zeroed to the vertical prior to use, will be placed on the shank segment just distal to the tibial plateau to measure the angle between the true vertical and the tibial shaft.

**Figure 3.1: Weight bearing lunge ROM measurement using digital inclinometer**

This will be completed in a quick, fluid motion to minimize the chance of the Golgi tendon organs eliciting a relaxation reflex, which would allow a further stretch in the muscle. This process will be completed three times and the average of the three consecutive measurements will be used as a measure of the weight bearing dorsiflexion ROM.

*Non Weight Bearing ROM Measurements*

Non weight-bearing ROM measurements will be obtained with the participant supine on a plinth with a foam roller under the knee and the ankle 2-3 inches off the end of the table. A digital inclinometer aligned parallel to the participant's 5$^{th}$ metatarsal will be used to measure ankle ROM as the participant actively plantarflexes and then dorsiflexes her foot. The inclinometer will be zeroed with the foot in neutral (90$^{o}$ angle between the foot and shank verified via a manual goniometer) prior to measuring ankle ROM. Measurements will be recorded when the participant reaches end ROM in each direction alternating between plantarflexion and dorsiflexion. Intrarater reliability for plantarflexion and dorsiflexion ROM were calculated with intraclass correlations at $ICC_{2,k}$=0.953-0.954 and a SEM=0.325 degrees. This measurement will be completed five times and the average will be used. A ratio of dorsiflexion ROM compared to total ROM will also be used to assess how much of the available motion in the ankle is due to dorsiflexion.

*Triceps Surae Muscle Stiffness Measurements*

To measure triceps surae muscle stiffness, the participant will be placed into the perturbation device with her hip, knee, and ankle all at 90 degrees and the metatarsal heads resting on two blocks that are secured on top of a force plate (Bertec 4060, Columbus, OH). The computer samples ground reaction force data at 1000Hz during MVIC and muscle stiffness measurements. Triceps surae stiffness will be obtained via the damped oscillatory technique. A perturbation will be applied to the knee which will create an oscillation of the ankle. The force plate below will record the vertical ground reaction force from the oscillation. The frequency of the oscillation will be calculated from the inverse of the interval between the first two oscillatory peaks in the vertical ground reaction force. Stiffness will be calculated using the equation $k=4\pi^2mf^2$ where k is stiffness, m is the mass of the system (applied load + mass of the shank and foot segment (Dempster et al)), and f is the frequency of oscillation.

MVIC

Before measuring stiffness, a maximum voluntary isometric contraction (MVIC) force of the plantar flexors will be recorded to determine the load that will be used during the muscle stiffness assessment. A level will ensure the perturbation device is placed parallel to the ground. The center of the load will be placed directly in line with the tibia so the lever sits directly on top of the knee.  A strap will be secured over the top of the knee and hooked onto the second block which is securely anchored to the ground (Figure 3.2). The force plates will be zeroed after this set up. The participant will then maximally contract her plantar flexors for five seconds. Three trials will be performed with a 90 second rest interval in between trials. Similar to previous research, twenty percent of the highest force found from the three measurements will be used as the load during triceps surae stiffness measures.[66]

**Figure 3.2 Experimental setup for collecting MVIC data. The participant's hip, knee, and ankle will be flexed to 90 degrees. A strap will hold the perturbation lever in place while the participant maximally contracts their plantarflexor muscles forcing their knee into the lever.**

Triceps Surae Muscle Stiffness Measure

To measure stiffness, a load of 20% of the MVIC will be placed on top of the loading device. The setup for the stiffness measurements is similar to the MVIC measurements with the exception that the block under the participant's heel will be removed and there will no longer be a strap from the ground over the knee (Figure 3.3). This will permit unrestricted motion at the ankle.  When the block is removed from underneath the participant's heel, she will be instructed to keep the ankle in neutral at 90 degrees by isometrically contracting the triceps surae. A digital inclinometer will be used to make sure the tibia remains aligned with the vertical. The force plate will be zeroed prior to obtaining the stiffness measure. The participant will close her eyes to reduce anticipation of perturbation. The examiner will apply a manual perturbation to the device at a random time within 5 seconds of the participant closing her eyes. The perturbation will create an oscillation of the shank about the ankle in plantarflexion and dorsiflexion which will be reflected in the vertical ground reaction force on the force plate. The first two peaks in vertical ground reaction force will be used to measure the time in between them. This time ($t_2$-$t_1$) will be used to calculate the frequency by using the equation $f=1/(t_2-t_1)$. This frequency will then be used to calculate muscle stiffness by entering it into the following equation: $k=4\pi^2mf^2$. Data collection for triceps surae muscle stiffness will begin with three practice trials followed by five usable trials separated by 1 minute of rest. A trial will be considered unusable if it does not have an oscillatory pattern because the participant either resists the motion and contracts her triceps surae enough to lift the perturbation device, or if she completely relaxed after perturbation and her heel touches the floor. If a trial is unusable, the participant will have the same one minute rest period and repeat the trial. The average of the five usable trials will be used as the active stiffness measurement of the triceps surae. In previous studies the intra-class correlation coefficient has been between 0.80 and 0.89 and after pilot testing the intra-class correlation coefficient was calculated at $ICC_{2,k}$=0.846 and SEM=30.538 (N m-1*kg-1).[46,66]

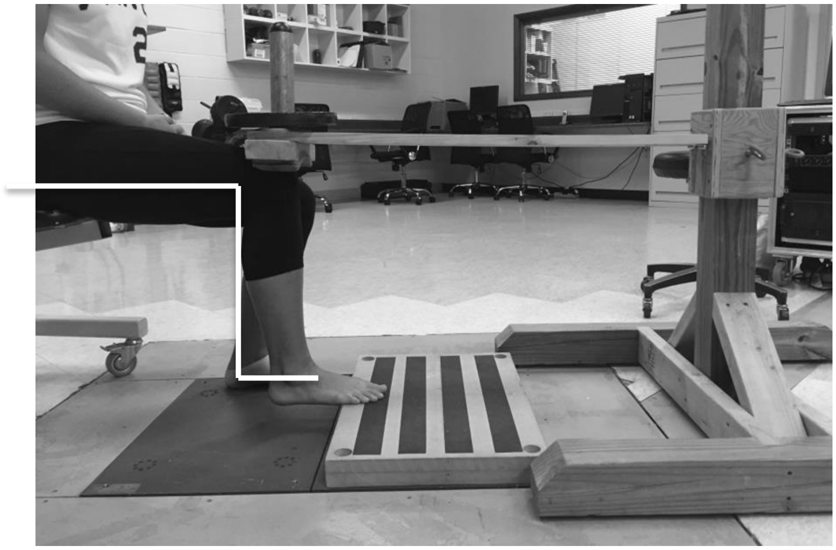

**Figure 3.3 Triceps surae muscle stiffness perturbation device and set up with hip, knee, and ankle at 90 degrees and perturbation lever parallel with ground.**

*Talocural Joint Motion Measurements*

Talar Glide Measurement

Ankle joint arthrokinematic motion will be evaluated with a talar glide technique and with an arthrometer.  With the talar glide technique, the participant will be seated on a table with their knees off the table and flexed to 90 degrees (Figure3.4). Participants will be barefoot and measurements will be obtained on the dominant leg. A research assistant will hold the digital inclinometer, zeroed to the true vertical, along the tibial shaft directly inferior to the tibial plateau. The examiner will palpate the talar dome and place the foot into neutral in regards to dorsiflexion and plantar flexion as well as inversion and eversion. The talus will be pushed posteriorly by the examiner, while keeping the foot in neutral, until the first restriction is felt. The capsular end restriction felt is the talus pushing against the posterior joint capsule. When that restriction is felt a research assistant will record the angle measured by the digital inclinometer. This will be measured five times and the average will be used as the final data point.

Intra-class correlation coefficients of the talar glide after pilot testing was calculated at $ICC_{2,k}$= 0.981.

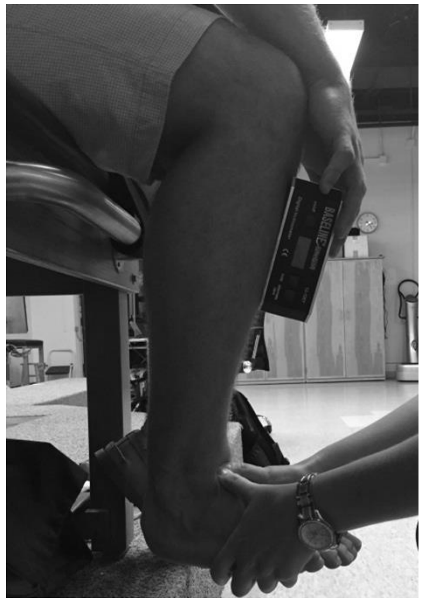

**Figure 3.4: Talar glide measurement with foot in neutral eversion/inversion and plantarflexion/dorsiflexion and digital inclinometer below tibial tuberosity.**

<u>Ankle Arthrometer Posterior Glide Measurement</u>

The Hollis ankle arthrometer will be utilized to measure talocrural anteroposterior (AP) glide. This equipment has been used in previous studies and similar methods will be used to collect arthrokinematic motion.[59-61] The arthrometer is a unique tool that has been created specifically for research on ankle joint motion, but has little clinical use as it is an expensive tool and not readily available in the clinical setting.[59,61] The participant will lay supine on the table with their foot hanging off the table 2-3 inches. The arthrometer consists of a foot plate with an adjustable heel cup that can be adjusted to firmly grasp the heel and keep the foot in place (Figure3.5). The foot plate is attached to a tibial pad which is attached to the distal shank. There is also an adjustable pad which is placed over the talar dome to hold the anterior aspect of the ankle in place. The knee and ankle will be held in place by straps across the table (Figure 3.6).

**Figure 3.5: Hollis Ankle Arthrometer**

Once the arthrometer is in place, the foot will be placed in neutral dorsiflexion and plantarflexion, and inversion and eversion. Then the examiner will apply a force of 125 N in a posterior direction.[61] The participant will be asked to report if the heel slides during the testing and if it does the trial will be discarded and repeated. The position of the foot will be measured using a spatial kinematic linkage system with a 6 degrees of freedom electrogoniometer which utilizes a reference pad on the tibia. The arthrometer is connected to a laptop via a USB cable and a custom LabVIEW program that will collect the posterior displacement of the talus in the syndesmosis joint when the force from the examiner reaches 125N. This measurement will be repeated five times and the average of the data points will be used for comparison. Intra-class correlation coefficient for ankle arthrometer measurements after pilot testing was calculated at $ICC_{2,k}$= 0.822.

**Figure 3.6: Medial view of Hollis ankle arthrometer set up with straps securing knee and ankle**

**Figure 3.7: Lateral view of Hollis ankle arthrometer set up.**

## Statistical Analysis

Independent samples t-tests will be used to compare arthrokinematic motion measured by talar glide, weight bearing lunge ROM, ratio of dorsiflexion ROM to total non-weight bearing ROM at the ankle, non-weight bearing dorsiflexion ROM, non-weight bearing plantarflexion

ROM, and triceps surae stiffness between gymnasts and non-jumping athletes. Pearson correlations will be used to assess the relationships between the ratio of dorsiflexion ROM to total ROM, talar glide measurement, and triceps surae stiffness. Pearson correlations will also be used to assess the relationship between talar glide motion and arthrokinematic motion measured by the arthrometer. Statistical significance will be at $\alpha<0.05$. All data will be analyzed using SPSS 23.0 statistical software (SPSS, Inc., Chicago, IL).

## CHAPTER 4 MANUSCRIPT

### Introduction

Ankle injuries plague the athletic population each year, particularly in female gymnasts.[1,20,29,37] Gymnasts sustain ankle and foot injuries at a rate of 4.41 injuries per 1000 athletic exposures in competition and 1.18 injuries per 1000 practice exposures, representing a 2.5 to 3 times greater risk of ankle injury compared to other sports such as volleyball or lacrosse.[1] Volleyball and lacrosse have injury incidence rates of 1.51[3] and 1.8[5] injuries per 1000 competition exposures. However, there is limited research evaluating this heightened risk of injury.

A number of factors could contribute to greater ankle injury risk in gymnasts. External factors that play a role in greater ankle injury risk include greater height of jump or fall, greater velocity of landing, type of landing surface, and greater ground reaction force.[9,11,17,23,67] Over the years, gymnastics has adapted to these findings in research by adding padding to landing surfaces, removing the trampoline event, and landing into a foam pit during practice.[13] This could explain the higher risk of injury during competition when compared to practice.[13] While there are a number of external factors contributing to greater ankle injury risk in gymnasts, internal risk factors are poorly understood in this population. Internal ankle injury risk factors include lesser plantar flexor strength and ankle range of motion (ROM).[10,17] Range of motion can be affected by a bony block, lesser joint capsule mobility, or greater muscle stiffness. These factors all influence gymnasts performance during competition and practice as a strong take-off or a ‘punch’ requires a large amount of concentric plantar flexor strength as the ankle moves through full plantarflexion ROM. Landing from those take offs requires a large amount of dorsiflexion range of motion (DFROM) and eccentric plantar flexor strength to dissipate forces. As previous literature demonstrates that greater dorsiflexion ROM is associated with smaller ground reaction forces, restricted dorsiflexion ROM may contribute to the heightened risk of ankle injury in gymnasts.[17]

The need to determine internal ankle injury risk factors for gymnasts differs from other sports because of the increased need for both flexibility and strength.[34] To perform well in sport, gymnasts need an increased plantarflexion ROM to maintain pointed toes throughout routines. They also need increased strength in the plantar flexors as well as the ankle dorsiflexors to both push off and propel themselves high into the air, and for eccentric control of the body while landing. Maintenance of both strength and flexibility requires a demand on the body rarely achieved in other sports. Another potential contributor to the heightened risk of ankle injury in gymnasts is arthrokinematic motion at the talocrural joint, particularly in a posterior glide. This is currently best measured with an arthrometer, an expensive piece of equipment used in laboratory research studies. The arthrometer is a tool which if used by the same person can be very reliable, but that same person with a high reliability on one machine can have very poor reliability between two different machines. The lack of one machine's reliability and validity compared to other machines, along with the high cost, are reasons that athletic trainers do not have access to an athrometer on a daily basis in an athletic training room setting. An alternative method that has been used is the talar glide method, which eliminates the need for an expensive piece of equipment by using either a digital inclinometer or a goniometer. One purpose of this study was to assess these two measurements to see if they could be used interchangeably. This was done by using the measurements for each participant and running a correlation between the two measurements.

The primamry purpose of this study was to compare ankle ROM, talar glide arthrokinematic motion, and triceps surae muscle stiffness between Division 1 female gymnasts and Division 1 female non-jumping athletes. A secondary purpose of this study was to evaluate relationships between the ratio of dorsiflexion ROM to total ROM, arthrokinematic motion, and triceps surae muscle stiffness. Finally, we also sought to evaluate the validity of the clinical talar glide assessment relative to the ankle arthrometer.

## Methods

### *Participants*

A total of 40 female participants volunteered for this study. The experimental group consisted of a total of 20 gymnasts; 12 from The University of North Carolina at Chapel Hill (UNC-CH) and eight from North Carolina State University (NCSU). The non-jumping control group consisted of 20 females split between softball (10), field hockey (8), and tennis (2) athletes at UNC-CH. Participants from both groups were excluded if they were limited during practice due to a lower extremity injury in the two months prior to participation or had a history of bilateral ankle surgery. Participants were excluded from the control group if they participated competitively in any jumping sport (e.g. basketball, volleyball, gymnastics, hurdling, or jumping field events for track) over the past 3 years.

Qualifying participants provided informed consent and the study was approved by the Institutional Review Board (IRB) at the University of North Carolina at Chapel Hill. Once the participants signed the consent form, they completed a health history questionnaire to confirm exclusion criteria and leg dominance. The dominant leg was defined as the stance leg when kicking a soccer ball for maximum distance for control participants and the stance leg in gymnasts during single leg skill.

*Procedures*

Range of motion

Ankle ROM was measured first with a digital inclinometer (Saunders Group, Inc., Chaska, MN). Good intra-rater reliability was established prior to data collection (Table 4.1). Participants performed a weight bearing lunge (WBL) to assess dorsiflexion ROM. The participant stood with her dominant foot placed in front and moved in a lunge position as far as forward as possible, moving the knee over the toes without lifting the heel off the floor (Figure 4.1). Trials were repeated if the heel came off the floor. A digital inclinometer placed on the tibial tuberosity was used to assess the angle between the tibia and the vertical.[53] An observer ensured there was no noticeable knee valgus or varus during the lunge. Non-weight bearing plantarflexion and dorsiflexion ROM were assessed with the participant seated on a plinth with the knee flexed over a foam roller. The digital inclinometer was placed parallel to the 5$^{th}$ metatarsal and was zeroed with the ankle in neutral dorsiflexion and plantar flexion verified by a standard goniometer (i.e.90 degree angle between the shank and foot). The participant then moved her foot into end range plantarflexion and dorsiflexion, and the maximal angle was recorded. All ROM measurements were repeated five times with the maximum motion measurements recorded for each trial.

**Figure 4.1: Weight bearing lunge ROM measurement using digital inclinometer**

<u>Muscle stiffness</u>

Participants performed a maximum voluntary isometric contraction (MVIC) first to determine the load used during active muscle stiffness testing. Participants were seated at the edge of a chair with their metatarsal heads on a block firmly attached to a force plate (Bertec Corp., Columbus, OH). A second firmly attached block of equal height was placed under the participant's heel to place the ankle, knee, and hip at 90 degrees (Figure 4.2). A perturbation device was placed on the participant's knee was set parallel to the ground as verified by a bubble level. A strap attached to cup hooks secured to the ground ensured the perturbation device was securely anchored to the ground (Figure 4.2). The force plate was zeroed prior to the participant maximally contracting her plantar flexors for five seconds while vertical ground reaction force data were sampled at 1000 Hz. The participant was given a 90 second rest period and this process was completed three times. The average MVIC was then calculated and converted from newtons to pounds. Twenty percent of the MVIC was used to load the perturbation device for the following muscle stiffness trials.

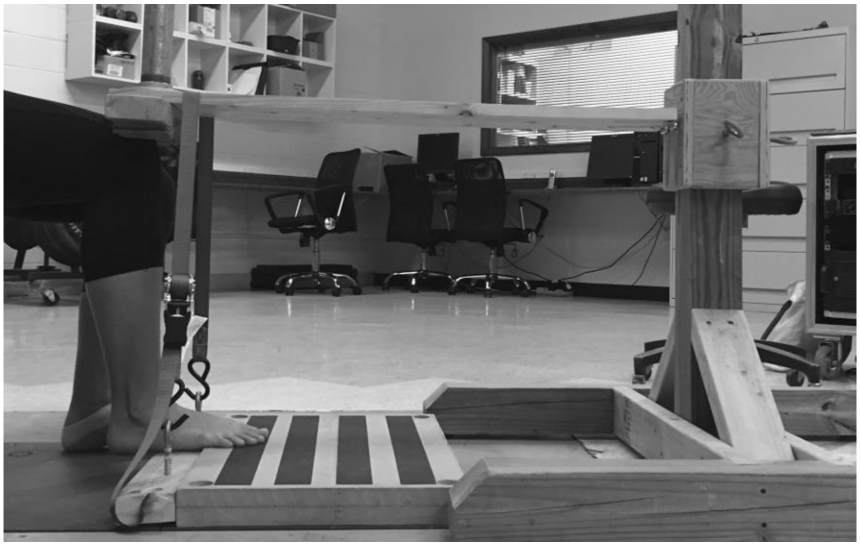

**Figure 4.2 Experimental setup for collecting MVIC data. The participant's hip, knee, and ankle will be flexed to 90 degrees. A strap will hold the perturbation lever in place while the participant maximally contracts their plantarflexor muscles forcing their knee into the lever**

Set up of the muscle stiffness trials was similar to the MVIC setup, but the plank under the foot and the strap were removed. A load equal to 20% MVIC was placed on the perturbation device directly in line with the tibia. The force plate was zeroed with the participant's heel on the ground and metatarsal heads rested on the force plate. The participant was instructed to lift her heel off the ground so her foot was parallel to the ground and her ankle was at 90 degrees (Figure 4.3). The participant then closed her eyes and the examiner applied a manual force to the perturbation device within 5 seconds of the participant closing their eyes. This force resulted in oscillatory plantarflexion and dorsiflexion that was reflected in the vertical ground reaction force. Participants performed three familiarization trials followed by five assessment trials. Participants were given a one minute rest period in between trials.

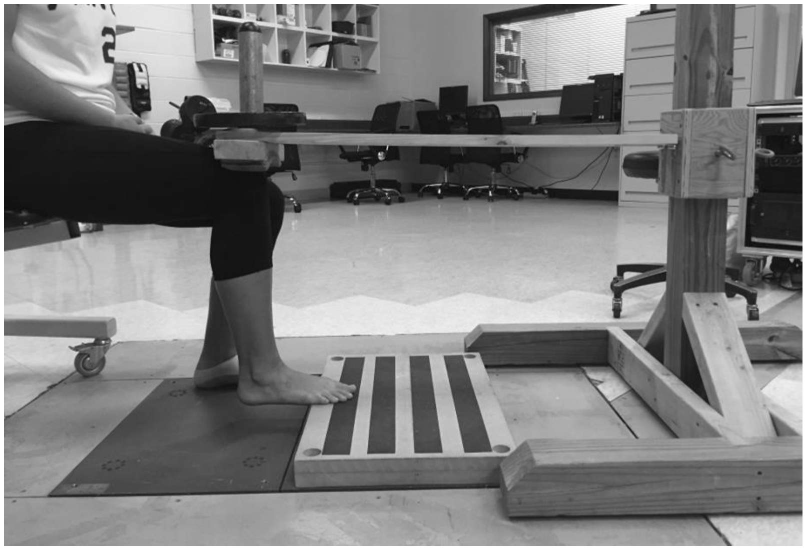

**Figure 4.3: Triceps surae muscle stiffness perturbation device and set up with hip, knee, and ankle at 90 degrees and perturbation lever parallel with ground.**

Arthrokinematic measurements

Talar glide and ankle arthrometer measurements were counterbalanced with muscle stiffness assessment performed in between arthrokinematic assessments. During the talar glide assessment, the participant sat on a plinth with her knees about 6” over the edge to allow for full knee flexion. The examiner then palpated the talus and held the foot in neutral (Figure 4.4). While the ankle remained in neutral, the examiner pushed posteriorly until a restriction was felt at the talus where the knee no longer freely moved into more flexion. The research assistant held the inclinometer, which was zeroed to vertical, along the participant’s tibia just inferior to the tibial tuberosity and recorded the angle at the point of restriction. This measurement was completed five times.

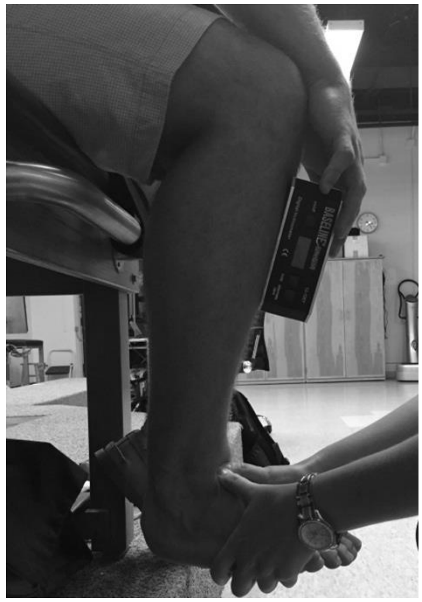

**Figure 4.4: Talar glide measurement with foot in neutral eversion/inversion and plantarflexion/dorsiflexion. A digital inclinometer placed along the tibia inferior to the tibial tuberosity to measure the angle at the restriction point.**

The Hollis ankle arthrometer assessed the talocrural anterior to posterior glide at the ankle. The participant was laying supine on a plinth with her legs relaxed and her foot propped up on a cushion and her ankle hanging off the table 2-3”. Her leg was strapped to the table above the knee and at the ankle to resist any knee flexion or motion from the leg. The arthrometer consisted of a foot plate with an adjustable heel cup that was adjusted to firmly grasp the heel and keep the foot in place (Figure 4.5). The foot plate was attached to a tibial pad which was secured to the distal shank. There was also an adjustable pad which was placed over the talar dome that held the anterior aspect of the ankle in place. The examiner created a posterior force on the talocrural joint of 125N. The electrogoniometer in the ankle arthrometer assessed the displacement of the talus in millimeters. This measurement was completed five times.

**Figure 4.5: Medial view of Hollis ankle arthrometer set up with straps securing knee and ankle**

*Data reduction*

Ground reaction force data were lowpass filtered at 10Hz (4$^{th}$ order Butterworth). The time between the first two oscillatory peaks of vertical ground reaction force was used to calculate oscillation frequency ($f=1/(t_2-t_1)$). The frequency was then used to calculate triceps surae muscle stiffness by entering it into the following equation: $k=4\pi^2mf^2$ where k was stiffness, m was mass of the system (applied load + mass of the shank and foot segment (6.1% bodyweight)), and f is the frequency at which the oscillation occurs. Stiffness was normalized to the mass of each participant.

Arthrometer posterior displacement was measured when the force transducer within the arthrometer measured a 125N force from the examiner. The displacement was calculated by an electrogoniometer with six degrees of freedom. This data was analyzed by hand using excel to find the peak posterior displacement when the arthrometer measured a 125N posterior force.

*Statistical analysis*

Minimum sample size was estimated at 19 participants in each group using G*Power 3 based on an alpha level of 0.05 and a power of 0.80.[68] Independent t-tests were used to compare height, weight, ankle ROM, triceps surae stiffness, and arthrokinematic motion between gymnasts and non-jumping athletes. Bivariate correlations were used to assess the relationship between the ratio of dorsiflexion to total ROM, muscle stiffness, and talar glide. A bivariate correlation assessed the relationship between the arthrometer and talar glide measurements to assess clinical utility of the talar glide method. All statistical analyses were performed using SPSS 23.0 statistical software (SPSS, Inc., Chicago, IL) with statistical significance set at $\alpha<0.05$.

**Results**

Gymnasts had significantly lower weight (59.48 ± 5.91 vs 67.52 ± 7.90 kg, P =.001) and height (159.18 ± 4.72 vs 167.28 ± 6.07 cm, P <0.001) than non-jumping athletes. ICC values were calculated for each of the following assessments and ranged from 0.82 to 0.98 which are all good to excellent values (Table 4.1). Gymnasts had significantly less non-weight bearing dorsiflexion ROM (15.19 ± 4.59 vs 19.47 ± 5.93 degrees, P =0.015) and a significantly smaller ratio of non-weight bearing dorsiflexion ROM to total ROM (0.18 ± .05 vs 0.26 ± 0.08, P <0.001) than non-jumping athletes. Gymnasts had significantly more non-weight bearing plantar flexion ROM than non-jumping athletes (68.43 ± 6.36 vs 55.1 ± 9.53 degrees, P <0.001). Gymnasts and non-jumping athletes did not significantly differ on the weight bearing lunge ROM, talar glide arthrokinematic motion, or triceps surae muscle stiffness (Table 4.2). Unfortunately, arthrokinematic motion measured with the arthrometer was not compared between groups because a failure in data storage resulted in a loss of half the data. Available data, that was not lost, was compared between groups for the 10 gymnasts and 6 non-jumping athletes. Even with the small sample size, gymnasts had a significantly greater amount of arthrometric motion (9.31±3.6 vs 5.22±3.61 mm, P=0.045).

Neither triceps surae stiffness nor athrometric motion assessed with the talar glide method significantly correlated with the ratio of dorsiflexion ROM to total ROM (Table 4.3). Additionally, the talar glide measurement did not significantly correlate with the available arthrometer data we had (Table 4.4).

**Table 4.1 Intraclass Correlation Coefficient (ICC) and Standard Error of Measurements (SEM)**

| **Measure** | **ICC (2,5)** | **SEM** |
|---|---|---|
| Weight bearing lunge($^o$) | 0.976 | ± 0.297 |
| Non-weight bearing ROM($^o$) | 0.953 | ± 0.325 |
| Talar glide($^o$) | 0.981 | ± 0.263 |
| Normalized stiffness (N $m^{-1}$*$kg^{-1}$) | 0.846 | ± 30.538 |
| Arthrometer(mm) | 0.822 | ± 0.746 |

**Table 4.2 Mean (Standard Deviation) of ROM Measurements, Triceps Surae Muscle Stiffness, and Arthrokinematic Motion in Gymnasts Compared to Non-jumping Athletes**

| **Test** | **Gymnasts Mean (SD)** | **Non-Jumping Athletes Mean (SD)** | **95% Confidence Interval** | P |
|---|---|---|---|---|
| Weight bearing lunge ($^o$) | 37.49 (6.66) | 37.39 (5.64) | (-3.85, 4.04) | 0.961 |
| Non-weight bearing dorsiflexion ROM ($^o$) | 15.19 (4.59) | 19.47 (5.93) | (-7.67, -0.88) | 0.015 |
| Non-weight bearing plantarflexion ROM ($^o$) | 68.43 (6.36) | 55.1 (9.53) | (8.14, 18.51) | <0.001 |
| Ratio of dorsiflexion to total ankle ROM | 0.18 (.05) | 0.26 (0.08) | (-.12, -.04) | <0.001 |
| Talar glide ($^o$) | 26.15 (5.49) | 25.47 (6.79) | (-3.27, 4.63) | 0.73 |
| Normalized stiffness (N $m^{-1}$*$kg^{-1}$) | 91.13 (30.96) | 103.55 (40.98) | (-35.67, 10.82) | 0.286 |
| Arthrometer (mm) | 9.31 (3.6) | 5.22 (3.61) | (0.10, 8.08) | 0.045 |

**Table 4.3 Correlation Between Ratio of NWB DF ROM to Total ROM, Talar Glide, and Normalized Triceps Surae Stiffness**

| | | Ratio of NWB DFROM to Total ROM | Talar Glide | Normalized Triceps Surae Stiffness |
|---|---|---|---|---|
| Ratio of NWB DFROM to Total ROM | r | 1 | | |
| | Significance | - | | |
| Talar Glide | r | 0.072 | 1 | |
| | Significance | 0.651 | - | |
| Normalized Triceps Surae Stiffness | r | -0.114 | -0.054 | 1 |
| | Significance | 0.483 | 0.739 | - |

**Table 4.4 Correlation of Ankle Arthrometer Measurements and Talar Glide Measurement**

| | | Talar Glide | Arthrometer |
|---|---|---|---|
| Talar Glide | r | 1 | |
| | Significance | - | |
| Arthrometer | r | -0.19 | 1 |
| | Significance | 0.481 | - |

## Discussion

The primary purpose of this study was to compare ankle ROM, muscle stiffness, and arthrokinematics between gymnasts and non-jumping athletes. The secondary purpose was to assess how ankle measurements are related to each other. We hypothesized that gymnasts would display less dorsiflexion ROM, dorsiflexion ROM to total ankle ROM ratio, weight bearing lunge dorsiflexion ROM, and talar glide motion than non-jumping athletes. We also hypothesized that gymnasts would display stiffer triceps surae muscles and greater plantar flexion ROM in gymnasts. The final purpose of the study was to assess the clinical utility of the talar glide test relative to the instrumented ankle arthrometer. We hypothesized that the talar glide methods would have a positive correlation with the arthrometer measurements.

Gymnasts had a significantly smaller height and weight when compared to the non-jumping athletes. This was expected to be the case as gymnasts tend to be smaller than other female athletes. This could potentially play a role in some of the results shown in this study.

The primary findings were that gymnasts displayed lesser dorsiflexion ROM, a smaller ratio of dorsiflexion ROM to total ankle ROM, and greater plantar flexion ROM compared to non-jumping athletes. However, gymnasts did not significantly differ on triceps surae muscle stiffness, arthrokinematic motion assessed with the talar glide, or a weight bearing lunge dorsiflexion ROM. Furthermore, triceps surae muscle stiffness and arthrokinematic motion assessments with the talar glide were not significantly correlated with the ratio to dorsiflexion ROM.

Greater plantarflexion was expected in gymnasts because of the requirement for the athlete to point her toes to form a straight line from the tibia that is introduced during a gymnasts formative years. As gymnasts start training heavily at an early age when they are skeletally immature, the body may adapt to the stressors put on it to allow for more plantarflexion ROM. Additionally, less dorsiflexion ROM than the normal range ($20^{o}$)[14,18], and compared to non-jumping athletes, was expected as gymnasts are constantly using their plantar flexors to punch and propel themselves into the air creating tightness of the triceps surae. Eccentric activity of repetitive landings also could play a role in the decreased dorsiflexion ROM seen in gymnasts as it strengthens the muscle thus decreasing flexibility and leading to decreased motion. The total arc was assessed through the ratio of dorsiflexion ROM to total ROM for similar reasons as the arc of motion is measured at the shoulder. In the shoulder the arc is measured to compare bilaterally as a right handed baseball pitcher through repetitions increases the available external rotation motion, while then decreasing the internal rotation available. However, the whole arc of motion is measured bilaterally to make sure the amount of motion is still the same. This could be similar at the ankle for gymnasts as they increase the plantar flexion ROM and thus decrease the available motion for dorsiflexion.

This difference in ROM is important because it has been shown that those with decreased dorsiflexion ROM are at a greater risk of ankle injury. In previous literature, it has been stated that decreased dorsiflexion ROM causes an alteration of kinematics at both the ankle and joints higher up the chain.[16,17,48,69] This then leads to increased injury risk not only at the knee but also at the ankle because of a compensatory knee valgus or pronation maneuver to make up for the lacking dorsiflexion ROM.[16,17,48,69]

There was no significant difference between groups in weight bearing lunge ROM, even though there were non-weight bearing differences. Both groups, however, had more ankle ROM while in the weight bearing lunge compared to the non-weight bearing ROM. The increase in dorsiflexion ROM from non-weight bearing to a weight bearing lunge has been seen in previous studies.[16,48] In those studies, an even greater amount of dorsiflexion ROM was seen with jump landing.[16,48] Ankle ROM differences from weight bearing to non-weight bearing can be attributed to a few things. First, a greater knee flexion angle at the time of measurement can decrease motion limitations caused by gastrocnemius tightness. As the gastrocnemius crosses the knee as well as the ankle, the angle of the knee affects available motion at the ankle. The gastrocnemius is relaxed and shortened at the knee when the knee is in a flexed position. Second, both measurements were taken with the knee flexed, but weight-bearing lunge measurements did not control the maximum knee flexion angle between participants or trials, while the non-weight bearing measures remained the same. The momentum of the body leaning forward into the lunge could have added a passive component forcing the participants into greater ROM. This is because body weight is greater than the force production of the ankle dorsiflexion musculature. The lack of difference seen in the weight bearing lunge could also be explained by compensations at other joints further up the chain which were not controlled for. The knee could have collapsed into valgus or the hip could have internally rotated allowing for more apparent motion at the ankle. The foot could have also pronated to allow for more dorsiflexion ROM motion in weight bearing that would not have been seen in non-weight bearing.

Gymnasts had significantly more arthrokinematic motion at the ankle when measured with the arthrometer than non-jumping athletes. This rejected our hypothesis that gymnasts would have less arthrokinematic motion than non-jumping athletes. A possible explanation for this could be differences in treatment protocols and use of joint mobilizations for their ankle which would increase the posterior arthrokinematic motion available at the ankle. This is considered a better tool for measurement of posterior ankle arthrokinematic motion as compared to the talar glide method which has little evidence to support its use. The talar glide method addressed the posterior talar glide at the ankle, but does so by moving the foot into dorsiflexion with a bent knee. As the ankle arthrometer requires the knee to be extended and locked into place, this could have inherently created a difference between the two measurements as structures other than the capsule, such as the gastroc-soleus complex, could have caused limitations. This could be further assessed by measuring non-weight bearing ROM in both knee flexed and extended positions to see the role of gastrocnemius tightness between groups.

The lack of a significant difference between groups in muscle stiffness and talar glide however is not as straight forward. There is not one distinct reason as to why this might be the case. We hypothesized that there would be greater muscle stiffness and less talar glide motion in gymnasts, and that this would contribute to less dorsiflexion ROM. This was also expected because of previous literature showing an increase in muscle stiffness in an injured population and most gymnasts have a history of ankle injury.[66] The values for muscle stiffness however are overall lower in this study than they were in Pamukoff's study of runners with and without stress history of stress fracture.[66] However, the participants in that study were all male which has been shown previously to have different stiffness measures even when controlled for weight.[63,66] Gymnasts lack dorsiflexion ROM, but what causes those restrictions could vary by the individual. Some have increased triceps surae stiffness, while others that are lacking dorsiflexion ROM are due to increased talocrural capsule tightness. Another component that was not assessed in the study was the bony alignment in the ankle joint. As gymnasts are constantly pointing their toes for both aesthetics and to propel themselves off the ground, they do not as consistently go into full dorsiflexion ROM. This repetitive motion, along with the constant pounding from landings on the ankle joint, could cause bony blocks that restrict dorsiflexion ROM. Future studies could take x-rays or bone scans to assess abnormalities in bony alignment in combination with joint capsular and musculotendinous facets which could explain alterations in ROM.

Previous history of injury could also play a role in our findings of altered ROM, but no differences in muscle stiffness or talar glide. No data was collected on past injury history other than for inclusion and exclusion criteria, but past history could alter some findings. Those with a history of ankle injury will be more likely to have decreased joint motion and increased stiffness that can affect dorsiflexion ROM. Those previously injured individuals are likely to have less ROM. This has been seen in runners with a history of 2nd metatarsal stress fractures.[66]

There were no significant relationships between the ratio of dorsiflexion ROM to total ankle ROM, talar glide, and triceps surae muscle stiffness. This further supports our rationale of the lack of significance between groups for muscle stiffness and talar glide. No relationship between ROM and stiffness or joint motion could mean the differences in ROM between groups cannot be attributed to one specific restriction. They instead could come from a combination of the many restrictions and one individual may have restricted motion due to either muscle stiffness or capsular restrictions, however, overall the trend is that there are differences due to variations in both measurements.

The secondary finding was that there is no significant relationship between the talar glide and posterior glide ankle arthrometer measurements. The relationship was being assessed to see if there was a clinical tool to similarly assess posterior talocrural glide motion with an ankle arthrometer. The ankle arthrometer is an expensive piece of laboratory equipment that is somewhat fragile. The talar glide is a measurement that can be completed easily with a goniometer and a plinth in the clinic. However, as the talar glide had a very weak correlation to the arthrometer measurements, this assessment cannot be recommended to measure the amount of posterior joint glide.

Limitations in this study could also be possible explanations to the results. As the data storage for the arthrometer measurements failed, the comparison between groups was done using the talar glide measurement which was shown to have little to no correlation with the arthrometer measurements. As there was no correlation, the talar glide should not be used to measure the magnitude of posterior glide clinically. Not controlling for knee valgus, knee flexion angle, or foot collapse during the weight bearing lunge could have also played a role in the lack of significance between the two groups, while a significant difference was seen for dorsiflexion ROM in a non-weight bearing stance. As gymnasts are subject to constant pounding of the ankle from landings, there is the possibility they have bone spurs on the talus or navicular which could restrict motion. No x-rays were taken in this study to assess the presence of these abnormalities, but future research could assess those differences.

In conclusion, gymnasts have significantly altered non-weight bearing ROM as compared to non-jumping athletes, but triceps surae stiffness and talar glide measurements do not show any significance. This could be due to previous injury history or bony abnormalities that were not taken into account in the current study. Further prospective studies need to be conducted to assess how these ROM differences affect injury risk in a population that is known to have an increased risk of ankle injury. The relationship between ROM, muscle stiffness, and arthrokinematic motion should further be assessed for possible injury risk factors as well as interventions that could lower injury rates.

APPENDIX A: HEALTH HISTORY QUESTIONNAIRE

Health History Questionnaire

1. Have you competed in any jumping sport (basketball, gymnastics, hurdling, volleyball, or jumping field events in track) during high school or currently? YES NO
2. Have you ever had surgery on your ankle or foot? YES NO
    a. If yes explain what procedure you had done, which leg, and when
    ______________________________________________________________________
    ______________________________________________________________________
    __
3. Have you had an ankle or foot injury in the past year? YES NO
    a. If yes how long did it restrict you from participation and when were you cleared?
    ______________________________________________________________________
    ______________________________________________________________________
    __
4. Do you have a history of stress fracture in your shin or foot? YES NO
    a. If yes where and when did this occur?
    ______________________________________________________________________
    _
5. Do you regularly experience a menstrual cycle? YES NO
    a. If yes, when was the start of your last cycle? ________________________________
    b. Are you on any medication to regulate your menstrual cycle? YES NO

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