THE ASSOCIATION BETWEEN MOVEMENT QUALITY, CUMULATIVE INTERNAL TRAINING LOAD, AND MUSCULOSKELETAL SYSTEM RESPONSE IN COLLEGIATE VOLLEYBALL PLAYERS

Samantha Nicole Cates

A thesis submitted to the faculty at the University North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Art in the Exercise and Sport Science Department in the College of Arts and Sciences.

Chapel Hill
2016

Approved by:

Darin Padua

William Prentice

Timothy Mauntel

ABSTRACT

Samantha Nicole Cates: The Association Between Movement Quality, Cumulative Internal Training Load, and Musculoskeletal System Response in Collegiate Volleyball Players
(Under the direction of Darin Padua)

Aberrant lower extremity biomechanics and high training loads are associated with increased injury risk. This study determined the relationship between biomechanical patterns, training load, cartilage thickness changes, and muscle response during the preseason of 17 collegiate female volleyball athletes (age= 19.7±1.2 years; weight= 77.1±8.7 kg; height= 170.4±10.1 cm). Lower extremity biomechanics were assessed using overhead squat and jump-landing assessments. Vastus lateralis cross sectional area (CSA) and echo intensity and femoral condylar cartilage thickness were measured via ultrasound prior to and following preseason. Session-RPE and jump counts were totaled across all practice sessions. Individuals with poorer LESS scores demonstrated less hypertrophy of the vastus lateralis (r= -0.672, p= 0.003). Individuals with poorer overhead squat scores demonstrated greater decreases in medial femoral condylar cartilage thickness (r= -0.544, p= 0.024). Poor movement quality could be an underlying factor to quadriceps muscle inefficiency and femoral cartilage damage, which may increase injury risk.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CSA	Cross sectional area
LESS	Landing error scoring system
RPE	Rate of perceived exertion

CHAPTER I

Introduction

Volleyball is one of the most popular sports to participate in worldwide.[1] The incidence of injuries in collegiate volleyball players is highest in the preseason practice period with a rate of 6.19 per 1000 athlete-exposures. Lower extremity injuries, primarily ankle sprains, upper leg muscle-tendon strains, and knee internal derangements are most common, accounting for approximately 55% of practice injuries.[2] Ankle injuries are the most common; however, knee injuries account for up to 20% of all injuries in volleyball players.[3] Knee injuries have been identified as the most severe injuries experienced by volleyball athletes and are the most common overuse injuries seen in volleyball players.[4 5] Even with appropriate treatment and rehabilitation, disability and time lost following a lower extremity injury is prevalent. Therefore, it is necessary to understand factors that may influence knee injuries in volleyball athletes.[6]

Two proposed factors that influence the risk of knee injury include aberrant lower extremity biomechanics and high training loads.[7 8] Aberrant lower extremity biomechanics are associated with increased risk for future acute and chronic knee injury.[7] Lower extremity biomechanical patterns associated with increased risk of injury include excessive hip frontal plane motion, which contributes to knee valgus collapse,[9] limited ankle dorsiflexion,[10] excessive knee hyperextension,[11] and less leg stiffness.[12] Volleyball players with a previous diagnosis of patellar tendonitis were found to land from a jump with a stiffer knee joint, as displayed by faster ankle plantar flexion and knee extensor moment development, in combination with higher knee angular velocity.[13] Volleyball athletes demonstrating aberrant biomechanical profiles during landing are believed to be at risk for knee injury.[14]

High training loads are also associated with increased injury rates in sport.[8 15] A positive relationship has been found between the incidence of training injuries and the duration, intensity, and internal load of training sessions.[15] Athletes who completed a high volume of training and high match exposures were at an increased risk for developing jumper's knee.[16] Training load modifications occur via alterations in frequency, duration, and intensity throughout a sport season.[17] Fatigue is often a result of the interaction of these loading methods as well as the type of muscle contraction, physiological and training status of the individual, and environmental conditions.[17] Due to the notable influence of both movement patterns and training load on injury risk, it is also important to understand how these factors may interact with each other.

Examining the interaction between movement patterns and training load requires the ability to assess both variables in a clinical or field based settings. Clinical assessments of movement quality are possible, as aberrant movement patterns identified through visual observation have been shown to influence the risk of lower extremity injury.[18 19] Common lower extremity movement assessments include the double leg and single leg squatting tasks where movement compensations such as, knee valgus or varus, foot flattening, asymmetrical weight shift, and foot external rotation are identified by a trained rater.[20 21] The Landing Error Scoring System (LESS) is another clinical assessment of movement quality. The LESS has been shown to be a reliable and valid assessment of jump-landing movement patterns associated with increase risk of ACL injury and lower extremity stress fractures.[22] Thus, movement quality can be reliably and validly assessed in a clinical/field based setting. Assessment of training load in a clinical/field assessment is also possible using the ratings of perceived exertion (RPE) method and quantifying minutes of physical training.[23] This method, session-RPE, has been demonstrated to be a valid marker of training load and is associated with future risk of injury.[17] As such, volleyball athletes displaying poor movement quality during clinical movement assessments like the LESS and squat tasks may experience greater overall training load, which can further increase one's risk of injury.

Exercise involving repeated exposure to increased joint loading is a risk factor for developing knee osteoarthritis.[24] After only a 30-minute duration of running or drop landing a significant deformation is seen using high-resolution magnetic resolution imaging (MRI) in femoral articular cartilage.[24 25] MRI has been shown to accurately depict structural knee joint damage, but is an expensive, time consuming, and not widely available for clinicians to use. Fortunately, high-resolution ultrasound, which is inexpensive and widely available, is accurate at measuring femoral articular cartilage thickness in normal to moderately damaged cartilage.[26] Due to the intense periods of exercise that athletes experience during a preseason, it is important to understand the effects of high training loads on musculoskeletal tissues and ultimately injury rates.[15]

Individuals' biomechanical profiles may influence their relative training load. Specifically, those with aberrant biomechanical profiles may be less mechanically efficient, thus experiencing greater relative training loads and placing greater stress on their soft tissue structures. Fatigue can lead to decreased muscle strength, reduced reaction time, impaired joint position sense, altered motor control and biomechanics, and deficits in dynamic stability.[27] These factors have been postulated to increase the risk of injury during sport activity. Lower extremity fatigue is associated with increased knee valgus moment, decreased knee flexion angles, and increased proximal tibial anterior shear force all of which are risk factors for ACL injury.[28]

Fatigue has also been associated with acute muscle damage through measurements of muscle cross sectional area and echo intensity during both concentric and eccentric fatigue exercises.[29] Furthermore, greater differences in right and left cross sectional area and higher echo intensity of the vastus lateralis using diagnostic ultrasound is associated with increased risk of lower extremity injury in professional basketball players.[30]

Purpose

We are unaware of previous research examining the association between biomechanical patterns, relative training load, cartilage thickness, and soft-tissue stress. Therefore the purpose of this study is to determine the relationship between biomechanical patterns, fatigue, cartilage thickness changes, and muscle response during the preseason practice period of division one female volleyball athletes. By determining the relationship between biomechanical patterns, fatigue, cartilage thickness changes, and muscle response clinicians will be better able to assess volleyball players at risk for future injury.

Variables

- Independent:
  - Overhead Squat
  - Single-Leg Squat
  - Landing Error Scoring System
  - Jump Count
- Dependent:
  - Cumulative Internal Training Load (RPE * minutes of training)
  - Femoral Condyle Cartilage Thickness
  - Vastus Lateralis Cross Sectional Area

- Vastus Lateralis Echo Intensity

Research Questions and Hypothesis

1. Research Question 1: What is the association between movement quality during the overhead squat, single-leg squat, and jump-landing tasks with the change in vastus lateralis musculature over the pre-season in Division I collegiate female volleyball athletes?
    - Research Hypothesis 1: Female volleyball athletes with poor movement quality during the overhead squat, single-leg squat, and jump-landing tasks will demonstrate a greater increase in vastus lateralis cross sectional area and echo intensity compared to those with good movement quality.
2. Research Question 2: What is the association between movement quality during the overhead squat, single-leg squat, and jump-landing tasks with the change in femoral condyle cartilage thickness over the pre-season in Division I collegiate female volleyball athletes?
    - Research Hypothesis 2: Female volleyball athletes with poor movement during the overhead squat, single-leg squat, and jump-landing tasks will demonstrate a greater decrease in femoral condyle cartilage thickness compared to those with good movement quality.

3. Research Question 3: What is the association between movement quality during the overhead squat, single-leg squat, and jump-landing tasks with cumulative internal training load over the pre-season in Division I collegiate female volleyball athletes?
    - Research Hypothesis 3: Female volleyball athletes with poor movement quality during the overhead squat, single-leg squat, and jump-landing tasks will demonstrate greater cumulative internal training loads compared to those with good movement quality.

CHAPTER II

Participation and Injury

Knee injuries are common and debilitating in the athletic population, accounting for 15-50% of all sport related injuries.[31] Of all sports-related knee injuries, patellofemoral disorders are the most common and are caused by patella mal-tracking, overuse, and trauma.[16 32 33] The most common surgical interventions about the knee are meniscal repairs.[32] During sport activities such as running, jumping, and pivoting the meniscus is put under tremendous stress, increasing the likelihood of injury.[34] In sports, ligamentous injuries, specifically anterior cruciate ligament (ACL) tears and collateral ligament tears, account for a large percentage of all knee injuries.[2] These injuries lead to serious consequences such as high treatment costs, decreased academic performance, time lost from sport, increased risk of early osteoarthritis, and increased risk of never returning to the same levels of activity as before injury.[31 35-37]

Volleyball has one of the highest participation rates worldwide and the knee has been identified as one of the most common and severe sites for acute and overuse injuries among volleyball players.[1 2 4 6 38 39] In a Danish casualty report volleyball injuries accounted for 5.3% of all sport related injuries.[40] Augustsson et al[38] found the prevalence of injury was 0.86 injuries per female volleyball player during one season. Similarly, Verhagen et al[41] found during a 36 week volleyball season that acute injury incidence was 2.0 per 1,000 hours of athletic exposure and overuse injury incidence was 0.6 per 1,000 hours of athletic exposure. The most frequently occurring acute injuries are ankle ligament sprains, upper leg muscle strains, and knee internal derangements.[2] Among collegiate women's volleyball players knee injuries occurred most frequently to the meniscus (37%), the collateral ligaments (33%), and anterior cruciate ligament (26%).[2]

Patellar tendinopathy is the most common overuse injury in elite volleyball players, with an incidence of 28-40%.[42] Jumper's knee afflicts 50% of male volleyball players.[43] Visnes et al[16] found the mean annual incidence of jumper's knee per year was 21% in males and 5% in females. Overuse injuries in the knee are associated with longer disability in female volleyball players compared to males.[4] Because knee injuries pose a threat to return to play and account for the most time lost from competition in volleyball compared to any other injury, researchers are focused on identifying potential risk factors that in the future will be beneficial in reducing the number of knee injuries.

Injury Risk Factors

A number of potential risk factors have been identified in an attempt to explain why some individuals are at an increased risk of knee injury.[44] Two commonly observed risk factors are aberrant biomechanical patterns and high internal training loads. Aberrant biomechanical patterns and high internal training loads are independently considered predisposing factors to sustaining a knee injury; however, little research exists regarding the relationship between these two entities.[7,8]

Musculoskeletal injuries occurring during volleyball commonly result from jumping or landing during spiking and blocking maneuvers, and occur most often to the lower extremity.[3,4,35] Outside and middle hitters have a higher rate of injury compared to setters and liberos.[39] Bahr and Bahr[45] found that 89% of injuries occurred at the net where jumping was frequently required, and more specifically Jadhav et al[3] observed that injuries occurred 33% of the time during spiking and 24% of the time during blocking. These findings are not surprising, as volleyball athletes commonly display lower extremity mechanics that are associated with elevated knee loading and injury risk when landing from a jump, including greater knee valgus angles and greater vertical ground reaction forces.[46 47] In fact, Ferritti et al[42] found that nearly all ligamentous injuries in volleyball occurred during a phase of jumping. Severe knee injuries are primarily the result of a non-contact mechanism with no direct blow to the knee, implicating the individual's movement pattern as the cause for injury.[2]

Aberrant lower extremity biomechanics are associated with an increased risk of acute and chronic knee injury in volleyball athletes. Greater knee valgus angle during functional tasks is a predisposing factor for non-contact knee injuries.[48] Restricted ankle dorsiflexion and excessive hip adduction and internal rotation are associated with dynamic knee valgus collapse.[49-51] Deficits in neuromuscular control of the trunk and consequently increased trunk displacement are associated with increased risk of knee injury.[52] Furthermore, athletes who sustained an in-season injury generally displayed decreased core stability compared to uninjured athletes.[53] Therefore, athletes must have adequate strength and range of motion in the hip, core, and ankle to aid in the prevention of acute and chronic knee injury.

Volleyball athletes who use a step back landing method when landing from a block in volleyball demonstrated increased vertical ground reaction force, greater valgus moments, and lower knee energy absorption compared to players who utilized a stick landing.[47] Female athletes who went on to injure their ACLs displayed greater knee abduction angles and higher ground reaction force during a drop vertical jump task.[48] Volleyball athletes who jump the highest and land from a spike with the deepest knee flexion angle demonstrate a higher incidence of jumper's knee.[54 55] Patellar tendinopathy is associated with reduced ankle dorsiflexion range of motion, deep knee flexion angles, large external tibial torsional moments, high knee extensor moment loading rates, and high ankle inversion-eversion moments during jump-landing.[10 13 56 57] Athletes that developed patellar tendinitis demonstrated decreased hamstring and quadriceps flexibility compared to athletes who were asymptomatic.[58] Fortunately, these aberrant lower extremity biomechanics that put athletes at greater risk for future injury can be identified using quick, cost-effective movement assessments.

Movement Quality Assessments

Clinical movement assessments have been developed to identify individuals at increased risk for lower extremity injury through the observation of aberrant lower extremity biomechanics.[18] Specifically the overhead squat, single leg squat, and jump-landing tasks have been used.[19 21 59] Females are more likely to demonstrate greater hip adduction and flexion combined with knee valgus, greater knee frontal plane projection ankles, and generate less trunk, hip and knee isometric torque during a single leg squat task.[60 59] Individuals who displayed medial knee displacement were found to have less passive ankle dorsiflexion range of motion during a single leg squat, increased hip adductor activation, and increased coactivation of the gastrocnemius and tibialis anterior during an overhead squat.[61 62] Additionally, during a jump-landing task females tended to land in a more erect posture with less hip and knee flexion.[63]

The overhead squat assessment is used to qualitatively assess an individual's overall movement patterns and is reliable in identifying aberrant movement patterns.[64] The overhead squat task is capable of identifying individuals with medial knee displacement as related to dynamic knee valgus.[21] The overhead squat assessment is commonly used by sports medicine professionals due to the ease and reliability of training a novice rater.[64] The single leg squat assessment has yet to be validated as a screening tool for identifying knee injury risk factors, however it is commonly used to identify aberrant lower extremity biomechanics.[61 65] It is frequently used in the clinical setting due to the simplicity of observing knee alignment during a weight-bearing task.[59] Specifically medial knee displacement has been observed using the single leg squat, which is related to dynamic knee valgus.[60] Studies show that females begin and end a single-leg squat maneuver in greater knee valgus compared to males, which could increase the risk for injury.[60]

The Landing Error Scoring System (LESS) possesses good criterion validity and reliability in identifying individuals who exhibit aberrant jump-landing biomechanics.[19] For the LESS, a higher score indicates poor jump-landing technique and a low score indicates a better jump-landing technique.[19] The LESS consist of 22 scored items to determine a composite score for individuals: knee flexion angle at initial contact, hip flexion angle at initial contact, trunk flexion angle at initial contact, ankle plantar-flexion angle at initial contact, knee valgus angle at initial contact, lateral trunk flexion angle at initial contact, medial knee position at initial contact, stand width, foot position, asymmetric initial foot contact, asymmetric timing, asymmetric heel-toe/toe-heel, knee flexion displacement, hip flexion displacement, trunk flexion displacement, excessive trunk flexion displacement, maximum medial knee position, asymmetric loading, joint displacement, wobble, and overall impression.[66] In general, females demonstrate significantly more landing errors when performing the LESS.[67]

Femoral Articular Cartilage

Aberrant biomechanics and increased and repetitive joint loading place abnormal stresses on the musculoskeletal system, resulting in excessive stress on articular cartilage and increase the likelihood of developing knee osteoarthritis.[24 68 69] Furthermore, female athletes that participate in long-term weight-bearing sports are at an increased risk for developing osteoarthritis at the knee and hip compared to non-athletic females.[70] Volleyball is a sport that is considered to have high intensity of joint impact and torsional loading.[71] Individuals with mild valgus malalignment (1.1-3.0 degrees) and greater valgus malalignment (3.1-5.0 degrees) are at increased risk for osteoarthritis disease progression. Individuals without evidence of radiographic osteoarthritis that have valgus malalignment greater than 5.1 degrees are at an elevated risk for future cartilage damage.[68]

High resolution MRI is the gold standard in examining cartilage morphology. However due to the high cost and limited access, high-resolution ultrasound has recently been described as a valid and reliable tool for assessment of distal femoral cartilage.[26 72 73] Decreases in patellar, medial and lateral tibial, and medial and lateral femoral cartilage volume and thickness have been found following 30-60 minutes of running.[24 74] After a 30-minute drop landing exercise, decreased cartilage volume and thickness were found at the patella and medial and lateral tibia. Compared to the drop landing, greater cartilage deformation was noted after running.[75]

Training Loads

The majority of volleyball specific injuries occur during practice sessions rather than matches.[38 55 76] During a five year period of volleyball play, 230 injuries occurred during training whereas only 133 injuries occurred during games in 114 Greek volleyball championship and local division players[39]. Augustsson et al[38] reported 47% of all injuries occurred during volleyball specific training and in particular, 47% of major injuries (those resulting in inability to participate for greater than 4 weeks) occurred during this training period. Compared to the regular season, preseason practice injury rates in collegiate women's volleyball players were more than twice as high.[2] The preseason period is typically the most difficult and physically demanding practices of the season for athletes.[77] During a rugby season, more injuries occurred during the first half of the season with an overall preseason incidence of injury at 6.9 per 1,000 training hours.[78 15]

High internal training loads, high training intensity, and high training duration are associated with increased risk of acute injuries in athletes.[15 16 79] Gabbett and Jenkins[80] found that high training load was significantly related to contact and non-contact injuries in rugby players. Furthermore, overuse injuries are associated with increases in training volume.[81] Volleyball players who suffered from jumper's knee had increased training volume and higher match exposure compared to asymptomatic volleyball players.[16] Monitoring internal load is important to measure the physiological and psychological stress imposed and is critical in determining the training load and adaptations.[17] Session rating of perceived exertion (RPE) is a validated tool for measuring training load and is associated with future risk of injury.[23 82] This method of quantifying internal training load was developed by Foster et al[23] and involves multiplying the athlete's RPE (1-10) by the duration of the session (minutes). The category ratio rating of perceived exertion scale is as follows: 0- rest, 1- very, very easy, 2- easy, 3- moderate, 4- somewhat hard, 5- hard, 7- very hard, 10- maximal. 6, 8, and 9 are considered intermediary values between 5-10 with no RPE definition.

Increases in training frequency are associated with increases in acute exercise-induced fatigue.[83] Musculoskeletal fatigue results in reduced muscle activity, decreased alertness, loss in motor control, and delayed neuromuscular response all of which decrease the capacity to perform therefore increasing the likelihood of injury.[27] Fatigue is one of the most common injury factors in elite volleyball players.[76] Cielsa et al[55] found that 50% of volleyball players attributed their injury to exhaustion or lack of rest. Acute fatigue causes alterations in lower extremity kinetics and kinematics when landing.[84] Individuals with prior ACL reconstruction and uninjured individuals both demonstrated higher LESS scores, reflective of poor movement quality, when they were acutely fatigued.[85] Researchers found decreased knee flexion joint angles, greater knee valgus joint angles, lower ground reaction force, increased lateral and forward trunk flexion and increased peak proximal tibial anterior shear forces in acutely fatigued individiuals.[28 86-89] Fatigue is also correlated to muscle and tendon damage through observing cross sectional area and echo intensity following acute bouts of concentric and eccentric fatigue exercises.[29]

Musculoskeletal Response

Muscle cross sectional area (CSA), an index of muscle size can be used as a direct measurement of muscle edema.[90] The gold standard for the assessment of whole-muscle CSA is currently magnetic resonance imaging (MRI), but there are high cost and limited access associated with this device. Recently, panoramic ultrasonography has been validated against MRI for detecting training induced changes in muscle CSA.[91] Repetitive eccentric contractions cause muscle swelling as indicated by increases in muscle CSA measured via ultrasound imaging.[90] More specifically, measurements of the vastus lateralis CSA using ultrasound have been validated against MRI.[91 92] Takahashi et al[93] found CSA of the vastus lateralis, intermedius, and medialis peaked 12-24 hours following a 20-minute bout of eccentric exercise. Similarly, Oyama et al[94] found that increases in infraspinatus CSA were present immediately following and 24 hours after eccentric exercises.

Echo intensity is a measurement of muscle quality that is obtained through gray-scale analysis (0:black, 256:white) of the pixels of an ultrasound image and is highly correlated to fatty infiltration and fibrous tissue within skeletal muscle.[95 96] Nosaka and Clarkson[97] found increases in echo intensity are related to muscle enlargement, indicating muscle damage as reflected by swelling. Panoramic ultrasound is a reliable indicator of muscle damage as determined through echo intensity.[98] Radaelli et al[29] found significant increases in echo intensity 24-72 hours following a bout of resistive exercises. After a maximum eccentric exercise of the elbow flexors echo intensity and muscle thickness significantly increased and peaked 4-5 days following exercise.[99] Following 30 maximal voluntary lengthening contractions of the elbow flexors, echo intensity continued to increase at 48 and 120 hours post-exercise.[96]

Conclusion

In conclusion, aberrant lower extremity biomechanics and high internal training loads may influence the increased incidence of knee injuries in female volleyball athletes. For female athletes to safely participate in their sport, monitoring training load and preventative strategies for knee injuries must continue to progress. Because the number of female athletes continues to grow, using screening tools and monitoring training loads may aid in the reduction of future sport-related injuries. This will allow female athletes to continue sport participation and avoid long-term disability associated with knee injuries.

CHAPTER III

Methodology

Subjects

17 women's NCAA Division I varsity volleyball players were included in this study.

Inclusion Criteria

Member of the varsity volleyball team at the University of North Carolina at Chapel Hill for the 2015 season.

Exclusion Criteria

Participants who were unable to complete one or more of the tasks during baseline assessment were excluded from this study. Participants not currently cleared to participate in varsity athletics for any reason were excluded from this study. Participants who were unable to participate in a total of 3 or more pre-season practice sessions will be excluded from this study.

Instrumentation

Standard Goniometer

Knee flexion angles were measured using a standard 30.5 cm plastic goniometer for femoral condyle cartilage measurements. Goniometric measurements of the knee have been validated against radiographic measurements.[100]

2D Cameras

Two standard video cameras (Sony Electronics, San Diego, California) were used to capture frontal and sagittal plane view of participants performing the Landing Error Scoring System testing procedures and squat assessment. Standard video cameras were used to record all practice sessions and watched at a later date by the primary investigator to count the number of jumps experienced by each participants.

Diagnostic Ultrasound

GE B-mode ultrasound (LOGIQ e 5, General Electric Company, Wisconsin, USA) was used to generate real-time panoramic cross-sectional image of the vastus lateralis and still frame images of the distal femoral cartilage.

Testing Procedures (Figure 3.1)

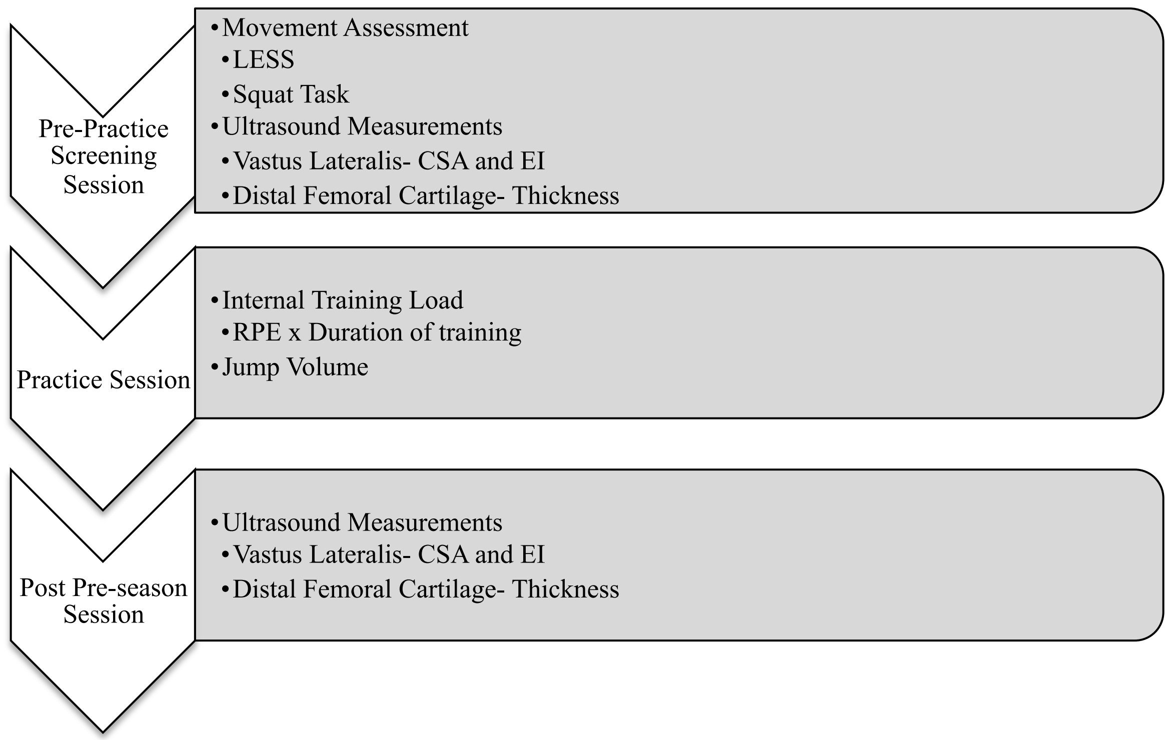

Figure 3.1 Flow Chart of Data Collection

Pre Practice Screening Session

Participants reported to the Sports Medicine Research Laboratory on the day prior to the start of the preseason practice period. The participants read and signed an informed consent form approved by the Institutional Review Board (IRB) of the University of North Carolina at Chapel

Hill. Participants then completed a questionnaire to confirm player position, medical history, and contact information.

Panoramic Ultrasound Assessment

Vastus Lateralis

The participant was supine with the dominant leg (the leg they would use to jump off of for maximum height) extended and relaxed on the examination table. The ultrasound probe was held perpendicular to the tissue at the midpoint between the greater trochanter and lateral femoral epicondyle and was moved manually with slow and continuous movement from the lateral vastus lateralis border to the medial fascia separation.[101 102] (Figure 3.2) Minimal pressure was applied to the skin to prevent muscular compression and distortion. Water-soluble transmission gel was applied to the skin to enhance vastus lateralis imaging. GE B-mode ultrasound (LOGIQ e 5, General Electric Company, Wisconsin, USA) was used to generate real-time panoramic cross-sectional image of the vastus lateralis. The ultrasound settings (frequency: 12Hz, gain: 68, depth: 4.0 cm) were kept consistent for all participants.

Figure 3.2 Vastus lateralis ultrasound measurement procedure.

Femoral Articular Cartilage

The knee was examined with the participant supine with her dominant leg in 130° of knee flexion. This knee flexion angle was measured using a standard goniometer to ensure the same knee flexion angle was used between subjects and during pre-testing and post-testing. The primary investigator palpated and drew a horizontal line at the most superior aspect of the patella. The transducer was centered at this marked point, and moved superiorly until the first point of the shadow of the patella was not observable. (Figure 3.3) The intercondylar notch was aligned to the middle bold line of the ultrasound screen grid. Three still framed images of the transverse femoral cartilage were obtained using GE B-mode ultrasound (LOGIQ e 5, General Electric Company, Wisconsin, USA). The height (screen grid reference point) of the bony interface of the middle and lateral femoral condyles were recorded to ensure the same pre-testing and post-testing anatomical alignment. The ultrasound settings (frequency: 12Hz, gain: 68, depth: 4.0 cm) were kept consistent for each scan.

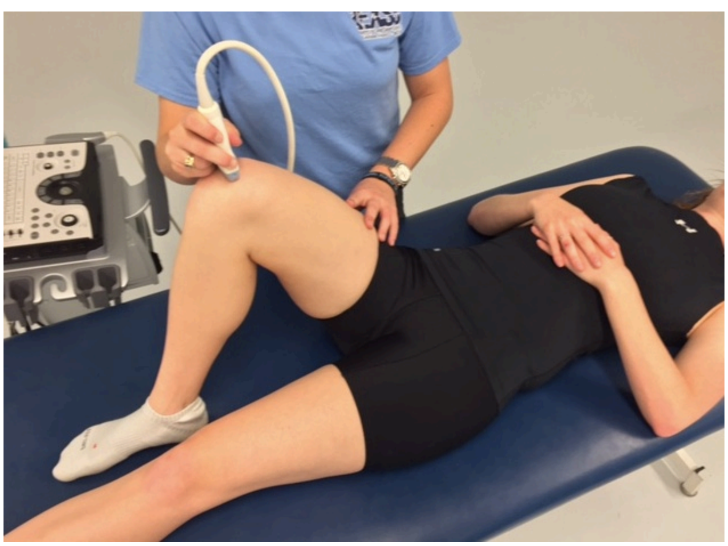

Figure 3.3. Femoral condylar cartilage ultrasound measurement procedure.

Movement Quality Assessment

Landing Error Scoring System (LESS)[19]

Participants wore a team issues sports bra and spandex shorts during movement quality assessments. During the Landing Error Scoring System (LESS), participants jumped down from a 30 cm high box placed at a distance ½ of the participant's body height away from the target area. Participants were instructed to jump down and forward onto the target and immediately perform a second vertical jump for maximum vertical height. Three trials were performed.[19] (Figure 3.4 and 3.5) Movement quality during the jump-landing was later scored using the LESS rubric, which is scored based on 22 observable items of human movement from initial contact to maximum knee flexion displacement. Lower extremity and trunk positioning are observed and rated at initial ground contact and between initial ground contact and the moment of maximum knee flexion angle. Foot positioning errors are assessed at initial ground contact and between initial contact and the moment of maximum knee flexion angle. Overall sagittal plane movement displacement and the rater's general perception of the landing quality are scored. A higher LESS score indicated more high-risk movement patterns and a lower score indicated fewer high-risk movement patterns. Each jump was videotaped from the frontal and sagittal views. The videos were watched at a later date by the primary investigator and a LESS score was generated for each participant using the grading rubric. (Table 3.1)

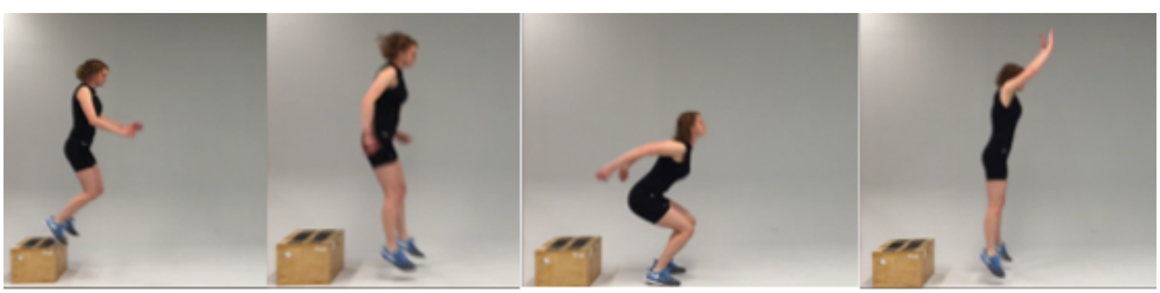

Figure 3.4. Sagittal view of jump-landing task.

Figure 3.5 Frontal view of jump-landing task.

Table 3.1 Landing Error Scoring System Grading Rubric[19 66]

Landing Error Scoring System: LESS 4
1. Knee Flexion at Initial Contact < *30 deg*
2. Hip Flexion at Initial Contact *Hips are not flexed*
3. Trunk Flexion at Initial Contact *Trunk is not flexed*
4. Ankle Plantar-Flexion Angle at Initial Contact *Land Heel to Toe (or) Flat Foot*
5. Asymmetrical Foot Contact *Not Symmetric*
6. Asymmetrical Timing *Feet do not land at the same time*
7. Asymmetrical Heel-Toe/Toe-Heel *Lands flat/heel-toe and the other foot lands toe-heel*
8. Lateral Trunk Flexion at Initial Contact *Trunk is NOT vertical*
9. Medial Knee Position at Initial Contact *Knees medial to midfoot*
10. Stance Width: > shoulder width
11. Stance Width: < shoulder width
12. Max IR Foot Position *Toes > 30 deg. IR*
13. Max ER Foot Position *Toes > 30 deg. ER*
14. Knee Flexion Displacement < *an additional 45 deg. of flexion after initial contact*
15. Hip Flexion Displacement *Hips DO NOT flex more than at initial contact*
16. Trunk Flexion Displacement *Trunk DOES NOT flex more than at initial contact*
17. Excessive Trunk Flexion Displacement *Trunk flexes past parallel with lower leg*
18. Maximum Medial Knee Position≥ *great toe*
19. Asymmetrical Loading *A weight shift is present*
20. Wobble: in REAL-TIME *Knee wobbles (demonstrates quick varus/valgus motion)*
21. Joint Displacement *Sagittal Plane*
22. Overall Impression

Squat Assessment

For each of the following movement assessments, participants were scored based on readily observable items of human movement. Each squat was videotaped from the frontal and sagittal views. The primary investigator replayed the videos at a later date and squat scores were generated for each participant using the grading rubrics (Table 3.2, 3.3). A higher squat score indicated poor technique and a lower score indicated better technique.

Table 3.2 Overhead Squat Grading Rubric

Overhead Leg Squat (feet shoulder width apart)
1. Foot Turns Out
2. Foot Flattens
3. Knee Moves In (Valgus)
4. Knee Moves Out (Varus)
5. Excessive Forward Lean
6. Low Back Arches
7. Low Back Rounds
8. Arms Fall Forward
9. Heel of Foot Lifts
10. Asymmetrical Weight Shift

Table 3.3 Single Leg Squat Grading Rubric

Single Leg Squat
1. Foot Flattens/Turns Out
2. Knee Moves In (Valgus)
3. Knee Moves Out (Varus)
4. Uncontrolled Trunk/Hip Shift
5. Loss of Balance
6. < 60° Knee Flexion
7. Low Back Rounds
8. Trunk FLX, ROT, SB
9. Hip Drop/Hike

Overhead Squat Assessment (1 set of 5 repetitions)[64]

The participant stood with her feet shoulder-width apart with her arms extended vertically overhead. She descended into a squat to maximal comfortable flexion and then returned to the initial upright position. (Figure 3.6, 3.7) Participants were instructed to complete the squat in a slow and controlled manner. The participant completed 5 practice trials to familiarize herself with the task. The participant performed 5 consecutive squat trials.

Figure 3.6 Sagittal view of overhead squat assessment.

Figure 3.7 Frontal view of overhead squat assessment.

Single Leg Squat Assessment (1 set of 5 repetitions bilateral)

The participant stood with her feet shoulder-width apart and raised one leg to 90° of hip and knee flexion. (Figure 3.8, 3.9) The participant's hands were placed on her hips. Participants were instructed to complete the squat in a slow and controlled manner. The participant descended into a squat to maximal comfort and then returned to the initial upright position. The participant completed 5 practice trials to familiarize herself with the task. The participant performed 5 consecutive squat trials on each leg.

Figure 3.8 Sagittal view of single leg squat assessment.

Figure 3.9 Frontal view of single leg squat assessment.

Practice Session

Session Rate of Perceived Exertion

Within 30 minutes of the conclusion of each preseason practice session, participants verbalized their RPE to the primary investigator who recorded this number along with the type of training performed (volleyball practice, conditioning, weight lifting) and duration of training. This number was multiplied by the duration of practice in minutes. This produced a self-reported internal training load value for each participant. This method of quantifying internal training load was developed by Foster et al[23] and involves multiplying the athlete's RPE (1-10) by the duration of the session (minutes). The category ratio rating of perceived exertion scale is as follows: 0- rest, 1- very, very easy, 2- easy, 3- moderate, 4- somewhat hard, 5- hard, 7- very hard, 10- maximal. 6, 8, and 9 are considered intermediary values between 5-10 with no RPE definition.[23] The session rate of perceived exertion has been found to be a reliable and valid method of quantitating exercise training load.[23 82] This method was developed to eliminate the need to utilize other methods of assessing exercise intensity.

Jump Volume

Each practice session was filmed and watched at a later date by the investigator to count the number of jumps experienced by each participant. A jump was defined as any volleyball maneuver that resulted in both feet leaving the ground.

Post Pre-season Session

Participants returned to the Sports Medicine Research Laboratory on the day following the final preseason practice. Ultrasound measurements of the vastus lateralis and femoral cartilage were obtained using the exact same methods and procedures as previously described.

Data Reduction

Ultrasound Analysis of Muscle and Cartilage

Ultrasound images were analyzed using ImageJ 1.48v software (National Institute of Health) by the primary investigator. The primary investigator performed all ultrasound measurements and analyzed all ultrasound images. The primary investigator had excellent intra-rater reliability for CSA ($ICC_{3,k}$= 0.994, SEM= 0.501), good intra-rater reliability for echo intensity ($ICC_{3,k}$ = 0.878, SEM= 1.816), and excellent intra-rater reliability for medial ($ICC_{3,k}$ = 0.991, SEM= 0.004), intercondylar groove ($ICC_{3,k}$ = 0.997, SEM= 0.002), and lateral femoral condyle cartilage thickness ($ICC_{3,k}$ = 0.993, SEM= 0.002).

Images were calibrated by measuring the number of pixels within a known distance of 1 cm, prior to analysis. An outline of the vastus lateralis along the fascia border was traced to capture only the muscle to determine CSA (Figure 3.10).[101 102] Muscle quality was determined from the echo intensity values by using grayscale- imaging software in the standard histogram function of pixels ranging from 0-255 (black= 0, white= 255).[101-103] The same pre-selected region of interest used for the calculation of CSA was used to determine the mean echo intensity value. The average of the 3 images from pre-preseason testing and the average of 3 images from post-preseason testing were used as CSA and echo intensity pre and post results, respectively. To obtain the absolute change in CSA and echo intensity we subtracted the post-preseason averages from the pre-preseason averages. To obtain the percent change in CSA and echo intensity we divided the absolute change by the pre-preseason average and then multiplied by 100.

The distance between the thin hyperechoic line at the synovial space-cartilage interface and the sharp hyperechoic line at the cartilage-bone interface was used to measure femoral cartilage thickness.[104] The midpoint of the image was used to determine femoral groove thickness.[105 106] In order to keep consistency amongst participants, 1.5 cm from the left and right of the femoral groove thickness was used to determine the lateral and medial condyle cartilage thickness (Figure 3.11). The average thickness of each location from all 3 images from pre- and post-preseason testing sessions was used as pre and post thickness measurements, respectively. To obtain the absolute change in femoral condylar cartilage thickness we subtracted the post-preseason average from the pre-preseason average. To obtain the percent change in femoral condylar cartilage thickness we divided the absolute change by the pre-preseason average and then multiplied by 100.

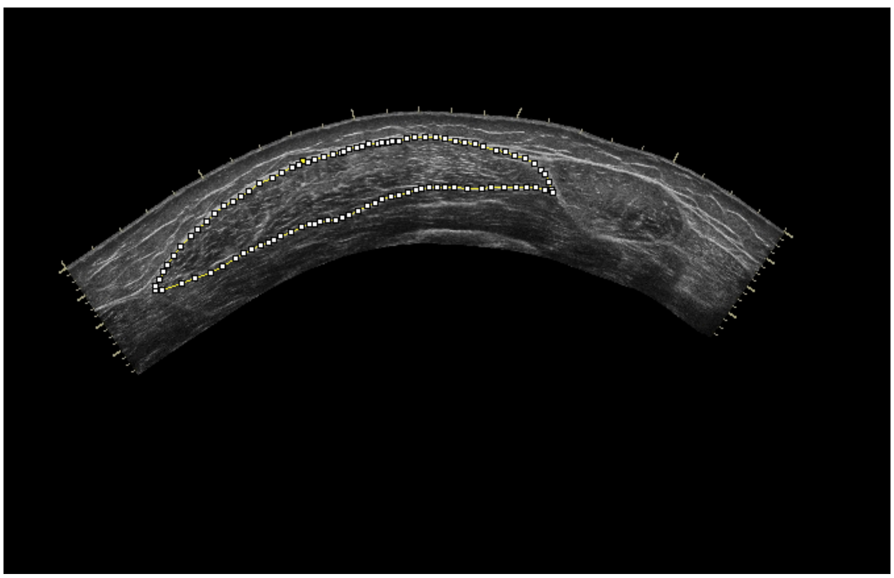

Figure 3.10. CSA of vastus lateralis panoramic ultrasound image.

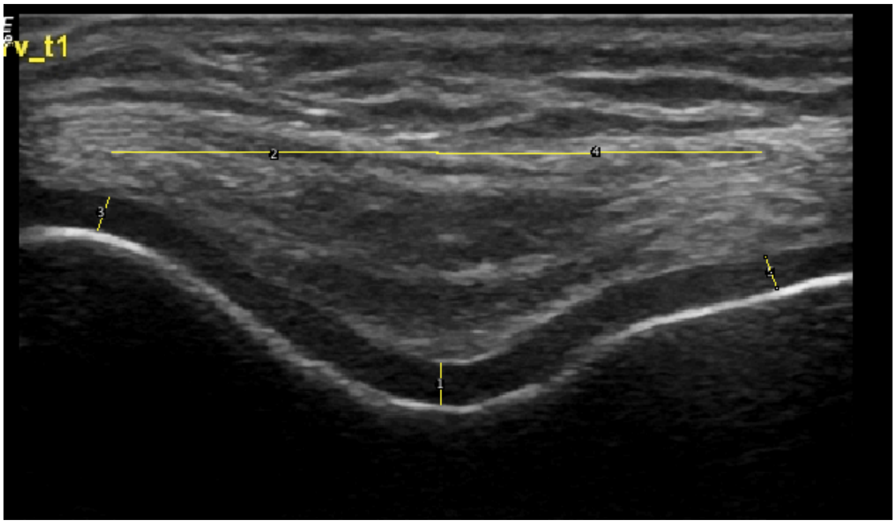

Figure 3.11 Cartilage thickness measurement of femoral condylar cartilage.

Cumulative Internal Training Load

The total session-RPE for each individual was calculated by adding all session-RPE values together.

Jump Frequency

The total jumps for each individual was calculated by adding all jump frequencies from each practice together.

Statistical Analysis

Paired sample t-tests were performed to compare vastus lateralis CSA and echo intensity changes from pre- to post-preseason testing sessions and femoral condyle cartilage thickness changes from pre- to post-preseason testing sessions. A Pearson's product-moment correlation coefficient was computed to determine the association between movement quality and cumulative internal training load, movement quality and vastus lateralis muscle damage (muscle cross sectional area and echo intensity), and movement quality and femoral cartilage damage for all participants. The average LESS score and squat score determined overall movement quality for each participant. Cumulative internal training load was determined using the average session rate of perceived exertion recorded for each participant during the pre-season practice period. Vastus lateralis muscle damage was determined by the change in muscle cross sectional area prior to the pre-season practice period and the day following the final pre-season practice. Vastus lateralis muscle damage was determined by the change in echo intensity prior to the pre-season practice period and the day following the final pre-season practice. Femoral condyle cartilage damage was determined by the change in cartilage thickness prior to the pre-season practice period and the day following the final pre-season practice. Statistical significance was set at $\alpha<0.05$. All data was analyzed using SPSS 23.0 (International Business Machines Corporation, New York, USA) statistical software.

CHAPTER IV

Introduction

Volleyball has one of the highest participation rates worldwide.[45] The knee is one of the most common and severe sites for acute and overuse injuries among volleyball players.[1 2 4 6 38 39] Among collegiate women's volleyball players knee injuries occur most frequently to the meniscus (37%), the collateral ligaments (33%), and anterior cruciate ligament (26%).[2] Patellar tendinopathy is the most common overuse injury in elite volleyball players, with an incidence of 28-40%.[42] Even with appropriate treatment and rehabilitation, these injuries lead to serious consequences, including high treatment costs, decreased academic performance, time lost from sport, increased risk of early osteoarthritis, and increased risk of never returning to previous levels of activity as before injury.[31 35-37] Two factors that influence knee injury risk are aberrant lower extremity biomechanics and high training loads, thus these factors should be studied, so that interventions may be implemented to mitigate their negative effects.[6-8]

Aberrant lower extremity biomechanics are associated with both acute and chronic knee injuries.[10 13 48] Lower extremity biomechanics can be accurately assessed with clinical movement assessments. Common lower extremity movement assessments include squatting and jump-landing assessments where movement compensations are identified by a trained rater.[19-21] The overhead squat assessment is a reliable tool used to qualitatively assess an individual's functional movement patterns and is commonly used by sports medicine professionals.[64] The overhead squat assessment is capable of identifying individuals with medial knee displacement, a clinical representation of dynamic knee valgus.[21] The single leg squat assessment has yet to be validated as a screening tool for identifying knee injury risk factors, however it is commonly used to identify aberrant lower extremity biomechanics.[61 65] It is frequently used in the clinical setting due to the simplicity of observing knee alignment during a weight-bearing task.[59] The Landing Error Scoring System (LESS) is a reliable and valid assessment of a jump-landing task that identifies movement patterns associated with increase risk of ACL injury and lower extremity stress fractures.[22 107]

High internal training loads, high training intensity, and high training duration increase acute and chronic injury risk.[15] The session rate of perceived exertion (session-RPE) method is a valid marker of training load and is associated with future risk of injury.[23 82] Specifically, volleyball players with high training and high match exposures have an increased risk for developing jumper's knee.[16] Due to the notable influence of both movement patterns and training load on injury risk, it is important to understand how these factors may interact with each other and influence potential injury risks. This is especially true during preseason training periods.[15]

Internal training load may be influenced by an individual's biomechanics. Specifically, individuals with aberrant biomechanical profiles may be less mechanically efficient, thus experiencing greater relative training loads and placing greater stress on their soft tissue structures.[108] High internal training loads can result in musculoskeletal fatigue that leads to decreased muscle strength, reduced reaction time, impaired joint position sense, altered motor control and biomechanics, and deficits in dynamic stability.[27 28 86-89] These acute changes from fatigue can increase injury risk. [28 86-89] Musculoskeletal fatigue is also correlated to muscle and tendon damage through measurements of cross sectional area (CSA) and echo intensity following acute exercise bouts.[29] Panoramic ultrasound is a reliable and valid tool for detecting training induced changes in muscle CSA and echo intensity. [91 98] Increases in echo intensity are highly correlated to fatty infiltration and fibrous tissue within skeletal muscle. [95-97] Muscle enlargement as measured by increases in CSA and intramuscular fibrous tissue as measured by increases in echo intensity is indicative of muscle damage.[95-97]

Aberrant biomechanics and exercise that results in repetitive joint loading are risk factors for developing knee osteoarthritis.[24 68 69] Volleyball is considered to have high intensity of joint impact and torsional loading.[71] These forces may result in acute cartilage thickness changes that can be identified with high-resolution ultrasound images of the distal femoral cartilage.[26 72 73] The purpose of this study is to determine the relationship between biomechanical patterns, fatigue, cartilage thickness changes, and muscle response during the preseason practice period of division one female volleyball athletes. Determining the relationship between biomechanical patterns, internal training load, cartilage thickness changes, and muscle response will allow clinicians to better identify athletes at risk for future injury. Identifying these at-risk athletes will improve injury intervention strategy implementation.

Methods

Participants

Seventeen NCAA Division I female volleyball players (mean ± SD: age= 19.7±1.2 years; weight= 77.1±8.7 kg; height= 170.4±10.1 cm) volunteered for this study. (Table 4.1) Prior to testing, all participants read and signed an informed consent document and completed a health history questionnaire. The institutional review board of the University of North Carolina at Chapel Hill approved this study.

Table 4.1 Participant Demographics

Demographics	Mean±SD
Age	19.7±1.2
Height (cm)	170.4±10.1
Weight (kg)	77.1±8.7
BMI	26.6±3.1
Years of Experience	7.8±2.2

Research Design

This study employed a longitudinal cohort design. Participants visited the laboratory on 2 separate occasions separated by 11 days of preseason volleyball training. The pre-test session occurred the day prior to the start of pre-season training. During the pre-test session, participants completed ultrasound assessments of the vastus lateralis and femoral cartilage as well as clinical assessments of lower extremity movement quality. Training load was collected immediately following each of the 15 training sessions over the 11-day preseason period. The post-test session was completed within 24 hours following the pre-season training period; only the ultrasound assessments were completed during the post-test session.

Vastus Lateralis Ultrasound Measurement

Vastus lateralis muscle CSA was assessed from panoramic ultrasound scans with a portable B-Mode ultrasound device (LOGIQ e 5, General Electric Company, Wisconsin, USA). Images were taken of the dominant jumping limb[109] (the leg the participants identified that they would use to jump for maximum height) at 50% of the femur length. This location was identified by palpation of the greater trochanter and the lateral epicondyle of the femur by the primary investigator who then used a tape measure to find the midpoint and draw a line perpendicular to the length of the femur. Participants laid supine with the test leg fully extended and relaxed with a foam pad strapped to the midpoint of the thigh to standardize the measurement (Figure 3.2). The skin was prepared using a water-soluble transmission gel to reduce possible near field artifacts and enhance acoustic coupling.[98] The ultrasound probe was held perpendicular to the muscle and swept across the skin from the lateral vastus lateralis border to the medial fascia separation.[101 102] The ultrasound settings were kept consistent for all participants (Frequency: 12 Hz, Gain: 68, Depth: 4.0 cm).

Femoral Articular Cartilage Ultrasound Measurement

Nine still framed images of the transverse femoral condyle cartilage (3- lateral; 3-femoral groove; 3-medial) at pre- and post-testing sessions were obtained for each participant. Participants were seated with their dominant jumping limb[109] in 130° of knee flexion. A horizontal line was drawn at the most superior aspect of the patella, as identified by palpation. The ultrasound probe was placed at this marked point, perpendicular to the knee articular surface (Figure 3.3).[105] The intercondylar notch was aligned to the middle bold line of the ultrasound screen grid. The height (1 cm screen grid reference point) of the bony interface of the middle and lateral femoral condyles were recorded to ensure the same pre-testing and post-testing anatomical alignment. The ultrasound settings were kept consistent for each scan (Frequency: 12 Hz, Gain: 68, Depth: 4.0 cm).

Movement Quality Assessment

Jump-Landing Assessment

Participants performed a jump-landing task from a 30 cm high box placed at a distance ½ of the participants' body height away from the target area. Participants were instructed to jump down and forward onto the target and immediately perform a second vertical jump for maximum vertical height (Figure 3.4, 3.5).[19] Participants were not provided feedback or coaching on their landing techniques unless they were performing the assessment incorrectly (e.g., feet leaving the box at different times, landing outside the target area). Participants were given as many practice trials as needed to perform the assessment correctly. Three trials were recorded in frontal and sagittal views using standard 2-dimensional video cameras (Sony Handycam DCR-SX44, Sony Electronics, San Diego, California). The videos were scored at a later date by the primary investigator, using the LESS grading rubric (Table 3.1).[110] The total LESS score for each individual was calculated by determining the number of errors (22 total) presented in each jump-landing assessment.[66] In order to be considered an error the participant had to demonstrate the compensation on at least 2 of the 3 jumps.

Overhead Squat Assessment

Participants stood with their feet shoulder-width apart, toes facing forward with their arms extended vertically overhead. Participants were instructed to descend into a squat to maximal comfortable flexion and then return to the initial upright position (Figure 3.6, 3.7). Participants completed the squat in a slow and controlled manner. Participants were not provided feedback or coaching on their squatting techniques unless they were performing the assessment incorrectly (e.g., beginning squats with feet rotated in/out). Participants completed five practice trials. Five consecutive trials were recorded in the frontal and sagittal views using standard 2-dimensional video cameras (Sony Handycam, DCR-SX44, Sony Electronics, San Diego, California). The videos were scored at a later date by the primary investigator and a overhead squat score was generated for each participant using the grading rubric (Table 3.2). The total overhead squat score for each individual was calculated by determining the number of errors (10 total) presented in each squatting assessment. In order to be considered an error the participant had to demonstrate the compensation on at least 3 of the 5 squats.

Single Leg Squat Assessment

Participants stood with their feet shoulder-width apart and raised one leg to 90° of hip and knee flexion. (Figure 3.8, 3.9) The participant's hands were placed on her hips. Participants were instructed to complete the squat in a slow and controlled manner. The participant descended into a squat to maximal comfort and then returned to the initial upright position. Participants were not provided feedback or coaching on their squatting techniques unless they were performing the assessment incorrectly (e.g., beginning squats with the foot rotated in/out). Participants completed 5 practice trials. 5 consecutive trials were recorded in the frontal and sagittal views using standard 2-dimensional video cameras (Sony Handycam, DCR-SX44, Sony Electronics, San Diego, California). The videos were scored at a later date by the primary investigator and a single leg squat score was generated for each participant using the grading rubric (Table 3.3). The total single leg squat score for each individual was calculated by determining the number of errors (9 total) presented in each squatting assessment. In order to be considered an error the participant had to demonstrate the compensation on at least 3 of the 5 squats.

Session Rate of Perceived Exertion

Within 30 minutes of the conclusion of each preseason practice session, participants verbalized their RPE were shown the RPE scale of 1-10 and verbalized their RPE to the primary investigator who recorded this number along with the duration of training (minutes). These values were multiplied together to provide an internal training load value (session-RPE) for each participant. [23 82] The category ratio rating of perceived exertion scale is as follows: 0- rest, 1- very, very easy, 2- easy, 3- moderate, 4- somewhat hard, 5- hard, 7- very hard, 10- maximal. 6, 8, and 9 are considered intermediary values between 5-10 with no RPE definition.[23]

Jump Volume

Practice sessions were filmed and watched at a later date by the primary investigator, who counted the number of jumps each participant completed. A jump was defined as any volleyball maneuver that resulted in both feet leaving the ground.

Data Reduction

Ultrasound Analysis of Muscle and Cartilage

Ultrasound images were analyzed using ImageJ 1.48v software (National Institute of Health) by the primary investigator. The primary investigator performed all ultrasound measurements and analyzed all ultrasound images. The primary investigator had excellent intra-rater reliability for CSA (ICC= 0.994, SEM= 0.501), good intra-rater reliability for echo intensity (ICC= 0.878, SEM= 1.816), and excellent intra-rater reliability for medial (ICC= 0.991, SEM= 0.004), intercondylar groove (ICC= 0.997, SEM= 0.002), and lateral femoral condyle cartilage thickness (ICC= 0.993, SEM= 0.002).

Images were calibrated by measuring the number of pixels within a known distance of 1 cm, prior to analysis. An outline of the vastus lateralis along the fascia border was traced to capture only the muscle to determine CSA (Figure 4.7).[101 102] Muscle quality was determined from the echo intensity values by using grayscale- imaging software in the standard histogram function of pixels ranging from 0-255 (black= 0, white= 255).[101-103] The same pre-selected region of interest used for the calculation of CSA was used to determine the mean echo intensity value. The average of the 3 images from pre-preseason testing and the average of 3 images from post-preseason testing were used as CSA and echo intensity pre and post results, respectively. To obtain the absolute change in CSA and echo intensity we subtracted the post-preseason averages from the pre-preseason averages. To obtain the percent change in CSA and echo intensity we divided the absolute change by the pre-preseason average and then multiplied by 100.

The distance between the thin hyperechoic line at the synovial space-cartilage interface and the sharp hyperechoic line at the cartilage-bone interface was used to measure femoral cartilage thickness.[104] The midpoint of the image was used to determine femoral groove thickness.[105 106] In order to keep consistency amongst participants, 1.5 cm from the left and right of the femoral groove thickness was used to determine the lateral and medial condyle cartilage thickness (Figure 4.8). The average thickness of each location from all 3 images from pre- and post-preseason testing sessions was used as pre and post thickness measurements, respectively. To obtain the absolute change in femoral condylar cartilage thickness we subtracted the post-preseason average from the pre-preseason average. To obtain the percent change in femoral condylar cartilage thickness we divided the absolute change by the pre-preseason average and then multiplied by 100.

Cumulative Internal Training Load

The total session-RPE for the entire preseason period for each individual was calculated by adding all session-RPE values together.

Jump Frequency

The total jumps for each individual was calculated by adding all jump counts from each preseason practice together.

Statistical Analysis

Paired sample t-tests compared vastus lateralis CSA and echo intensity (absolute and percent change) from pre-testing to post-testing sessions and femoral condyle cartilage thickness (absolute and percent changes) from pre-testing to post-testing sessions. Pearson's product-moment correlations determined the association between movement quality (jump landing, overhead squat, and single leg squat assessments) and cumulative internal training load (session-RPE), movement quality and vastus lateralis muscle change, and movement quality and femoral condyle cartilage thickness change for all participants (Criteria for strength interpretation: strong= 1- 0.80 moderate to strong= 0.79- 0.66 moderate= 0.65-0.45, weak to moderate= 0.44-0.21, weak= 0.20- 0)[111] Statistical significance was set at $\alpha<0.05$. All data were analyzed using SPSS 23 (International Business Machines Corporation, New York, USA) statistical software

Results

Pre-to-Post Preseason Period Muscle and Femoral Condylar Cartilage Comparisons

Muscle Characteristics

Vastus lateralis cross sectional area significantly increased from the pre- to post-preseason testing sessions (absolute change= 1.41±1.33cm^2; t_{16}= -4.37, p<0.001; percent change= 6.48±7.42%). No change was observed in vastus lateralis echo intensity (absolute change= 0.24±3.60; t_{16}= -0.27, p= 0.79; percent change= 0.64±5.21%). Descriptive statistics and p-values are presented in Table 4.2.

Femoral Condyle Cartilage Characteristics

Medial femoral condyle cartilage thickness (absolute change= -0.031±0.033cm; t_{16}= 3.832, p< 0.001; percent change= -13.456±10.499%) and lateral femoral condyle cartilage thickness (absolute change= -0.023±0.016cm; t_{16}= 5.844, p <0.001; percent change= -11.716±7.705%) significantly decreased from the pre- and post-preseason testing sessions. Femoral intercondylar groove cartilage thickness did not significantly change from the pre- and post-preseason testing sessions (absolute change= 0.001±0.026cm; t_{16}= 0.057, p= 0.955; percent change= 0.323±10.542%). Descriptive statistics and P-values are presented for all femoral condyle cartilage characteristics data in Table 4.2.

Table 4.2. Movement Quality Assessment Means

Movement Assessment	Mean ± SD
LESS	6.5±2.5
Overhead Squat	4.9±1.5
Single Leg Squat	5.6±2.1

Relationship Between Movement Quality, Muscle Characteristics, Femoral Condyle Cartilage Thickness, and Internal Training Load

Movement Quality and Muscle Characteristics Relationship

A strong negative correlation (r (17)= -0.672, p= 0.003) was observed between the cross sectional area absolute change and the LESS scores (Figure 4.1). A moderate negative correlation (r (17)= -0.563, p= 0.019) was observed between the cross sectional area percent change and the LESS scores (Figure 4.2). No significant relationships were observed between cross sectional area absolute change (r (17)= -0.132, p= 0.614) or percent change (r (17)= 0.015, p= 0.995) and the overhead squat scores, the absolute change (r (17)= -0.129, p= 0.621) or percent change (r (17)= -0.223, p= 0.389) in cross sectional area and the single leg squat scores, the absolute change (r (17)= 0.400, p= 0.111) or percent change (r (17)= 0.419, p= 0.191) in echo intensity and the LESS scores, the absolute change (r (17)= 0.083, p= 0.751) or percent change (r (17)= 0.077, p= 0.769) in echo intensity and overhead squat scores, or the absolute change (r (17)= 0.281, p= 0.275) or percent change (r (17)= 0.221, p= 0.394) in echo intensity and single leg squat scores. R-values and P-values are presented for all movement quality and muscle characteristic relationships in Table 4.3 and 4.4.

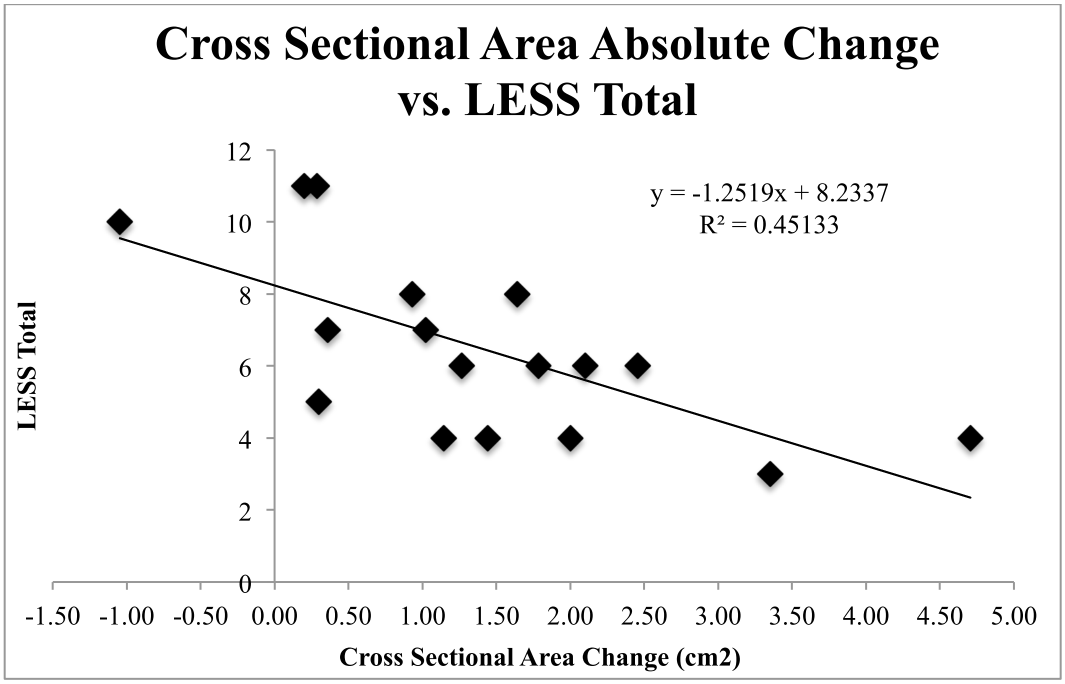

Figure 4.1. Cross Sectional Area Change (cm^2) vs. LESS Total

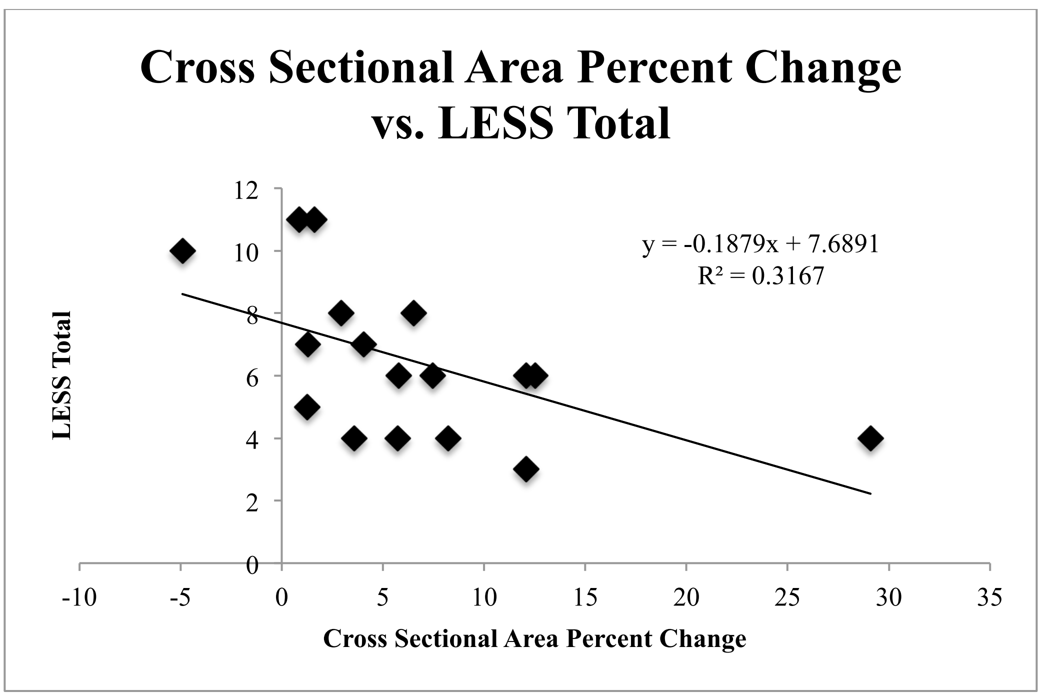

Figure 4.2 Cross Sectional Area Percent Change vs. LESS Total

Movement Quality and Femoral Condyle Cartilage Thickness Relationship

A moderate negative correlation (r (17)= -0.544, p= 0.024) exists between the absolute medial cartilage thickness change and the overhead squat scores (Figure 4.3). Though not significant, a moderate negative correlation r (17)= -0.438, p= 0.079) exists between the medial cartilage thickness percent change and the overhead squat scores (Figure 4.4). No significant relationships were observed between medial cartilage thickness absolute change (r (17)= -0.139, p= 0.596) or percent change (r (17)= -0.191, p= 0.463) and the LESS scores, medial cartilage thickness absolute change (r (17)= 0.040, p= 0.878) or percent change (r (17)= 0.161, p= 0.536) and the single leg squat scores, the lateral cartilage thickness absolute change (r (17)= 0.319, p= 0.212) or percent change (r (17)= 0.254, p= 0.325) and the LESS scores, the lateral cartilage thickness absolute change (r (17)= -0.137, p= 0.600) or percent change (r (17)= -0.122, p= 0.642) and the overhead squat scores;, the lateral cartilage thickness absolute change (r (17)= -0.161, p= 0.537) or percent change (r (17)= -0.050, p= 0.848) and single leg squat scores, the femoral intercondylar groove cartilage thickness absolute change (r (17)= 0.388, p= 0.124) or percent change (r (17)= -0..385, p= 0.127) and the LESS scores, the femoral intercondylar groove cartilage thickness absolute change (r (17)= 0.158, p= 0.544) or percent change (r (17)= 0.124, p= 0.637) and overhead squat scores, or the femoral intercondylar groove cartilage thickness absolute change (r (17)= -0.275, p= 0.286) or percent change (r (17)= -0.331, p= 0.194) and single leg squat scores. R-values and P-values are presented for all movement quality and femoral condyle cartilage thickness relationships in Table 4.3 and 4.4.

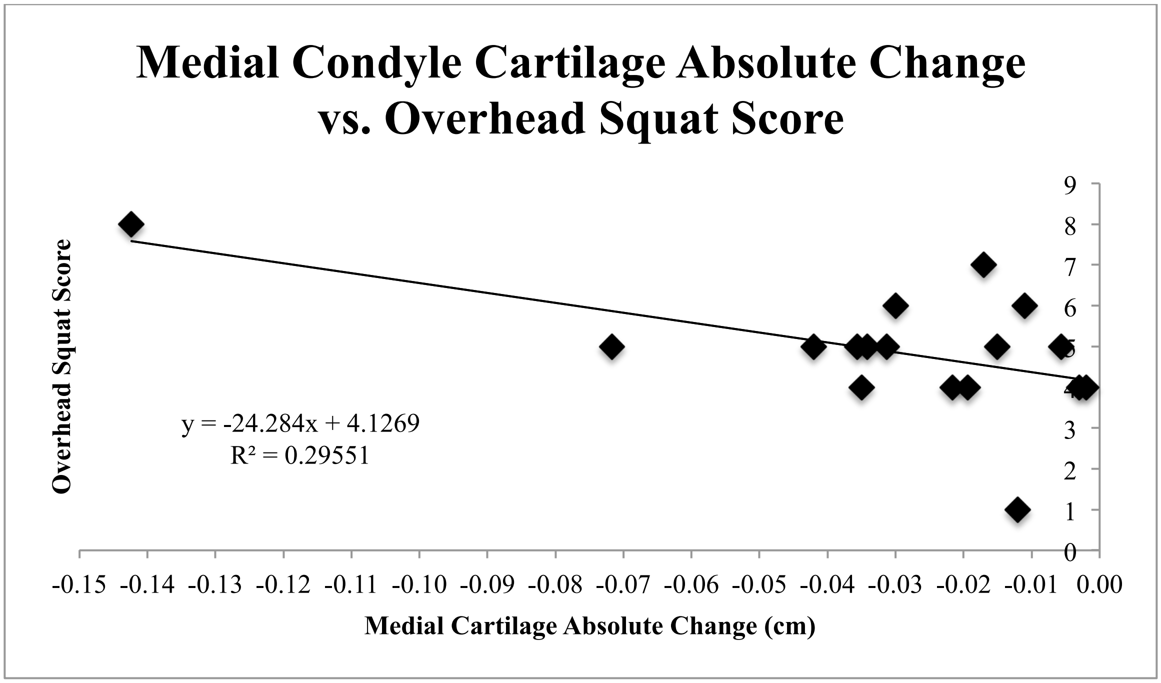

Figure 4.3. Medial Cartilage Thickness Absolute Change (cm) vs. Overhead Squat Score

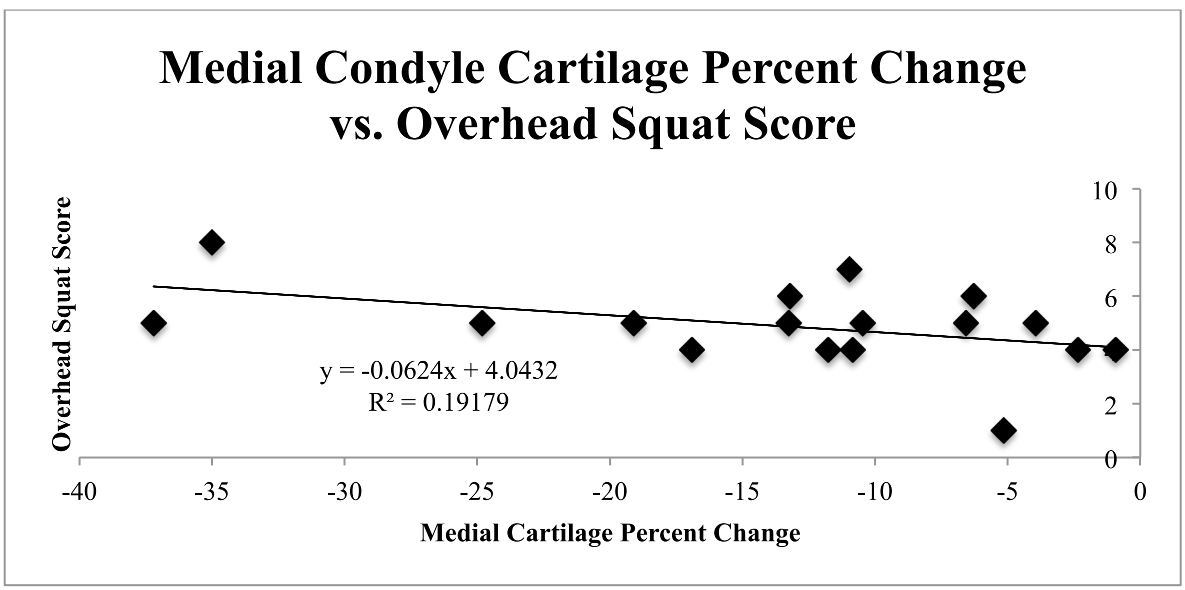

Figure 4.4. Medial Cartilage Thickness Percent Change vs. Overhead Squat Score

Table 4.3 Loading Variable Means

Loading Variable	Mean ± SD
Jump Total	1016.1±511.8
Session-RPE Total	8309.4±1005.9

Movement Quality and Internal Training Load Relationship

Session-RPE was not significantly correlated to the LESS (r (17)= -0.223, p= 0.389) (Figure 4.3), overhead squat scores (r (17)= -0.066, p= 0.802), or single leg squat scores (r (17)= -0.002, p= 0.993) (Figure 4.5, 4.6, 4.7). Session-RPE was strongly positively correlated with jump total (r (17)= 0.716, p< 0.001) (Figure 4.8).

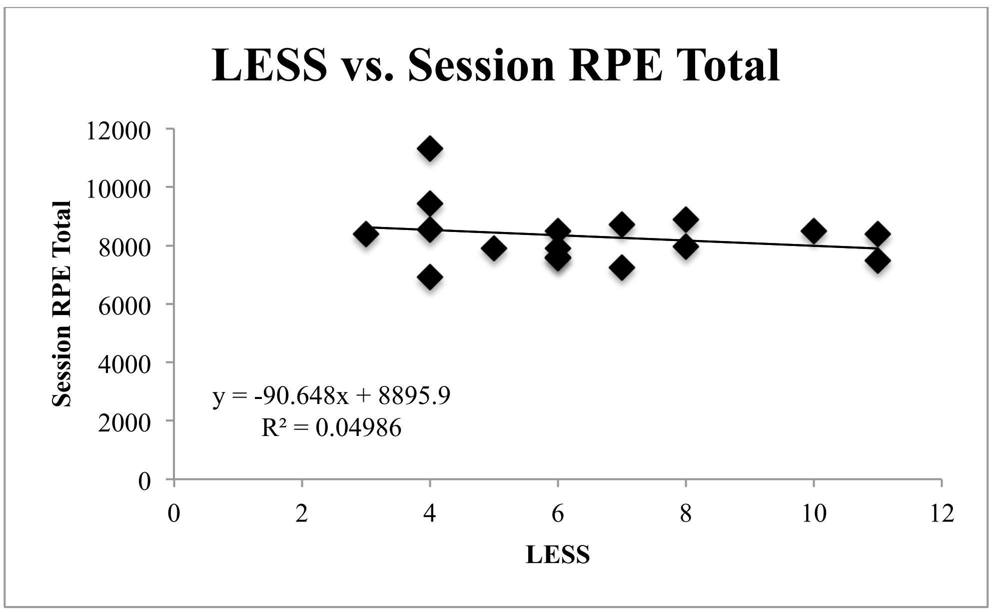

Figure 4.5. LESS score vs. Session RPE Total

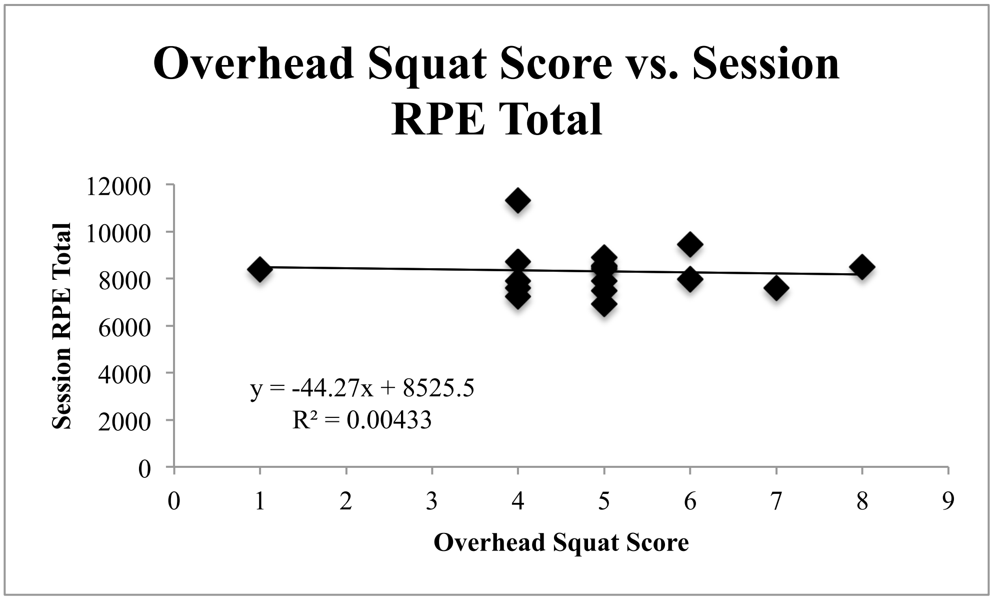

Figure 4.6. Overhead Squat Score vs. Session RPE Total

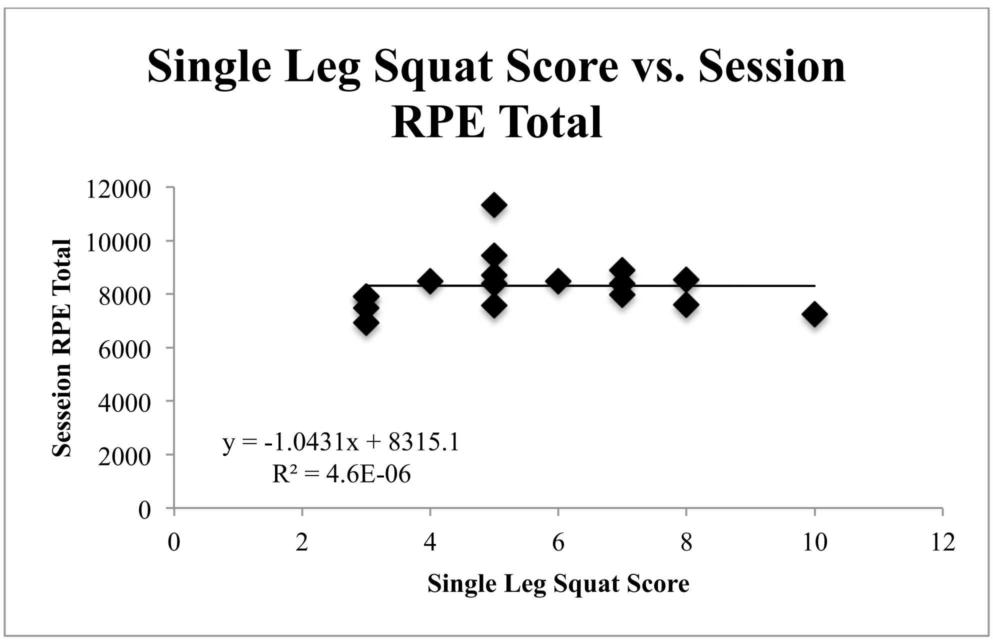

Figure 4.7. Single Leg Squat Score vs. Session RPE Total

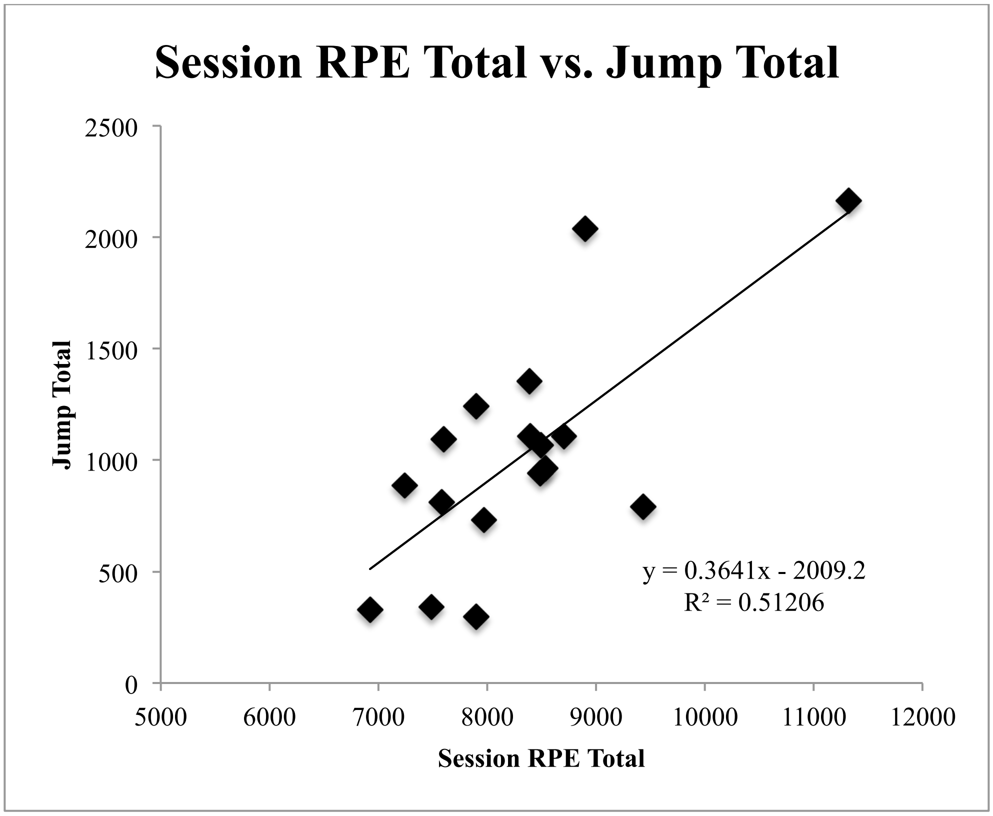

Figure 4.8. Session RPE Total vs. Jump Total

Table 4.4. Pre to Post-Preseason Ultrasound Measurements, presented as means, standard deviations, and percent change.

	PRE			POST			PRE TO POST CHANGE					
	Mean	SD	95% CI	Mean	SD	95% CI	Absolute Change	SD	95% CI	Percent Change	SD	P value
Cross Sectional Area (cm^2)*	23.84	4.96	(21.29, 26.39)	25.25	4.92	(22.72, 27.78)	1.41	1.33	(-2.09, -0.72)	6.48	7.42	0.001
Echo Intensity	74.47	8.19	(70.26, 78.68)	74.70	6.78	(71.22, 78.19)	0.24	3.60	(-2.09, 1.61)	0.64	5.21	0.79
Medial Cartilage Thickness (cm)*	0.211	0.066	(0.177, 0.245)	0.180	0.047	(0.156, 0.204)	-0.031	0.033	(0.014, 0.048)	-13.456	10.499	0.001
Femoral Groove Cartilage Thickness (cm)	0.238	0.045	(0.215, 0.261)	0.238	0.049	(0.212, 0.263)	0.000	0.026	(-0.013, 0.013)	0.323	10.542	0.955
Lateral Cartilage Thickness (cm)*	0.198	0.026	(0.185, 0.212)	0.175	0.026	(0.162, 0.189)	-0.023	0.016	(0.015, 0.032)	-11.716	7.705	0.001

* Significantly different between pre and post measurements at p=0.05.

Table 4.5. Pre to Post-Preseason Absolute Change in CSA and Cartilage Thickness vs. Movement quality and training load, presented as correlation coefficient and significance.

	Cross Sectional Area		Echo Intensity		Medial Cartilage Thickness		Femoral Groove Cartilage Thickness		Lateral Cartilage Thickness	
	R value	P value	R value	P value	R value	P value	R value	P value	R value	P value
LESS	-0.672*	0.003	0.400	0.111	-0.139	0.596	0.388	0.124	0.319	0.212
OHS	-0.132	0.614	0.083	0.751	-0.544*	0.024	0.158	0.544	-0.137	0.600
SLS	-0.203	0.434	0.043	0.871	0.040	0.878	-0.275	0.286	-0.161	0.537
Jump Total	-0.040	0.878	0.145	0.578	0.073	0.782	-0.146	0.576	-0.194	0.456
Session RPE Total	-0.203	0.434	0.043	0.871	0.429	0.086	-0.275	0.286	-0.161	0.537

* Significantly correlated at p= 0.05

Table 4.6. Pre to Post-Preseason Percent Change in CSA and Cartilage Thickness vs. Movement quality and training load, presented as correlation coefficient and significance.

	Cross Sectional Area		Echo Intensity		Medial Cartilage Thickness		Femoral Groove Cartilage Thickness		Lateral Cartilage Thickness	
	R value	P value	R value	P value	R value	P value	R value	P value	R value	P value
LESS	-0.563*	0.019	0.419	-0.191	-0.191	0.463	0.385	0.127	0.254	0.325
OHS	0.015	0.955	0.077	0.769	-0.438	0.079	0.124	0.637	-0.122	0.642
SLS	-0.297	0.247	0.018	0.946	0.161	0.536	-0.331	0.194	-0.050	0.848
Jump Total	-0.180	0.488	0.113	0.666	0.239	0.355	-0.214	0.410	-0.159	0.542
Session RPE Total	-0.297	0.247	0.018	0.946	0.161	0.536	-0.331	0.194	-0.050	0.848

* Significantly correlated at p= 0.05

Discussion

The findings of this study suggest that muscle CSA and femoral condylar cartilage thickness change in response to pre-season volleyball training and this change is significantly related to lower extremity biomechanical patterns. Individuals who demonstrate poorer movement quality as measured by the LESS and overhead squat demonstrate smaller increases in vastus lateralis hypertrophy and greater decreases in medial femoral condylar cartilage thickness. There was no relationship between the single leg squat and muscle CSA and femoral condylar cartilage thickness. We believe finding no relationship between single leg squat and muscle CSA and femoral condylar cartilage thickness is directly related to the functionality of the single leg squat. The single leg squat is not a maneuver that is commonly performed in volleyball, while double-leg squatting and jumping are performed frequently and thus could be reason for the relationships found in these particular movement quality assessments and musculoskeletal response.

Quadriceps hypertrophy occurs early in resistance training programs.[112 113] Defreitas et al[112] found a gradual weekly increase in quadriceps femoris CSA over an 8 week resistance training period, with the highest increase in CSA and muscle quality noted in week 3 after only 9 resistance training sessions. Similar findings were observed for the hypertrophy of the vastus lateralis and rectus femoris after 20 days of resistance training along with a significant increase in maximal voluntary contraction of the quadriceps.[113] We observed similar increases in vastus lateralis hypertrophy (i.e. increases in vastus lateralis CSA; (mean difference= 1.41 cm^2, SD= 1.33cm^2)) following 11 days of volleyball training.

Changes in vastus lateralis CSA were negatively correlated with changes in echo intensity (r= -0.735). This indicates that the muscle underwent hypertrophy, and that the increase in CSA was not the result of edema. Echo intensity is a direct marker of interstitial fluid, adipose tissue, and intramuscular fibrous tissue located within the muscle belly and is an established measurement to quantify edema-induced muscle swelling.[29 95-98] Damas et al[114] proposed that early increases in muscle cross sectional area during resistance training are not caused by increases in myofibers due to the expansion of myofibrillar proteins (i.e. hypertrophy), but instead are directly related to edema-induced muscle swelling, measured by echo intensity. This suggests that there is a positive link between cross sectional area and echo intensity. Surprisingly, in our study we found that vastus lateralis CSA is associated with a decrease in echo intensity, which signifies that hypertrophy is occurring rather than muscle damage due to edema or fibrous/fatty infiltration.[114] Our findings are similar to Jajtner et al[115] who observed increased vastus lateralis CSA and decrease in echo intensity from preseason to postseason during a collegiate soccer season.

Acute muscle hypertrophy may be population specific. Muscle hypertrophy appears to occur in well trained athletes following acute periods of intense training, as observed in our study, but this does not appear to be the case in studies that looked at untrained individuals. Radaelli et al[29] found increases in echo intensity and muscle thickness in the elbow flexors following a resistance training protocol. They used untrained females in their study, while our population included elite volleyball players with an average of 7.8 years of experience.[29] Damas et al[114] conclude that edema and muscle swelling occurs within 1-2 weeks of resistance training as opposed to hypertrophy, but their study included 10 males with no previous resistance training experience in the past 6 months. The discrepancy could also be linked to the time course the measurements were taken. Previous research suggests that the highest increase in echo intensity is generally observed 48-96 hours after exercise.[29 97 116] Our study completed vastus lateralis ultrasound measurements within 12 hours post pre-season training. Furthermore, our study and previous work employed vastly different training regimens. To our knowledge we are the only study to examine vastus lateralis response to an 11-day pre-season training period for elite female athletes. Previous research focuses on smaller bouts of resistance training on untrained individuals.[29 96 97 114]

A significant moderate negative correlation was found between vastus lateralis CSA and the LESS scores (r= -0.672). We propose that individuals with poor movement quality do not use their quadriceps as efficiently as individuals with good movement quality and thus resulting in less hypertrophy (i.e. smaller increases in CSA) in individuals with poor movement quality. Less efficient and balanced use of the quadriceps during dynamic tasks may place increased stress on the passive ligament structures of the knee, which could ultimately result in injury.[117 118]

Furthermore less quadriceps strength is linked to decreased stability of the patella, which could lead to patella maltracking, and subsequent injury.[119 120] Individuals with anterior knee pain demonstrated less isokinetic quadriceps muscle strength compared to healthy individuals.[121] Also, individuals with patellofemoral pain syndrome have lower quadriceps muscle activity during concentric and eccentric knee extension actions compared to healthy individuals.[122] Quadriceps CSA, peak torque, and muscle volume were all smaller in women with patellofemoral pain syndrome compared to the unaffected leg.[123] These studies indicate knee injuries potentially result from inefficient use of the quadriceps muscles due to aberrant movement including lower vertical ground reaction force, knee extension moment, hip external rotation moment, and greater navicular drop.[120] Therefore, it is important to correct the aberrant movement patterns, improve neuromuscular control, and reduce injury risk.

Lateral and medial femoral condylar cartilage thickness decreased across all participants following an 11-day training cycle. Our findings are similar to other studies that have observed decreases in femoral condylar cartilage thickness after short-term bouts of exercise.[24 74 75] Previous studies, observed these changes immediately following single bouts of exercise lasting less than 60 minutes[24 74] We observed these changes approximately 18-hours following multiple bouts of high intensity exercise. This is interesting because we are now aware that cartilage changes can occur and continue after longer periods of exercise. Future studies should focus on cartilage changes following an entire season or longer and determine the duration of cartilage deformation following exercise sessions.

Individuals who demonstrate poorer movement quality as measured by the overhead squat are associated with a greater decrease in medial femoral condylar cartilage thickness (r= -0.544). We are aware of the outlier present in the current study, but feel this value is acceptable as it aligns with pervious studies that found similar changes in femoral condyle cartilage thickness following acute bouts of exercise.[24] Furthermore, the two individuals who exhibited the largest absolute change in cartilage thickness are middle hitters. This finding signifies the need to continue studying the volleyball population to determine the role of player position on musculoskeletal response. While previous studies suggest that frequent squatting predisposes an individual to the development of knee osteoarthritis,[124] our study is the first to look at aberrant squatting movement and how it relates to cartilage thickness changes. The relationship between poor movement quality and greater medial femoral condylar cartilage thickness decrease across the preseason period suggests that significant compressive loading on the medial cartilage is occurring during training due to aberrant movement patterns. In our study nearly 60% of the participants demonstrated knee varus when completing the overhead squat. Varus alignment of the knee is believed to increase the medial tibiofemoral compartment loading.[125 126] This abnormal loading of the knee articular cartilage is directly related to an increase risk of knee joint osteoarthritis development.[69 70 127] Previous studies have found varus alignment during gait analysis in individuals with medial knee joint osteoarthritis, but to our knowledge we are the first study to find an association between dynamic knee varus during an observational squatting assessment and decreases in medial condylar cartilage thickness.

It is important to correct aberrant movement patterns in order to decrease joint loading and ultimately decrease the risk of osteoarthritis. Biomechanical strategies aim at decreasing high knee adduction moments, which are associated with knee varus alignment.[128] Hip abductor strengthening programs help stabilize the frontal plane motion of the pelvis and trunk and decrease the external knee adduction moment.[129 130] Hip abductor strengthening programs and proper jumping and landing technique training result in decreases in peak knee adduction moments.[129 131] Conversely, another study found no decrease in knee adduction moments after an abductor strengthening program, but this program included adductor strengthening as well.[132] Bennel et al[133] found after completing a 12-week exercise program consisting of either neuromuscular training or quadriceps training that individuals with medial knee osteoarthritis had no change in knee adduction moments, but reported a decrease in pain and improvement in physical function.

Biomechanical strategies aimed at reducing joint loading are a novel, yet debated, approach in the field of osteoarthritis research. Traditionally, orthotics, gait training, walking aids, and bracing have been used to help decrease and prevent knee osteoarthritis progression.[134-142] These methods can effectively reduce knee adduction moments, but our study supports the need to continue studying biomechanical treatment options aimed at reducing aberrant movement as they relate to knee osteoarthritis.[134-142]

In addition to providing insight into potential knee injury risk factors, this study may have important implications for efficiently determining and monitoring training load. Training load is commonly monitored through measures of external loading (e.g., jumps, hits, etc.), the total training duration, and the duration of burst and recovery intervals during the session.[143] However, internal load is also important to measure the physiological and psychological stress imposed and is critical in determining the training load and adaptations.[17] This includes, but is not limited to session-RPE, heart rate, and training impulse methods.[17] Previous studies support that session-RPE is a good indicator of internal training load.[17 23] In our study we found a strong positive correlation (r= 0.716) between cumulative internal training load (session-RPE) and total jumps (external load) during the pre-season volleyball training period. To our knowledge we are the first study to find a strong relationship between session-RPE and jump frequency. Our finding supports the use of the session-RPE method to monitor athlete's training adaptations and minimize the risk of fatigue, injury, and illness.[17] Session-RPE could be a method that coaches and clinicians use in the future to decrease time and money spent towards automatic jump detection equipment or film analysis.

Limitations

The correlative nature of our study does not allow for the causative nature of changes in musculoskeletal measurements to be determined. Thus, more research is necessary to determine if poor movement quality is the underlying cause to smaller increases in cross sectional area and greater decreases in femoral condylar cartilage thickness.

Our study included 17 female volleyball players. Future research should compare males and females as well as other athletic populations. We were unable to account for treatment, rehabilitation, and soft tissue work. However, there is limited research on the effects of therapeutic interventions on muscle CSA, echo intensity, cartilage, and RPE values. Though, every participant had access to treatment, rehabilitation, and soft tissue work throughout the preseason, so no participant was denied these interventions. Due to the novel approach and finding of a significant relationship between movement quality and the vastus lateralis CSA this should lead to further research exploring various musculature groups relation to movement quality. We chose the vastus lateralis due to its CSA measurement validity using panoramic ultrasound as well as its role as a knee extensor and synergistic ability with the other quadriceps musculature.[91]

Conclusion

Vastus lateralis CSA increased following an 11-day preseason volleyball training period regardless of movement quality scores. Clinically, a percent change in vastus lateralis CSA of 6.48% can have implications for increased risk of injury. Mangine et al[30] found that a bilateral percentage difference in vastus lateralis CSA of 6.2% is positively correlated to games missed due to lower extremity injury in NBA players. Smaller increases in CSA were noted in those with poor movement quality as measured by the LESS. Medial and lateral femoral condyle cartilage thickness decreased following an 11-day preseason volleyball training period regardless of movement quality scores. While the decrease in femoral condyle cartilage thickness is significant, the clinical significance of this decrease needs to be studied further. Previous research has found an average of a 5% annual decrease of femoral cartilage volume in osteoarthritic patients.[144] Greater decreases were observed in the medial cartilage in those with poor movement quality as measured by the overhead squat. The results of this study indicate a need for further research regarding the musculoskeletal response in relation to movement quality in an attempt to monitor and identify knee injury risk factors.

REFERENCES

1. Reeser JC, Verhagen E, Briner WW, et al. Strategies for the prevention of volleyball related injuries. British journal of sports medicine 2006;40(7):594-600; discussion 599-600.

2. Agel J, Palmieri-Smith RM, Dick R, et al. Descriptive epidemiology of collegiate women's volleyball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. Journal of athletic training 2007;42(2):295-302.

3. K.G. Jadhav PND, R.P. Tuppekar, S.K. Sinku. A Survey of Injuries Prevalence in Varsity Volleyball Players. Journal of Exercise Science and Physiotherapy 2010;6(2):102-05.

4. Aagaard H, Jorgensen U. Injuries in elite volleyball. Scandinavian journal of medicine & science in sports 1996;6(4):228-32.

5. Gisslen K, Gyulai C, Soderman K, et al. High prevalence of jumper's knee and sonographic changes in Swedish elite junior volleyball players compared to matched controls. British journal of sports medicine 2005;39(5):298-301.

6. Clarsen B, Bahr R, Heymans MW, et al. The prevalence and impact of overuse injuries in five Norwegian sports: Application of a new surveillance method. Scandinavian journal of medicine & science in sports 2014.

7. Chappell JD, Creighton RA, Giuliani C, et al. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. The American journal of sports medicine 2007;35(2):235-41.

8. Gabbett TJ. The development and application of an injury prediction model for noncontact, soft-tissue injuries in elite collision sport athletes. Journal of strength and conditioning research / National Strength & Conditioning Association 2010;24(10):2593-603.

9. Fox AS, Bonacci J, McLean SG, et al. What is normal? Female lower limb kinematic profiles during athletic tasks used to examine anterior cruciate ligament injury risk: a systematic review. Sports medicine 2014;44(6):815-32.

10. Malliaras P, Cook JL, Kent P. Reduced ankle dorsiflexion range may increase the risk of patellar tendon injury among volleyball players. Journal of science and medicine in sport / Sports Medicine Australia 2006;9(4):304-9.

11. Soderman K, Alfredson H, Pietila T, et al. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2001;9(5):313-21.

12. Hughes G, Watkins J. Lower limb coordination and stiffness during landing from volleyball block jumps. Research in sports medicine 2008;16(2):138-54.

13. Bisseling RW, Hof AL, Bredeweg SW, et al. Relationship between landing strategy and patellar tendinopathy in volleyball. British journal of sports medicine 2007;41(7):e8.

14. Sinsurin K, Vachalathiti R, Jalayondeja W, et al. Altered Peak Knee Valgus during Jump-Landing among Various Directions in Basketball and Volleyball Athletes. Asian journal of sports medicine 2013;4(3):195-200.

15. Gabbett TJ. Influence of training and match intensity on injuries in rugby league. Journal of sports sciences 2004;22(5):409-17.

16. Visnes H, Bahr R. Training volume and body composition as risk factors for developing jumper's knee among young elite volleyball players. Scandinavian journal of medicine & science in sports 2013;23(5):607-13.

17. Halson SL. Monitoring training load to understand fatigue in athletes. Sports medicine 2014;44 Suppl 2:S139-47.

18. Kiesel K, Plisky PJ, Voight ML. Can Serious Injury in Professional Football be Predicted by a Preseason Functional Movement Screen? North American journal of sports physical therapy : NAJSPT 2007;2(3):147-58.

19. Padua DA, Marshall SW, Boling MC, et al. The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. The American journal of sports medicine 2009;37(10):1996-2002.

20. Stensrud S, Myklebust G, Kristianslund E, et al. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. British journal of sports medicine 2011;45(7):589-95.

21. Bell DR, Padua DA, Clark MA. Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. Archives of physical medicine and rehabilitation 2008;89(7):1323-8.

22. Padua DA, Boling MC, Distefano LJ, et al. Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. Journal of sport rehabilitation 2011;20(2):145-56.

23. Foster C, Florhaug JA, Franklin J, et al. A new approach to monitoring exercise training. Journal of strength and conditioning research / National Strength & Conditioning Association 2001;15(1):109-15.

24. Boocock M, McNair P, Cicuttini F, et al. The short-term effects of running on the deformation of knee articular cartilage and its relationship to biomechanical loads at the knee. Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society 2009;17(7):883-90.

25. Niehoff A, Muller M, Bruggemann L, et al. Deformational behaviour of knee cartilage and changes in serum cartilage oligomeric matrix protein (COMP) after running and drop landing. Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society 2011;19(8):1003-10.

26. Naredo E, Acebes C, Moller I, et al. Ultrasound validity in the measurement of knee cartilage thickness. Annals of the rheumatic diseases 2009;68(8):1322-7.

27. Caroline Finch AW, Brendan O'Brien. An overview of the epidemiological evidence linking injury risk to fatigue in sport. In: Marino FE, ed. Regulation of Fatigue in Exercise. New York: Nova Science Publishers Inc, 2014.

28. Chappell JD, Herman DC, Knight BS, et al. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. The American journal of sports medicine 2005;33(7):1022-9.

29. Radaelli R, Bottaro M, Wilhelm EN, et al. Time course of strength and echo intensity recovery after resistance exercise in women. Journal of strength and conditioning research / National Strength & Conditioning Association 2012;26(9):2577-84.

30. Mangine GT, Hoffman JR, Gonzalez AM, et al. Bilateral Differences in Muscle Architecture Are Associated With Increased Rate of Injury in National Basketball Association Players. Journal of athletic training 2014.

31. de Loes M, Dahlstedt LJ, Thomee R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. Scandinavian journal of medicine & science in sports 2000;10(2):90-7.

32. Fadale PD, Hulstyn MJ. Common athletic knee injuries. Clinics in sports medicine 1997;16(3):479-99.

33. Fulkerson JP. Diagnosis and treatment of patients with patellofemoral pain. The American journal of sports medicine 2002;30(3):447-56.

34. Yeh PC, Starkey C, Lombardo S, et al. Epidemiology of isolated meniscal injury and its effect on performance in athletes from the National Basketball Association. The American journal of sports medicine 2012;40(3):589-94.

35. Ferretti A, Papandrea P, Conteduca F, et al. Knee ligament injuries in volleyball players. The American journal of sports medicine 1992;20(2):203-7.

36. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. British journal of sports medicine 2005;39(3):127-31.

37. Freedman KB, Glasgow MT, Glasgow SG, et al. Anterior cruciate ligament injury and reconstruction among university students. Clinical orthopaedics and related research 1998(356):208-12.

38. Augustsson SR, Augustsson J, Thomee R, et al. Injuries and preventive actions in elite Swedish volleyball. Scandinavian journal of medicine & science in sports 2006;16(6):433-40.

39. E. Zetou PM, A. Lola, G. Tsigganos, G. Godolias. Factors related to the incidence of injuries' appearance to volleyball players. Journal of Back and Musculoskeletal Rehabilitation 2006;19:129-34.

40. Solgard L, Nielsen AB, Moller-Madsen B, et al. Volleyball injuries presenting in casualty: a prospective study. British journal of sports medicine 1995;29(3):200-4.

41. Verhagen EA, Van der Beek AJ, Bouter LM, et al. A one season prospective cohort study of volleyball injuries. British journal of sports medicine 2004;38(4):477-81.

42. Ferretti A, Papandrea P, Conteduca F. Knee injuries in volleyball. Sports medicine 1990;10(2):132-8.

43. Lian OB, Engebretsen L, Bahr R. Prevalence of jumper's knee among elite athletes from different sports: a cross-sectional study. The American journal of sports medicine 2005;33(4):561-7.

44. Murphy DF, Connolly DA, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. British journal of sports medicine 2003;37(1):13-29.

45. Bahr R, Bahr IA. Incidence of acute volleyball injuries: a prospective cohort study of injury mechanisms and risk factors. Scandinavian journal of medicine & science in sports 1997;7(3):166-71.

46. Zahradnik D, Uchytil J, Farana R, et al. Ground Reaction Force and Valgus Knee Loading during Landing after a Block in Female Volleyball Players. Journal of human kinetics 2014;40:67-75.

47. Zahradnik D, Jandacka D, Uchytil J, et al. Lower extremity mechanics during landing after a volleyball block as a risk factor for anterior cruciate ligament injury. Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine 2015;16(1):53-8.

48. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. The American journal of sports medicine 2005;33(4):492-501.

49. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. The Journal of orthopaedic and sports physical therapy 2010;40(2):42-51.

50. Hollman JH, Ginos BE, Kozuchowski J, et al. Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. Journal of sport rehabilitation 2009;18(1):104-17.

51. Dill KE, Begalle RL, Frank BS, et al. Altered knee and ankle kinematics during squatting in those with limited weight-bearing-lunge ankle-dorsiflexion range of motion. Journal of athletic training 2014;49(6):723-32.

52. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. The American journal of sports medicine 2007;35(7):1123-30.

53. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. Medicine and science in sports and exercise 2004;36(6):926-34.

54. Lian O, Refsnes PE, Engebretsen L, et al. Performance characteristics of volleyball players with patellar tendinopathy. The American journal of sports medicine 2003;31(3):408-13.

55. Ciesla E, Dutkiewicz R, Mglosiek M, et al. Sports injuries in Plus League volleyball players. The Journal of sports medicine and physical fitness 2014.

56. Richards DP, Ajemian SV, Wiley JP, et al. Relation between ankle joint dynamics and patellar tendinopathy in elite volleyball players. Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine 2002;12(5):266-72.

57. Richards DP, Ajemian SV, Wiley JP, et al. Knee joint dynamics predict patellar tendinitis in elite volleyball players. The American journal of sports medicine 1996;24(5):676-83.

58. Witvrouw E, Bellemans J, Lysens R, et al. Intrinsic risk factors for the development of patellar tendinitis in an athletic population. A two-year prospective study. The American journal of sports medicine 2001;29(2):190-5.

59. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. Medicine and science in sports and exercise 2006;38(5):945-52.

60. Zeller BL, McCrory JL, Kibler WB, et al. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. The American journal of sports medicine 2003;31(3):449-56.

61. Mauntel TC, Begalle RL, Cram TR, et al. The effects of lower extremity muscle activation and passive range of motion on single leg squat performance. Journal of strength and conditioning research / National Strength & Conditioning Association 2013;27(7):1813-23.

62. Padua DA, Bell DR, Clark MA. Neuromuscular characteristics of individuals displaying excessive medial knee displacement. Journal of athletic training 2012;47(5):525-36.

63. Decker MJ, Torry MR, Wyland DJ, et al. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clinical biomechanics 2003;18(7):662-9.

64. Hirth CJ. Clinical Movement Analysis to Identify Muscle Imbalances and Guide Exercise. Athletic Therapy Today 2007;12(4):10-14.

65. Claiborne TL, Armstrong CW, Gandhi V, et al. Relationship between hip and knee strength and knee valgus during a single leg squat. Journal of applied biomechanics 2006;22(1):41-50.

66. Root H, Trojian T, Martinez J, et al. Landing Technique and Performance in Youth Athletes After a Single Injury-Prevention Program Session. Journal of athletic training 2015;50(11):1149-57.

67. Theiss JL, Gerber JP, Cameron KL, et al. Jump-landing differences between varsity, club, and intramural athletes: the Jump-ACL Study. Journal of strength and conditioning research / National Strength & Conditioning Association 2014;28(4):1164-71.

68. Felson DT, Niu J, Gross KD, et al. Valgus malalignment is a risk factor for lateral knee osteoarthritis incidence and progression: findings from the Multicenter Osteoarthritis Study and the Osteoarthritis Initiative. Arthritis and rheumatism 2013;65(2):355-62.

69. Maly MR. Abnormal and cumulative loading in knee osteoarthritis. Current opinion in rheumatology 2008;20(5):547-52.

70. Spector TD, Harris PA, Hart DJ, et al. Risk of osteoarthritis associated with long-term weight-bearing sports: a radiologic survey of the hips and knees in female ex-athletes and population controls. Arthritis and rheumatism 1996;39(6):988-95.

71. Buckwalter JA, Martin JA. Sports and osteoarthritis. Current opinion in rheumatology 2004;16(5):634-9.

72. Castriota-Scanderbeg A, De Micheli V, Scarale MG, et al. Precision of sonographic measurement of articular cartilage: inter- and intraobserver analysis. Skeletal radiology 1996;25(6):545-9.

73. Mathiesen O, Konradsen L, Torp-Pedersen S, et al. Ultrasonography and articular cartilage defects in the knee: an in vitro evaluation of the accuracy of cartilage thickness and defect size assessment. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2004;12(5):440-3.

74. Kersting UG, Stubendorff JJ, Schmidt MC, et al. Changes in knee cartilage volume and serum COMP concentration after running exercise. Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society 2005;13(10):925-34.

75. A. Niehoff MM, L. Bruggemann, T. Savage, F. Zauke, F. Eckstein, U. Muller-Lung, G.P. Bruggermann. Deformational behaviour of knee cartilage and changes in serum cartilage oligomeric martix protein after running and drop landing Osteoarthritis and Cartilage 2011;19:1003-10.

76. A. Beneka PM, G. Tsigganos, A. Gioftsidou, M. Michalopoulou, E. Germanou, and G. Godolias. A prospective study of injury incidence among elite and local division volleyball players in Greece. Journal of Back and Musculoskeletal Rehabilitation 2007;20:115-21.

77. Anderson L, Triplett-McBride T, Foster C, et al. Impact of training patterns on incidence of illness and injury during a women's collegiate basketball season. Journal of strength and conditioning research / National Strength & Conditioning Association 2003;17(4):734-8.

78. Killen NM, Gabbett TJ, Jenkins DG. Training loads and incidence of injury during the preseason in professional rugby league players. Journal of strength and conditioning research / National Strength & Conditioning Association 2010;24(8):2079-84.

79. Woods C, Hawkins R, Hulse M, et al. The Football Association Medical Research Programme: an audit of injuries in professional football-analysis of preseason injuries. British journal of sports medicine 2002;36(6):436-41; discussion 41.

80. Gabbett TJ, Jenkins DG. Relationship between training load and injury in professional rugby league players. Journal of science and medicine in sport / Sports Medicine Australia 2011;14(3):204-9.

81. Bahr MA, Bahr R. Jump frequency may contribute to risk of jumper's knee: a study of interindividual and sex differences in a total of 11,943 jumps video recorded during training and matches in young elite volleyball players. British journal of sports medicine 2014;48(17):1322-6.

82. Minganti C, Capranica L, Meeusen R, et al. The validity of sessionrating of perceived exertion method for quantifying training load in teamgym. Journal of strength and conditioning research / National Strength & Conditioning Association 2010;24(11):3063-8.

83. Busso T, Benoit H, Bonnefoy R, et al. Effects of training frequency on the dynamics of performance response to a single training bout. Journal of applied physiology 2002;92(2):572-80.

84. Kuni B, Cardenas-Montemayor E, Bangert Y, et al. Impaired jump landing after exercise in recreational and in high-performance athletes. Journal of strength and conditioning research / National Strength & Conditioning Association 2014;28(8):2306-13.

85. A. Gokeler PE, P.U. Dijkstra, W. Welling, D. Padua, E. Otten, A. Benjaminse. Effect of Fatigue on Landing Performance Assessed with the Landing Error Scoring System in Patients After ACL Reconstruction. A Pilot Study. The International Journal of Sports Physical Therapy 2014;9 (3):301-11.

86. Ortiz A, Olson SL, Etnyre B, et al. Fatigue effects on knee joint stability during two jump tasks in women. Journal of strength and conditioning research / National Strength & Conditioning Association 2010;24(4):1019-27.

87. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2008;16(4):400-7.

88. Augustsson J, Thomee R, Linden C, et al. Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. Scandinavian journal of medicine & science in sports 2006;16(2):111-20.

89. Liederbach M, Kremenic IJ, Orishimo KF, et al. Comparison of landing biomechanics between male and female dancers and athletes, part 2: Influence of fatigue and implications for anterior cruciate ligament injury. The American journal of sports medicine 2014;42(5):1089-95.

90. Chleboun GS, Howell JN, Conatser RR, et al. Relationship between muscle swelling and stiffness after eccentric exercise. Medicine and science in sports and exercise 1998;30(4):529-35.

91. Ahtiainen JP, Hoffren M, Hulmi JJ, et al. Panoramic ultrasonography is a valid method to measure changes in skeletal muscle cross-sectional area. European journal of applied physiology 2010;108(2):273-9.

92. Scott JM, Martin DS, Ploutz-Snyder R, et al. Reliability and validity of panoramic ultrasound for muscle quantification. Ultrasound in medicine & biology 2012;38(9):1656-61.

93. Takahashi H, Kuno S, Miyamoto T, et al. Changes in magnetic resonance images in human skeletal muscle after eccentric exercise. European journal of applied physiology and occupational physiology 1994;69(5):408-13.

94. Oyama S, Myers JB, Blackburn JT, et al. Changes in infraspinatus cross-sectional area and shoulder range of motion with repetitive eccentric external rotator contraction. Clinical biomechanics 2011;26(2):130-5.

95. Pillen S, Tak RO, Zwarts MJ, et al. Skeletal muscle ultrasound: correlation between fibrous tissue and echo intensity. Ultrasound in medicine & biology 2009;35(3):443-6.

96. Chen TC, Chen HL, Lin MJ, et al. Muscle damage responses of the elbow flexors to four maximal eccentric exercise bouts performed every 4 weeks. European journal of applied physiology 2009;106(2):267-75.

97. Nosaka K, Clarkson PM. Changes in indicators of inflammation after eccentric exercise of the elbow flexors. Medicine and science in sports and exercise 1996;28(8):953-61.

98. Rosenberg JG, Ryan ED, Sobolewski EJ, et al. Reliability of panoramic ultrasound imaging to simultaneously examine muscle size and quality of the medial gastrocnemius. Muscle & nerve 2014;49(5):736-40.

99. Nosaka K, Newton M, Sacco P. Muscle damage and soreness after endurance exercise of the elbow flexors. Medicine and science in sports and exercise 2002;34(6):920-7.

100. Gogia PP, Braatz JH, Rose SJ, et al. Reliability and validity of goniometric measurements at the knee. Physical therapy 1987;67(2):192-5.

101. Roelofs EJ, Smith-Ryan AE, Melvin MN, et al. Muscle size, quality, and body composition: characteristics of division I cross-country runners. Journal of strength and conditioning research / National Strength & Conditioning Association 2015;29(2):290-6.

102. Melvin MN, Smith-Ryan AE, Wingfield HL, et al. Evaluation of muscle quality reliability and racial differences in body composition of overweight individuals. Ultrasound in medicine & biology 2014;40(9):1973-9.

103. Cadore EL, Izquierdo M, Conceicao M, et al. Echo intensity is associated with skeletal muscle power and cardiovascular performance in elderly men. Experimental gerontology 2012;47(6):473-8.

104. Ozturk GT, Malas FU, Yildizgoren MT, et al. Ultrasonographic Assessment of the Femoral Cartilage Thickness in Patients with Pes Planus: A Multicenter Study by TURK-MUSCULUS. American journal of physical medicine & rehabilitation / Association of Academic Physiatrists 2014.

105. Akkaya S, Akkaya N, Ozcakar L, et al. Ultrasonographic evaluation of the femoral cartilage thickness after unilateral arthroscopic partial meniscectomy. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2013;21(5):1104-10.

106. Ozcakar L, Tunc H, Oken O, et al. Femoral cartilage thickness measurements in healthy individuals: learning, practicing and publishing with TURK-MUSCULUS. J Back Musculoskelet Rehabil 2014;27(2):117-24.

107. Kenneth L. Cameron P, MPH, ATC, Karen Y. Peck, MEd, ATC, Brett D. Owens, MD, Steven J. Svoboda, MD, Lindsay J. DiStefano, PhD, ATC, Stephen W. Marshall, BSc, DAgrSc, PhD, Sarah de la Motte, PhD, MPH, ATC, Anthony I. Beutler, MD, Darin A. Padua, PhD, ATC. Landing Error Scoring System (LESS) Items are Associated with the Incidence Rate of Lower Extremity Stress Fracture. The Orthopaedic Journal of Sports Medicine 2014;2(7).

108. Huang TW, Shorter KA, Adamczyk PG, et al. Mechanical and energetic consequences of reduced ankle plantar-flexion in human walking. The Journal of experimental biology 2015;218(Pt 22):3541-50.

109. Schiltz M, Lehance C, Maquet D, et al. Explosive strength imbalances in professional basketball players. Journal of athletic training 2009;44(1):39-47.

110. Padua DA, DiStefano LJ, Beutler AI, et al. The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury-Prevention Program in Elite-Youth Soccer Athletes. Journal of athletic training 2015;50(6):589-95.

111. Rubin A. *Statistics for evidence-based practice and evaluation*. 3rd ed. Belmont, CA: Brooks/Cole, Cengage Learning, 2013.

112. DeFreitas JM, Beck TW, Stock MS, et al. An examination of the time course of training-induced skeletal muscle hypertrophy. European journal of applied physiology 2011;111(11):2785-90.

113. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. Journal of applied physiology 2007;102(1):368-73.

114. Damas F, Phillips SM, Lixandrao ME, et al. Early resistance training-induced increases in muscle cross-sectional area are concomitant with edema-induced muscle swelling. European journal of applied physiology 2016;116(1):49-56.

115. Jajtner AR, Hoffman JR, Scanlon TC, et al. Performance and muscle architecture comparisons between starters and nonstarters in National Collegiate Athletic Association Division I women's soccer. Journal of strength and conditioning research / National Strength & Conditioning Association 2013;27(9):2355-65.

116. Gonzalez-Izal M, Lusa Cadore E, Izquierdo M. Muscle conduction velocity, surface electromyography variables, and echo intensity during concentric and eccentric fatigue. Muscle & nerve 2014;49(3):389-97.

117. Myer GD, Ford KR, Barber Foss KD, et al. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine 2009;19(1):3-8.

118. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. Clinical orthopaedics and related research 2002(402):76-94.

119. Petersen W, Ellermann A, Gosele-Koppenburg A, et al. Patellofemoral pain syndrome. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2014;22(10):2264-74.

120. Boling MC, Padua DA, Marshall SW, et al. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. The American journal of sports medicine 2009;37(11):2108-16.

121. Witvrouw E, Lysens R, Bellemans J, et al. Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. The American journal of sports medicine 2000;28(4):480-9.

122. Werner S. An evaluation of knee extensor and knee flexor torques and EMGs in patients with patellofemoral pain syndrome in comparison with matched controls. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 1995;3(2):89-94.

123. Kaya D, Citaker S, Kerimoglu U, et al. Women with patellofemoral pain syndrome have quadriceps femoris volume and strength deficiency. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA 2011;19(2):242-7.

124. Zhang Y, Hunter DJ, Nevitt MC, et al. Association of squatting with increased prevalence of radiographic tibiofemoral knee osteoarthritis: the Beijing Osteoarthritis Study. Arthritis and rheumatism 2004;50(4):1187-92.

125. Sharma L, Lou C, Cahue S, et al. The mechanism of the effect of obesity in knee osteoarthritis: the mediating role of malalignment. Arthritis and rheumatism 2000;43(3):568-75.

126. Sharma L, Chmiel JS, Almagor O, et al. The role of varus and valgus alignment in the initial development of knee cartilage damage by MRI: the MOST study. Annals of the rheumatic diseases 2013;72(2):235-40.

127. Andriacchi TP, Mundermann A, Smith RL, et al. A framework for the in vivo pathomechanics of osteoarthritis at the knee. Annals of biomedical engineering 2004;32(3):447-57.

128. Barrios JA, Higginson JS, Royer TD, et al. Static and dynamic correlates of the knee adduction moment in healthy knees ranging from normal to varus-aligned. Clinical biomechanics 2009;24(10):850-4.

129. Thorp LE, Wimmer MA, Foucher KC, et al. The biomechanical effects of focused muscle training on medial knee loads in OA of the knee: a pilot, proof of concept study. Journal of musculoskeletal & neuronal interactions 2010;10(2):166-73.

130. Reeves ND, Bowling FL. Conservative biomechanical strategies for knee osteoarthritis. Nature reviews Rheumatology 2011;7(2):113-22.

131. Hewett TE, Stroupe AL, Nance TA, et al. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. The American journal of sports medicine 1996;24(6):765-73.

132. Bennell KL, Hunt MA, Wrigley TV, et al. Hip strengthening reduces symptoms but not knee load in people with medial knee osteoarthritis and varus malalignment: a randomised controlled trial. Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society 2010;18(5):621-8.

133. Bennell KL, Egerton T, Wrigley TV, et al. Comparison of neuromuscular and quadriceps strengthening exercise in the treatment of varus malaligned knees with medial knee osteoarthritis: a randomised controlled trial protocol. BMC musculoskeletal disorders 2011;12:276.

134. Pollo FE, Otis JC, Backus SI, et al. Reduction of medial compartment loads with valgus bracing of the osteoarthritic knee. The American journal of sports medicine 2002;30(3):414-21.

135. Fregly BJ, Reinbolt JA, Rooney KL, et al. Design of patient-specific gait modifications for knee osteoarthritis rehabilitation. IEEE transactions on bio-medical engineering 2007;54(9):1687-95.

136. Hinman RS, Bowles KA, Payne C, et al. Effect of length on laterally-wedged insoles in knee osteoarthritis. Arthritis and rheumatism 2008;59(1):144-7.

137. Hinman RS, Payne C, Metcalf BR, et al. Lateral wedges in knee osteoarthritis: what are their immediate clinical and biomechanical effects and can these predict a three-month clinical outcome? Arthritis and rheumatism 2008;59(3):408-15.

138. Kerrigan DC, Lelas JL, Goggins J, et al. Effectiveness of a lateral-wedge insole on knee varus torque in patients with knee osteoarthritis. Archives of physical medicine and rehabilitation 2002;83(7):889-93.

139. Butler RJ, Barrios JA, Royer T, et al. Effect of laterally wedged foot orthoses on rearfoot and hip mechanics in patients with medial knee osteoarthritis. Prosthetics and orthotics international 2009;33(2):107-16.

140. Jenkyn TR, Hunt MA, Jones IC, et al. Toe-out gait in patients with knee osteoarthritis partially transforms external knee adduction moment into flexion moment during early stance phase of gait: a tri-planar kinetic mechanism. Journal of biomechanics 2008;41(2):276-83.

141. Lynn SK, Costigan PA. Effect of foot rotation on knee kinetics and hamstring activation in older adults with and without signs of knee osteoarthritis. Clinical biomechanics 2008;23(6):779-86.

142. Kemp G, Crossley KM, Wrigley TV, et al. Reducing joint loading in medial knee osteoarthritis: shoes and canes. Arthritis and rheumatism 2008;59(5):609-14.

143. Moreira AF NF, Aoki MS. Session RPE and stress tolerance in young volleyball and basketball players. Rev Bras Cineantropom Desempenho Hum 2010;12(5):945-51.

144. Eckstein F, Glaser C. Measuring cartilage morphology with quantitative magnetic resonance imaging. Seminars in musculoskeletal radiology 2004;8(4):329-53.