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The effects of detraining on knee biomechanics in a stop-jump task: implications for ACL injury

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The effects of detraining on knee biomechanics in a stop-jump task: implications for ACL injury

by

Boyi Dai

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

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TABLE OF CONTENTS

ABSTRACT ................................................................................................................................................ iii

CHAPTER I. GENERAL INTRODUCTION ......................................................................................... 1
  INTRODUCTION ................................................................................................................................. 1
  THESIS ORGANIZATION .................................................................................................................. 6
  REVIEW OF LITERATURE ................................................................................................................... 6
  REFERENCES ....................................................................................................................................... 20

CHAPTER II. THE EFFECTS OF DETERMINING ON KNEE BIOMECHANICS IN A STOP-JUMP TASK: IMPLICATIONS FOR ACL INJURY ................................................................. 30
  ABSTRACT ........................................................................................................................................ 30
  INTRODUCTION ............................................................................................................................... 31
  METHODS .......................................................................................................................................... 34
  RESULTS ........................................................................................................................................... 41
  DISCUSSION ..................................................................................................................................... 46
  REFERENCES .................................................................................................................................... 52

CHAPTER III. GENERAL CONCLUSION ............................................................................................. 59

ACKNOWLEDGEMENTS .................................................................................................................. 62

APPENDIX A. EXTENDED RESULTS ............................................................................................... 63

APPENDIX B. INFORMED CONSENT DOCUMENT ........................................................................ 65
ABSTRACT

Introduction: ACL injuries have an annual incidence rate of 1 per 3000 people for the general population. Seventy to eighty percent of these injuries occur in noncontact maneuvers that involve sudden deceleration. The likelihood of sustaining an ACL injury for females is two to eight times greater than males. Movement studies and cadaver simulation studies suggested the biomechanical risk factors for ACL injuries increased with greater proximal anterior tibial shear forces, lower knee flexion angles, greater knee valgus angle/moments, greater quadriceps EMG, and lower hamstring EMG during deceleration movements. While the effects of different training programs on the biomechanical risk factors of ACL injuries were well investigated and were shown to be effective in preventing ACL injuries, no research has been conducted to investigate the effects of detraining on the knee biomechanics during functional movements in highly trained athletes.

Methods: Twelve NCAA Division I female volleyball players participated in two stop-jump tests before and after a one-month season interval. Twenty-one retroreflective markers were attached on the subjects and four surface electrodes were placed on the muscle belly of the subject’s right thigh. Isometric maximum voluntary contraction tests were conducted for quadriceps and hamstring muscle groups. Subjects were asked to perform five trials of a stop-jump task as fast and high as possible. Muscle electrical activity was collected by a surface EMG capture system. Three-dimensional coordinate data of retroreflective markers were recorded using eight optical video cameras. Ground reaction force data were collected by a force platform. The EMG linear envelopes of each muscle group during the stop-jump tasks were normalized as a percentage of the corresponding maximum EMG in maximum voluntary contractions. An inverse dynamics approach was used to calculate the 3-D knee
joint moments and resultant forces during the stop-jump tasks using a rigid body model.

Exact 2-tailed Wilcoxon signed-rank tests ($\alpha=0.05$) were used to compare dependent variables between pre-detraining and post-detraining stop-jump tests.

Results: Jump height at the time of post-detraining was significantly lower compared with jump height at the time of pre-detraining ($p=0.001$). Subjects had significantly smaller knee flexion angles at initial foot contact with the ground ($p=0.042$) and smaller maximum knee flexion angles ($p=0.042$) during stance phase at the time of post-detraining compared with pre-detraining. No significant differences were observed for frontal plane kinematic and kinetic data. Smaller pre-landing biceps femoris EMG ($p=0.002$) was found at the time of post-detraining compared with pre-detraining. No significant differences were observed for pre-landing vastus medialis oblique, vastus lateralis, and semitendinosus EMG as well as all muscles’ landing EMG.

Discussion: The decreased biceps femoris EMG could be the cause of decreased initial knee flexion angle which consequently resulted in a reduced maximum knee flexion angle. The decreased knee flexion angle indicates a possible increased strain on the ACL and thus an increased risk for ACL injury. Proper neuromuscular training programs should be implemented for highly trained volleyball players after detraining to recover their performance and motor control patterns for preventing ACL injuries. Future studies with longer detraining durations, larger sample sizes and diversities of sports are needed to confirm the generalization of the results to other ACL high risk sports and thoroughly understand the detraining effects on ACL risk factors.
CHAPTER I
GENERAL INTRODUCTION

INTRODUCTION

Anterior Cruciate Ligament (ACL) is a ligament connecting the distal femur and proximal tibia and the primary function of ACL is to stabilize the knee joint, particularly in resisting anterior translation, valgus, varus, and internal rotation of the tibia with respect to the femur.\(^2\) ACL injuries are common sports related knee injuries and have an annual incidence rate of 1 per 3000 people for the general population.\(^4^4\) Approximately 175,000 primary ACL reconstruction surgeries are performed annually in the USA. At an estimated cost of $11,500 per ACL reconstruction, the annual expenditures for these surgeries are over 2 billion dollars.\(^1^8\) Questionnaire and videotape analysis showed that 70% to 80% of these injuries occur in a noncontact maneuver such as cutting, planting, and jumping that involve sudden deceleration.\(^4\) Studies found a large percentage of ACL injuries happened in young athletes\(^1^6,6^5\) and the likelihood of sustaining an ACL injury for females was two to eight times greater than males in soccer,\(^1,6^1\) basketball,\(^1,6^1\) and volleyball.\(^1^3,1^4\) Treatment after ACL injuries mainly involves a reconstruction by using a graft to replace the torn ligament. Rehabilitation programs include range of motion training, weight bearing training, and finally return to light and contact sports activities.\(^3^3\) In a current accelerated ACL injury rehabilitation protocol,\(^3^3\) the patients are allowed to receive immediate training of range of motion. Weight bearing is encouraged within the first week. The patients are allowed to return to light sporting activities at 2–3 months after surgery and to contact sports after 6 months.
Not only do ACL injuries have an immediate physical and financial load on individuals, they also bring significant neuromuscular and psychological consequences to injured individuals. The neuromuscular changes involve decreased proprioceptive sensitivity, reflex inhibition of the quadriceps femoris muscle, and reduced quadriceps and hamstring strength. A six month longitudinal study after ACL reconstruction found a significant time-effect difference in mood for injured athletes and the disturbance rate was higher for competitive athletes than recreational athletes. In addition, a high prevalence of osteoarthritis in later life was also found to be associated with ACL injuries.

To investigate the mechanism of noncontact ACL injuries, comprehensive review articles summarized the potential causes for gender disparity and related risk factors for noncontact ACL injuries. Various external and internal risk factors have been defined and suggested to be potential risk factors. External factors include playing surface, footwear, knee brace, and type of competition. It was suggested that harder surfaces and shoes could increase shoe-surface traction and result in higher risk of ACL injuries. Prophylactic knee brace use was associated with a reduced rate of knee injury, but the biomechanical and epidemiologic literature on brace use (prophylactic and functional) is still equivocal. A higher incidence rate during competition than training suggested that the level of competition and the phase of season could play an important role in ACL injuries. From the perspective of intrinsic factors, female athletes tend to have larger Q angles, greater ligamentous laxity, larger patellar tendon tibia angle, narrower intercondylar notch, smaller ligament size, and less normalized muscle strength in the quadriceps and hamstrings than male athletes and those differences might predispose female athletes to a
higher risk situation than males. In addition, the hormone variation was also considered as a factor in causing higher ACL injury rates in female athletes.\textsuperscript{72}

Proprioceptive activities, muscular strength, and recruitment patterns are crucial for optimal motor performance and may have a major role in injury reduction.\textsuperscript{70} The quadriceps muscle increases the anterior shear force on the tibia and serves as an antagonist to the ACL. The hamstring muscle prevents the excessive anterior translation of the tibia and acts as an agonist to the ACL. Neuromuscular control of the knee involves a complex interaction between the afferent and efferent neurological system and the muscles that control the knee joint. “Proprioceptive” information is delivered to the somatosensory cortex and is used to garner information about joint position and joint motion in space in order to elicit active and reflexive movement. Proprioceptive activities are crucial for optimal motor performance and may have a major role in injury reduction. If the hamstring shows weakness or a delay in contraction time in comparison with the quadriceps, the ACL may be at increased risk of injury, leading to tensile failure.\textsuperscript{70}

Neuromuscular control pattern differences of lower limb biomechanics between males and females have received much attention during recent years and have been suggested to be the most important reason for the increased risk of ACL injuries in women.\textsuperscript{20} Comparisons of neuromuscular control of the lower limb biomechanics between males and females during different tasks and conditions were conducted to explore the gender biomechanical differences which may contribute to the disparity of injury rate.\textsuperscript{5-8,10,17,34,36,40,42,53,60,63,64,67,69,80,81}

When combining the results of the movement studies and cadaver simulation studies,\textsuperscript{2,11,24,39,41,76,77} the reasons why females tended to sustain a higher ACL strain may be because of the greater proximal anterior shear force, lower knee flexion
angles, greater valgus angle/moments, greater quadriceps EMG, and lower hamstring EMG during deceleration movements.

Based on the links between lower limb mechanics and noncontact ACL injury risk, different training interventions were developed to prevent ACL injury, particularly in female athletes.21-23,25,38,49-51,57-59 More recent interventions that included different combinations of plyometric, strength, speed, balance, and agility exercises were considered to be effective in reducing ACL injury rate.21,23,25,38,58,59 The underlying mechanisms of preventive training programs were also investigated by studying the change of biomechanical risk factors before and after intervention.22,48-51,57 Specific to the effect of a single component of exercise, both plyometric and balance training were thought to be enough to reduce risk factors in the frontal plane, but the changes in the sagittal plane were specific to different tasks.50 However, no significant differences were observed in knee and hip kinematics and kinetics between groups before and after the strength-training protocol.22 People with different motor control patterns were inclined to have different changes after training programs.48 In addition, use of proper techniques and preventive instruments were able to reduce the biomechanical risk factors of ACL injuries.3,9,12,56,79

Based on the epidemiology studies showing that ACL injury for females were much greater than males, gender differences in biomechanical parameters during athletic tasks in these studies have been evaluated to identify potential underlying neuromuscular mechanisms of ACL injuries and clinical suggestions were given to prevent ACL injuries by optimizing these movement parameters. Different training programs were developed in order to reduce the incidence of ACL injuries. Combinations of strength, plyometric, balance, flexibility, and biomechanical and technique evaluation training have positive effects on
reducing the risk factors of ACL injuries. Although each component of the combined injury prevention programs is largely unknown at present, studies showed that plyometric training or feedback technique training solely could reduce the risk factors of ACL injuries whereas strength training or balance training solely may not be enough to change the motor control pattern of movements. However, since the training time is limited for athletes, the best training program should consider both the aspect of function enhancement and the aspect of time consumption. Therefore, it is important for athletic trainers to develop different training programs for different cohorts as well as different phases of a season in order to prevent ACL injuries as well as improving professional skills.

Due to competition schedule, season interval, onset of injury, and retirement, athletes frequently adjust their training. Detraining, which is the partial or complete loss of training-induced adaptations in response to an insufficient training stimulus,\textsuperscript{47} can be induced by injuries which can cause athletes to be absent from normal training from several days to years. Training duration and intensity is often lower during off season than during competition season also resulting in detraining effects. The human body is characterized by its ability to adapt to different levels of functional demands. Proper training is often accompanied by functional improvements. On the other hand, detraining as long as four weeks decreases the muscle strength,\textsuperscript{26,31,46} physiological function,\textsuperscript{47} and has potential effects on proprioception\textsuperscript{32} for highly trained individuals.

While the effects of different training programs on the biomechanical risk factors of ACL injuries were well investigated and were shown to be effective in preventing ACL injuries, no research was conducted to investigate the effects of detraining on the knee biomechanics during functional movement in highly trained athletes. Therefore, evaluating the
biomechanical changes prior and after the detraining may provide important information in applying effective and efficient training programs at different phases of a competition season in order to prevent ACL injuries.

The purpose of this study was to evaluate the effects of one-month detraining on the knee biomechanics in a stop-jump task in collegiate female volleyball players. It was hypothesized that after one-month detraining, subjects would demonstrate greater biomechanical risk factors associated with ACL injuries.

THESIS ORGANIZATION
This thesis is organized into General Introduction, Manuscript and General Conclusions chapters. The manuscript is formatted according to The American Journal of Sports Medicine specifications. The primary author for this article is Boyi Dai, Master student of Kinesiology at Iowa State University. Dr. Jason C. Gillette, an Associate Professor of Kinesiology at Iowa State University, contributed to experiment design, data analysis, and preparation of manuscripts. Dr. Timothy R. Derrick, an Associate Professor in the Department of Kinesiology at Iowa State University, contributed to Matlab programming and data analysis.

REVIEW OF LITERATURE
1. Gender comparison
Neuromuscular control pattern differences of lower limb biomechanics between males and females received much attention during recent years and were suggested to be the most important reason for the increased risk of ACL injuries in women. It was shown that males
and females demonstrated different kinematics, kinetics, and electromyography patterns during vigorous movements such as landing, cutting, and jumping.

In the landing studies, Nagano et al\textsuperscript{53} found that internal tibial rotation of females was significantly larger than that of the males while differences were not observed in knee flexion, varus, valgus, and anterior tibial translation while asking athletes to perform a single limb drop landing from a 30 cm platform. Quadriceps/hamstring EMG ratio for the 50ms time period before foot contact was also greater in females than males.

Ford et al\textsuperscript{17} showed that female basketball players landed with greater total valgus knee motion and maximum knee valgus angle than male players in a drop landing-jumping maneuver.

In the study of McLean et al\textsuperscript{40}, NCAA athletes were asked to conduct drop landing-jumping both before and after fatigue. Females landed with more initial ankle plantar flexion and peak-stance ankle supination, knee abduction, and knee internal rotation compared with males. Females also had larger knee adduction, abduction, and internal rotation, and smaller ankle dorsiflexion moments during the stance phase.

In addition, less knee flexion angle and more hip maximum internal rotation were found in collegiate female basketball, soccer, and volleyball players than males in a single-leg landing task.\textsuperscript{36}

Salci et al\textsuperscript{63} focused on gender comparison in volleyball players during spike and block landings. It was found that female volleyball players demonstrated less knee and hip flexion angles and they suggested that females may not use thigh muscles to attenuate as effectively as males in landing.
A more erect landing posture was also found by Decker et al.\textsuperscript{10} in females compared to males as well as greater hip and ankle joint ranges of motion and maximum joint angular velocities.

In cutting studies, Malinzak et al.\textsuperscript{37} found that female recreational athletes tend to have less knee flexion angles, more knee valgus angles, greater quadriceps activation and lower hamstring activation in comparison to men during the stance phase of side-cutting and cross-cutting movements.

In contrast to that, Sigward et al.\textsuperscript{69} did not find differences in kinematics while collegiate soccer players were performing side-step cutting. However, females demonstrated a smaller peak knee flexor moment and greater knee adductor moment during early deceleration. In addition, females displayed greater average quadriceps EMG intensity that males.

Sigward et al.\textsuperscript{68} also compared experienced and novice female athletes during side-step cutting. They found smaller knee moments and greater muscle coactivation in novice groups and these results indicated that more skilled athletes might be at greater risk for ACL injuries.

Due to the relationship between lower extremity alignments, hip motion during cutting maneuvers were also investigated. Landry et al.\textsuperscript{34} found that female elite adolescent soccer players had higher gastrocnemius activity, less hip flexion, more hip external rotation, and smaller hip flexion moment compared with the male athletes during an unanticipated side-cut maneuver.

Pollard et al.\textsuperscript{60} also observed significantly greater hip internal rotation and decreased hip flexion in female soccer players and proposed such differences might influence loading at the knee.
In the stop-jump studies, the researchers focused on the landing and take off phase before the subjects jumped off the ground. In the study of Chappell et al., recreational athletes were asked to perform vertical, backward and forward stop-jump tasks. The results have shown that females exhibited greater proximal anterior shear force, greater knee extension and valgus moments than males.

The landing preparation in vertical stop-jump was also investigated by Chappell et al. They found that in the flight phase before landing, female recreational athletes generally exhibited decreased knee flexion, hip flexion, hip abduction, increased knee internal rotation and increased quadriceps activation.

Significant gender and age interaction effects were found on lower extremity kinematics of youth soccer players. It was shown that compared to male players, youth female players had less knee and hip flexion angles at initial ground contact and decreased knee and hip flexion motion during the landing phase of the stop-jump task. More important, these gender differences occurred after 12 years of age and increased with age before 16 years.

Moreover, studies showed that the pre-landing motion before foot-ground contact was associated with peak knee motion during landing and was suggested to be an important technical factor that could reduce ACL loading. McLean et al. found that this greater peak valgus moment was associated with larger initial hip flexion and internal rotation and with larger initial knee valgus angle at the contact point in cutting. Furthermore, in the study of Sigward and Powers, they divided subjects into normal frontal plane moment group and excessive valgus moment group. They found that the excessive valgus moment group demonstrated an initial loading pattern that included greater laterally directed ground reaction...
forces, increased hip abduction, increased hip internal rotation and a more internally rotated foot progression angle.

2. Influence of fatigue and reaction

Besides gender comparison, studies showed that these biomechanical risk factors became more pronounced when the effects of reaction and fatigue were introduced.

McLean et al\textsuperscript{40} demonstrated that fatigue increased initial and peak knee abduction and internal rotation motions and peak knee internal rotation, adduction, and abduction moments, with the latter being more pronounced in females during landing. Fatigue also induced increased peak proximal tibial anterior shear forces, increased valgus moments and decreased knee flexion angles in the landing phase of forward, vertical, and backward stop-jump tasks.\textsuperscript{7}

Borotikar et al\textsuperscript{5} investigated the combined effects of fatigue and reaction on lower extremity biomechanics during a single leg landing task. Jump direction was controlled by light stimuli and fatigue effects were induced by repetitive squat. It was found that fatigue caused significant increases in initial contact hip extension and internal rotation, and in peak stance knee abduction and internal rotation and ankle supination angles. These increases in initial contact hip rotations and in peak knee abduction angle were more pronounced during unanticipated reaction landing compared to anticipated landings. They suggested that the integration of the effects of fatigue and decision making may represent a worst case scenario in terms of ACL injury risk during single leg landings.

The effect of direction and reaction on the biomechanical characteristics of the knee during a stop-jump task was investigated by Sell et al\textsuperscript{64}. The gender comparisons indicated that females performed the reactive jumps with less knee flexion, greater maximum valgus angle, greater anterior tibial shear force and greater knee flexion moment than males at the
point of maximum peak posterior ground-reaction force (PPGRF) data during reactive jumps. Female subjects also demonstrated less knee flexion, less maximum knee flexion, and greater knee valgus at PPGRF during the jumps to the left. They suggested that lateral jumps are the most dangerous of the stop-jumps. Reactive jumps resulted in significantly different angles, ground-reaction forces, knee joint moments, and proximal anterior tibia shear forces.

3. Cadaver studies-Sagittal plane injury mechanism

Berns et al\textsuperscript{2} measured strain within the anteromedial bundle of the ACL under different loading combinations with 25-30 Nm varus/valgus moment, 150-200 N medial/lateral force, 6-10 Nm internal/external moment, 150-200 N anterior/posterior force and 100-400 N compression force. The results showed that neither isolated internal/external moments nor pure varus/valgus moments were observed to strain significantly the anterior medial bundle of the ACL.

Markolf et al\textsuperscript{39} also investigated the effects of anterior tibial shear force, knee internal rotation, external rotation, valgus, and varus moments on the ACL strain. The individual loading states were a 100-N anterior shear force and 10-Nm knee internal rotation, external rotation, valgus, and varus moments. Knee angle range was from 90 degrees of flexion to 5 degrees of hyperextension. It was found that anterior shear force was the most direct loading, while the additions of internal rotation, external rotation, valgus, and varus moments to anterior shear force could significantly increase ACL strain compared to anterior shear force loading only.

An aggressive quadriceps loading as high as 4500 N was able to cause ACL injury with the knee in slight flexion without additional internal rotation, external rotation, valgus, and
varus moments. An anterior drawer force if 2000 N was considered to be necessary to disrupt the ACL while knee was positioned in 30 degrees flexion in the tibial orientation.

Based on gender differences in kinetic and kinematic factors during vertical stop-jump, gender-specific loading patterns were applied to cadaver knees to investigate if female movement patterns could cause a higher ACL strain. Cadaver knee loading patterns included tibial compression, quadriceps force, hamstrings force, external posterior tibial shear, and tibial torque. It was found that the female loading pattern was significantly higher than males after the posterior tibial shear force was applied.

A recent review of ACL injury mechanisms indicated that sagittal plane biomechanical factors, such as small knee flexion angle, large posterior ground reaction force and large quadriceps muscle force are the major ACL loading mechanisms. The anterior shear force at the proximal end of the tibia is a major contributor to ACL loading, while the knee valgus, varus and internal rotation moments may further increase ACL loading when combined with an anterior shear force.

Therefore, it has been proposed that sagittal plane biomechanical factors are the major ACL loading mechanisms and that knee valgus-varus moments and internal-external rotation moments alone are not likely to result in isolated ACL injuries without injuring other knee structures.

4. Simulation and prospective studies-Frontal plane injury mechanism

Not everyone supports the idea that sagittal plane biomechanics can injure the ACL. Based on as high as 2000 N of anterior drawer force considered to be necessary to disrupt the ACL, McLean et al used forward dynamic musculoskeletal models to simulate subject-specific cutting movements. Random perturbations were applied to initial contact conditions
and quadriceps/hamstrings activation levels to simulate their effect on peak knee loads. They found that the peak anterior drawer force never exceeded 2000 N in the models, but the valgus loads reached values that were high enough to rupture the ligament. So they concluded that sagittal plane knee joint forces cannot rapture the ACL during sidestep cutting, while valgus loading is a more likely injury mechanism.

Hewett et al. found that female athletes with increased dynamic knee valgus and high abduction loads were at increased risk of anterior cruciate ligament injury. In this prospective study, three-dimensional knee kinematics and kinetics during a jump-landing task were collected in 205 female adolescent soccer, basketball, and volleyball players. At the end, 9 athletes had a confirmed ACL rupture. The results showed that knee abduction angle at landing was 8° greater in anterior cruciate ligament–injured than in uninjured athletes. Anterior cruciate ligament–injured athletes had a 2.5 times greater knee abduction moment and 20% higher ground reaction force, whereas stance time was 16% shorter; hence, increased motion, force, and moments occurred more quickly.

5. Training program on injury rate

Based on the importance of muscular strength and proprioceptive information in the control of knee movements, many studies were conducted to evaluate the effects of different training programs on injury rate of ACL injuries.

Hewett et al. completed a prospective analysis of 1263 male and female athletes. The 6-week intervention program consisted of stretching, plyometrics and weight training with emphasis on proper alignment and technique. They found that the knee injury (ACL or MCL) incidence per 1000 athlete exposures was 0.43 in untrained female athletes, 0.12 in trained
female athletes, and 0.09 in male athletes. Untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes and 4.8 times higher than male athletes.

Petersen et al\textsuperscript{58} completed a prospective case control study of 134 female handball players with prevention training and 142 female players with regular training. At the beginning, information about the injury mechanism was instructed to coaches and trainers in the prevention group. Then it was followed by an eight-week preseason practice with a frequency of three times per week and the competition period with a frequency of once per week. The program was comprised of proprioceptive and jump exercises. It was found that the ACL ruptures incidence was 0.21 per 1000 hours for the control group and 0.04 per 1000 hours for the intervention group.

Mandelbaum et al\textsuperscript{38} conducted a 2-year follow-up study to determine whether a neuromuscular and proprioceptive performance program was effective in decreasing the incidence of ACL injury in female youth soccer players. The intervention consisted of education, stretching, strengthening, plyometrics, and sports-specific agility drills designed to replace the traditional warm-up. The results showed that there was a 74\%-88\% reduction in ACL injuries in the intervention group compared with the control group.

Heidt et al\textsuperscript{21} found that 7-week preseason conditioning training which included the treadmill and polymeric training induced a lower percentage of ACL injuries in high school players in the following season.

6. Training program on biomechanical mechanism

Previous prospective studies provide strong evidence that effective prevention training programs including plyometric, strength, speed, balance, agility exercises, and technique
instruction were able to reduce the incidence of ACL injuries. Meanwhile, the underlying biomechanical mechanism of different prevention programs was also investigated as well.

Holm et al\(^{25}\) implemented an ACL prevention study in female team handball players over 8 weeks. The training programs included floor exercises, wobble board exercises and balance mat exercises. They found that there was a significant improvement in dynamic balance between two tests, but no significant differences were found in proprioception, muscle strength and functional knee tests.

In the study of Pollard et al\(^{59}\), lower extremity biomechanics were examined prior to and following a season of soccer practice combined with injury prevention training which included stretching, strengthening, plyometrics and agility practice developed specific for ACL prevention. However, significant differences were only found in hip internal rotation and hip abduction. The reason why no significant differences of knee movements were found may be due to the testing task not requiring relatively high physical execution. The subjects were only tested for a drop-landing task from a 30 cm platform. Compared with landing with maximum jumping, this condition may not be enough to reveal the training effect on knee movement parameters.

Paterno et al\(^{57}\) studied the effects of 6-week neuromuscular training program designed to decrease the incidence of ACL injuries on single-limb postural stability in young female athletes. It was found that this training program was able to improve single-limb total stability and anterior-posterior stability, but not medial-lateral stability.

Myer et al\(^{51}\) investigated the effects of neuromuscular training on performance and lower extremity biomechanics. The 6 weeks of training included four main components (plyometric and movement, core strengthening and balance, resistance training, and speed training). The
results showed significant increases in maximum squat repetitions, bench press, right and left single-leg hop distance, vertical jump and speed. In addition, pre- and posttest 3-dimensional motion analysis demonstrated increased knee flexion-extension range of motion and decreased valgus and varus torques during the landing phase of a vertical jump.

To distinguish the effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics, Myer et al\textsuperscript{50} asked eighteen high school female athletes to participate in 18 training sessions during a 7-week period. The plyometric group performed maximum-effort jumping and cutting exercises and the balance group used dynamic stabilization/balance exercises during training. They found that plyometric and balance training protocols had similar effects on coronal plane measures of dynamic knee control. In the sagittal plane, plyometric training significantly increased knee flexion at the initial contact, whereas balance training did not affect knee flexion during the drop vertical jump. In contrast to the drop vertical jump testing, the plyometric training did not affect sagittal plane measures during the medial drop landing task. The measured changes during the medial drop landing were specific to balance training, with increased maximum knee flexion observed for this group. In addition, both groups decreased their standard deviation of center of pressure during hop landing in the medial/lateral direction and their hamstring strength and vertical jump both improved.\textsuperscript{49}

Herman et al\textsuperscript{22} collected knee and hip 3-dimensional kinematic and kinetic data for 66 female recreational athletes (33 intervention and 33 control) while performing 3 stop-jump tasks before and after completing a 9-week strength-training program targeting the quadriceps, hamstrings, gluteus medius, and gluteus maximus (intervention) or a 9-week period of no strength training (control). The results showed that the intervention group
increased in strength for all muscles. However, no significant differences were observed in knee and hip kinematics and kinetics between groups before and after the strength-training protocol. The authors suggested the lack of significant differences due to strength training observed in this study may be attributable to inappropriate neuromuscular patterns during the stop-jump task.

Myer et al\textsuperscript{48} conducted research to investigate the differential neuromuscular training effects on ACL injury risk factors in “high-risk” versus “low-risk” athletes. High school female soccer and basketball players were divided into two categories by their external knee abduction (25.25 Nm cutoff)\textsuperscript{24} during a jump-landing task. After a 7-week neuromuscular training, athletes classified as high-risk significantly decreased their knee abduction moments by 13\% following training. Athletes grouped into the low-risk category did not change their abduction moments following training.

The effects of technique change during movements on biomechanical risk factors of ACL injuries were also studied. Chaudhari et al\textsuperscript{9} found that arm position also influenced the landing mechanics in cutting. Compared with unconstrained arm position cutting, the lacrosse constrained and plant-side constrained cutting produced a significantly greater knee valgus moment.

Dempsey et al\textsuperscript{12} compared sidestep cutting tasks by asking subjects to use normal technique and nine different imposed techniques. It was observed that foot wide and torso leaning in the opposite direction to the cut, and torso rotating in the opposite direction to the cut resulted in higher valgus moments and internal rotation moments at the knee and hence place the athletes at higher risk of ACL injuries.
Blackburn et al\textsuperscript{3} found active trunk flexion during landing resulted in greater peak knee flexion angle which could be an effective strategy to prevent ACL injuries.

By using videotape feedback of jump-landing technique as an instructional component, Oñate et al\textsuperscript{56} incorporated several technique criterions to evaluate the jumping performance. Those criterion and instruction were represented by questions: (1) Did model land on both feet at the same time? (2) Did model land with excessive knee valgus or varus? (3) Did model land with feet shoulder-width apart? (4) Did model land on forefoot and roll toward rearfoot? (5) Did model land with optimal knee and hip flexion? The results showed that all feedback groups significantly increased knee flexion angular displacement and decreased peak vertical ground reaction forces during performance and retention tests.

As an example of preventive instruments, a knee extension constraint brace was designed and shown to be effective in decreasing the knee flexion angle at the landing by 5 degrees without decreasing the jump height.\textsuperscript{79}

7. Detraining effects
Hortobágyi et al\textsuperscript{26} studied the effects of 14 days resistive exercise detraining on power athletes. No significant changes were found in body mass, percentage fat, free weight bench press, parallel squat, isometric and isokinetic concentric knee extension force, vertical jumping, and knee flexion forces. However, significant decreases were found in isokinetic eccentric knee extension force and surface EMG activity of the vastus lateralis during isometric, and isokinetic eccentric and concentric knee extension.

Izquierdo et al\textsuperscript{31} investigated the effects of 4 weeks detraining on maximal strength and muscle power output of the arm and leg extensor muscles in Basque players, subsequent to 16 weeks of heavy resistance training. It was found that detraining results in significant
decreases in both strength and power output of the arm and leg extensor muscles without changes in body mass and percentage fat. Meanwhile, a larger detraining effect on muscle power output was found compared to strength. Detraining also caused a tendency for elevated resting serum insulin-like growth factor (IGF)-1 concentration.

Mujika and Padilla\textsuperscript{46} reviewed the effects of detraining on human muscular characteristics for highly trained individuals. They concluded that 2-3 weeks of training cessation could cause a decreased muscle capillary density. If the training stoppage continued beyond 3-8 weeks, arterial-venous oxygen difference would decline. For strength and sprint athletes, muscle fiber cross-sectional area declined rapidly during the detraining phase. For highly trained athletes, eccentric force and sport-specific power may suffer significant declines after 4 weeks of inactivity. This force reduction production decline was also related to decreased EMG activity.

From a physiological aspect, Mujika and Padilla\textsuperscript{47} summarized that short term detraining (less than 4 weeks) was able to cause decline in maximal oxygen uptake, blood volume, stroke volume during exercise, maximal cardiac output, ventricular mass, maximal ventilator volume, oxygen pulse, and endurance performance as well as increase in maximum heart rate, submaximal heart rate, mean blood pressure, and ventilatory equivalent for highly trained individuals.

Proprioceptive function appeared to decrease without sufficient stimulus. In the study of Kouzaki et al\textsuperscript{32}, subjects participated in a 20-day bed-rest study and were divided into two groups, strength training group and non-training group. After the bed-rest period, although the muscle volume in the strength training group was maintained, their mean velocity of center of pressure during the quiet stance increased in both groups.
REFERENCES


prevention training program in female team handball players: the German experience.


CHAPTER II

THE EFFECTS OF DETRAINING ON KNEE BIOMECHANICS IN A STOP-JUMP TASK: IMPLICATIONS FOR ACL INJURY

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Boyi Dai, Timothy R. Derrick, and Jason C. Gillette

ABSTRACT

Background: The effects of training on the biomechanical risk factors of ACL injuries have been investigated, but no research has studied the effects of detraining on the knee biomechanics during sport-related movement.

Hypothesis: After one-month detraining, subjects would demonstrate greater biomechanical risk factors associated with ACL injuries.

Study Design: Longitudinal pre-post intervention study.

Methods: Twelve NCAA Division I female volleyball players participated in two stop-jump tests before and after a one-month season interval. Knee kinematics, kinetics, and electromyographic activity were assessed during the tasks.

Results: Subjects demonstrated significantly lower jump height, smaller initial knee flexion, smaller maximum knee flexion angle, and smaller pre-landing biceps femoris EMG at the time of post-detraining compared with pre-detraining.

Conclusion and Clinical Relevance: The decreased biceps femoris muscle activation could be the cause of the decreased initial knee flexion angle which consequently resulted in a decreased maximum knee flexion angle. The decreased knee flexion angle indicates a possible increased strain on the ACL and thus an increased risk for ACL injury.
Proper neuromuscular training programs should be implemented for highly trained volleyball players after detraining for preventing ACL injuries.

INTRODUCTION

ACL injuries are common sports related knee injuries and have an annual incidence rate of 1 per 3000 people for the general population. Approximately 175,000 primary ACL reconstruction surgeries are performed annually in the USA. At an estimated cost of $11,500 per ACL reconstruction, the annual expenditures for these surgeries are over 2 billion dollars. Not only do ACL injuries place an immediate physical and financial load on individuals, they also bring significant neuromuscular and psychological consequences to injured individuals. Questionnaire and videotape analysis showed that 70% to 80% of these injuries occur in a noncontact maneuver such as cutting, planting, and jumping that involves sudden deceleration. Studies found a large percentage of ACL injuries happened in young athletes and the likelihood of sustaining an ACL injury for females was two to eight times greater than males in soccer, basketball, and volleyball.

To investigate the mechanism of noncontact ACL injuries, comprehensive review articles summarized the potential causes for gender disparity and related risk factors for noncontact ACL injuries. Various external and internal risk factors have been defined and suggested to be potential risk factors. External factors include playing shoe-surface interaction, knee brace, and type of competition. From the perspective of intrinsic factors, female athletes tend to have larger Q angles, greater ligamentous laxity, larger patellar tendon tibia angle, narrower intercondylar notch, and less normalized muscle strength in the quadriceps and hamstrings than male athletes and those differences might
predispose female athletes to a higher risk situation than males. In addition, the hormone variation was considered as a factor in causing higher ACL injury rates in female athletes.\textsuperscript{54}

Neuromuscular control pattern differences of lower extremity biomechanics between males and females have received much attention during recent years and have been suggested to be the most important reason for the increased risk of ACL injuries in women.\textsuperscript{14} Movements studies \textsuperscript{5,7, 28,30, 33,43, 47,48,60} suggested that females tended to have greater proximal anterior shear force, lower knee flexion angles, greater knee abduction angle, greater knee internal extension and adduction moments, greater quadriceps EMG, and lower hamstring EMG than males during deceleration movements. The results were supported by cadaver simulation studies,\textsuperscript{3,32,57,59} which indicated that those biomechanics characteristics could induce a higher ACL strain and increase the risks of ACL injuries. In addition, studies demonstrated that these biomechanical risk factors would increase when the effects of fatigue and unanticipated movements were introduced.\textsuperscript{6,28,48}

Based on the links between lower extremity mechanics and noncontact ACL injury risk, different training interventions were developed to prevent ACL injury, particularly in female athletes.\textsuperscript{15-17,31,40,41} More recent interventions that included different combinations of plyometric, strength, speed, balance, and agility exercises were considered to be effective in reducing ACL injury rate.\textsuperscript{15,17,31} The underlying mechanisms of preventive training programs were also investigated by studying the change of biomechanical risk factors before and after intervention.\textsuperscript{16,40,41} Specific to the effect of a single component of exercise, both plyometric and balance training were thought to be enough to reduce risk factors in the frontal plane, but the changes in the sagittal plane were specific to different tasks.\textsuperscript{40} Single strength training did not change knee and hip kinematics and kinetics,\textsuperscript{16} but strength training was suggested to
provide an increased capacity for the alteration of knee and hip biomechanics. Videotape feedback training of jump-landing technique significantly increased knee flexion angular displacement and decreased peak vertical ground reaction forces during performance and retention tests. In addition, people with different motor control patterns were inclined to have different changes after training programs.

Due to competition schedule, season interval, onset of injury, and retirement, athletes frequently adjust their training. Detraining, which is the partial or complete loss of training-induced adaptations in response to an insufficient training stimulus, can be induced by injuries which can cause athletes to be absent from normal training from several days to years. Training duration and intensity is often lower during off season than during competition season also resulting in detraining effects. The human body is characterized by its ability to adapt to different levels of functional demands. Proper training is often accompanied by functional improvements. On the other hand, detraining for as long as four weeks decreases the muscle strength, physiological function, and has potential effects on proprioception for highly trained individuals.

While the effects of different training programs on biomechanical risk factors of ACL injuries were investigated and effective in preventing ACL injuries, no research has been conducted to investigate the effects of detraining on the knee biomechanics during sport-related movements. Because a decreased relative strength was suggested to be associated with decreased knee flexion angle and proprioceptive activities were crucial for optimal motor performance, highly trained athletes might change their motor control strategies due to a decrease in strength abilities and proprioceptive functions after detraining. Since training time is limited for athletes, the best training program should consider both the aspect of
function enhancement and the aspect of time consumption. Therefore, it is important for athletic trainers to develop different training programs at different phases of a season in order to prevent ACL injuries as well as improving professional skills.

The purpose of this study was to evaluate the effects of one-month detraining on the knee biomechanics in a stop-jump task in collegiate female volleyball players. It was hypothesized that after one-month detraining, subjects would demonstrate greater biomechanical risk factors associated with ACL injuries.

METHODS

Subjects

Twelve NCAA Division I female volleyball players (Table 1) were recruited as subjects for this study on a volunteer basis. Subjects were excluded from this study if they had suffered ACL injury, meniscus damage or substantial ligament damage to the knee or ankle; had a lower extremity injury that prevented participation in physical activity for >2 weeks over the previous 6 months; or possessed any condition that prevented them from participating at maximal effort in sporting activities. Subjects participated in stop-jump tests before and after a one-month season interval. All procedures were orally explained to each subject and informed consent was obtained in accordance with the Iowa State University Institutional Review Board.

Instrumentation

Three-dimensional (3D) coordinate data of retroreflective markers were recorded using eight infrared video cameras (Vicon MX40, Oxford Metrics Ltd, Oxford, UK) at a sample rate of 160 Hz. Ground reaction force data were collected by one force platform (AMTI OR6 Series,
Muscle electrical activities were collected by a surface EMG capture system (Myomonitor, Delsys Inc., MA, USA) with a Bandwidth from 20 to 450 Hz at a sample rate of 1600 Hz. Surface EMG Sensors (DE-2.1, Delsys Inc., MA, USA) were placed on the muscle belly with compatible double-side adhesive tape. Motion data, ground reaction force data, and EMG data were time synchronized using Vicon Nexus videographic and analog data acquisition system (Oxford Metrics Ltd, Oxford, UK).

Table 1. Subject Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
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<tbody>
<tr>
<td>Age (yrs)</td>
<td>19.25 ± 1.22</td>
</tr>
<tr>
<td>Pre-detraining Height (cm)</td>
<td>178.49 ± 6.96</td>
</tr>
<tr>
<td>Post-detraining Height (cm)</td>
<td>178.37 ± 6.40</td>
</tr>
<tr>
<td>Pre-detraining Mass (kg)</td>
<td>71.17 ± 5.65</td>
</tr>
<tr>
<td>Post-detraining Mass (kg)</td>
<td>70.88 ± 5.86</td>
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<tr>
<td>Experience (yrs)</td>
<td>8.75 ± 2.22</td>
</tr>
<tr>
<td>Detraining Duration (days)</td>
<td>30.00 ± 1.28</td>
</tr>
</tbody>
</table>

Experimental Procedure

For the pre-detraining test, after consent was obtained, the subject’s injury history was asked and recorded. Once the subject met the criteria for this study, the subject’s anthropometric parameters were measured to build up a biomechanical model. The parameters included height and mass, segmental circumference of the thighs and shanks, and feet length and width. Other anthropometric parameters for the model were obtained from marker sets during static trials.
During the test, all subjects wore spandex shorts, t-shirts, and personal shoes and socks. Subjects were asked to conduct stretching exercises and run on a treadmill at a self-selected speed for warm-up purposes. Surface electrodes were placed on the muscle belly of selected muscles of the subject’s right leg after the subject’s skin was cleaned using alcohol. These muscles included vastus medialis oblique (VM), vastus lateralis (VL), biceps femoris (BF), and semitendinosus (ST). A common ground electrode was placed on the tibial tuberosity. The subject wore a harness above the pelvis to house the signal transmitter for the wireless EMG system.

Three trials of isometric maximum voluntary contractions (MVC) were conducted for each subject for quadriceps and hamstring muscle groups for 5 seconds. The MVC tests for quadriceps were performed while the subject was in a sitting position with the hip and knee flexed at 90° and the shank perpendicular to the ground (Figure 1a). An investigator held the participant’s lower anterior tibia just proximal to the ankle joint. The subject was instructed to extend the leg at the knee as hard as she could. The MVC tests for hamstring muscles were performed while the subject was in a prone position with the knee flexed at 90° and the shank perpendicular to the ground (Figure 1b). An investigator held the participant’s lower posterior shank just proximal to the ankle joint. The subject was instructed to flex the leg at the knee as hard as she could.

A total of 21 retroreflective markers were used for the collection of 3D coordinate data for each trial (Figure 2a, b, c). Retroreflective markers were attached on the spinous process of the right and left acromioclavicular joints, fifth cervical vertebra, upper edge of sternum, right and left anterior superior iliac spine (ASIS), right and left posterior superior iliac spine, and right and left greater trochanters. On the right side of the body, markers were placed on
the anterior and lateral thigh, medial and lateral femoral condyle, anterior and posterior shank, medial and lateral malleolus, lateral foot, dorsal foot and heel. The subjects were asked to stand upright with feet placed shoulder width apart in the center of the calibration volume for static collections.

Subjects were asked to perform five trials of a vertical stop-jump task (Figure 3). A vertical stop-jump task consisted of an approach run followed by a 1-footed takeoff, a 2-footed landing, followed by a 2-footed takeoff while raising their arms for maximum touching height. The distance of approach was not restricted because of variations in step length and personal preferences, but 2 steps during the approach was enforced. Subjects were instructed to jump vertically as fast and high as possible with the right foot landing on the force platform while no other technique instructions were given to avoid changing natural jump preferences. After the stop-jump task was described and demonstrated, subjects were allowed to practice the approach and maximum jump with unlimited time. For data collection, each subject performed 5 successful trials of the vertical stop-jump task. A successful trial was defined as the subject meeting the vertical stop-jump task requirements and all data were recorded.

After the pre-detraining tests, subjects were asked to record any injury that happened to them and any additional self-selected exercise they did during the season interval. After the one-month season interval, participants came to the lab again. Injuries and additional exercise during season interval were recorded and the same procedure was repeated at the end of the detraining.
Figure 1: Quadriceps and hamstring MVC tests

Figure 2: Retroreflective marker placement

Figure 3 The vertical stop-jump task (Used with permission)
Data reduction

The raw coordinate data were filtered using a fourth-order, zero-phase-shift Butterworth filter at a low-pass cutoff frequency of 9 Hz. The raw ground reaction data were filtered using a fourth-order, zero-phase-shift Butterworth filter at a low-pass cutoff frequency of 50 Hz.\textsuperscript{18,58} The videographic and force plate data collection were time-synchronized to 1600 Hz using linear interpolation.

The 3-D coordinates of the hip joint centers were projected from the hip marker to 14\% of the inter-ASIS distance medial to the ASIS and 30\% of the inter-ASIS distance distal to the ASIS.\textsuperscript{2} The knee joint center was defined as the midpoint between the medial and lateral femoral condyles. The ankle joint center was defined as the midpoint between the medial and lateral malleoli. Joint centers were defined during a static trial and rebuilt during stop-jump tests using a singular value decomposition method.\textsuperscript{55}

Foot reference frames were determined from the coordinates of ankle joint center, heel, and toe markers. Shank reference frames were determined from the coordinates of ankle joint center, knee joint center, and anterior shank markers. Thigh reference frames were determined from the coordinates of knee joint center, hip joint center, and lateral femoral condyle markers. Cardan joint angles were calculated in a flexion–extension, valgus–varus, and internal–external rotation order.\textsuperscript{12} Knee flexion, adduction, and internal rotation were denoted as positive joint angles. Segment masses, center of mass (COM) locations, and segment moments of inertia were based on Vaughan et al.\textsuperscript{56} An inverse dynamics approach with a rigid body model was used to calculate the 3-D knee joint moments and resultant forces during the stop-jump tasks. The knee joint resultant forces and moment vectors were finally transferred to the tibial reference frame and expressed as internal loading.\textsuperscript{58} Joint
resultant forces were normalized to body weight, and joint resultant moments were normalized to a product of body weight and height.\textsuperscript{6}

The initiation of landing was identified by the time when the vertical ground reaction force was more than 20N. The toe off event was identified by the time when the vertical ground reaction force was less than 20N after landing. The landing phase was defined as the first 20\% of the entire stance phase.\textsuperscript{6,51} Subject jump heights were calculated by subtracting the static right ASIS vertical height from the maximum right ASIS height during the stop-jump task. For knee joint loading, peak anterior tibial shear forces (PATSF) during the landing were calculated for each trial. Knee flexion and abduction angles at the initiation of landing and at PATSF were determined. The maximum knee flexion and knee abduction angles during the stance phase were also determined for each trial. Knee extension and adduction moments at PATSF as well as maximum knee extension and adduction moments during the landing phase were determined for each trial.\textsuperscript{6,18}

The raw EMG data for each muscle were filtered using a fourth–order, zero-phase-shift Butterworth filter at a low-pass cutoff frequency of 450 Hz and a high-pass cutoff frequency of 20 Hz. The filtered EMG data were then rectified and filtered through a fourth–order, zero-phase-shift Butterworth low-pass filter at a cutoff frequency of 10 Hz to obtain the EMG linear envelope. Maximum 1-s average EMG data during MVC for each muscle during all three trials was obtained. The EMG linear envelopes of each muscle group during the stop-jump task were normalized as a percentage of the corresponding maximum 1-s average EMG in MVC. EMG data 50 ms before landing were averaged for each muscle to represent pre-landing muscle activities.\textsuperscript{43} EMG data during the stance phase were normalized to 100\% of the stance phase time. The first 20\% of the stance phase EMG were averaged to represent
the muscle activities during landing. All of the kinematic, kinetic and EMG data calculations were performed in the MATLAB 7.4.0 (MathWorks Inc., PA, USA).

Data Analysis

Data were averaged across five trials for each subject during each test. Biomechanical parameters for the stop-jump were the dependent variables, whereas whether prior or after detraining was the independent variable. Exact 2-tailed Wilcoxon signed-rank test was used to compare dependent variables between pre-detraining and post-detraining stop-jump tests. A Type I error rate of 0.05 was selected as an indication of statistical significance. Statistical analyses were conducted in SPSS 16.0 (SPSS, Chicago, IL, USA).

RESULTS

No injuries happened to any subject during the season interval. One subject’s EMG data in the post-detraining test were missed due to a software failure during data collection, so only motion and force plate data were captured for that subject. Therefore, the data analysis for EMG was conducted for 11 subjects while other data analysis was conducted on 12 subjects. During the competition season, the training time was 20 hours/week (12-13 hours practice & 1-2 hours strength training & 6 hours game competition). During the one-month season interval, athletes performed self-selected training and the training duration was 2.62±1.53 hours/week (51% cardiovascular & 35% strength training & 14% volleyball playing). No statistically significant differences were observed between pre-detraining test and post-detraining test for subject height (p=0.914) or mass (p=0.332) (Table 1).

As Table 2 shows, jump height at the time of post-detraining was significantly lower compared with jump height at the time of pre-detraining (p=0.001). Subjects also had
significantly smaller knee flexion angle at initial foot contact with the ground (p=0.042) and smaller maximum knee flexion angle (p=0.042) during stance phase at the time of post-detraining compared with pre-detraining (Figure 4). A significant difference was approached for decrease knee flexion angle at PATSF (p=0.052) between pre-detraining and post-detraining. No significant differences were observed for the PATSF (p=0.519) during landing (Figure 5), knee extension moment at PATSF (p=0.110), maximum knee extension moment (p=0.151) during landing (Figure 6), knee abduction angle at initial foot contact with ground (p=0.791), knee abduction angle at PATSF (p=0.569), maximum knee abduction angle (p=0.380) during stance phase, knee adduction moment at PATSF (p=0.622), and maximum knee adduction moment (p=0.622) during landing between pre-detraining and post-detraining.

Smaller pre-landing BF EMG activities (p=0.002) were found at the time of post-detraining compared with pre-detraining (Table 2, Figure 7). A significant difference was approached for average VL EMG (p=0.054) during 50ms pre-landing between pre-detraining and post-detraining (Figure 8). No significant differences were observed for pre-landing VM EMG activities (p=0.24), pre-landing ST EMG activities (p=0.898), landing VM EMG activities (p=0.52), landing VL EMG activities (p=0.206), landing ST EMG activities (p=0.365), and landing BF EMG activities (p=0.147).
Table 2  Kinematics/kinetics and EMG comparisons between pre-detraining and post-detraining (Mean ± SD, * p<0.05, ** p<0.01)

<table>
<thead>
<tr>
<th></th>
<th>Pre-detraining</th>
<th>Post-detraining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump Height (m)</td>
<td>0.48 ± 0.05</td>
<td>0.44 ± 0.05**</td>
</tr>
<tr>
<td>PATSF during landing (BW)</td>
<td>0.77 ± 0.37</td>
<td>0.72 ± 0.21</td>
</tr>
<tr>
<td>Initial knee flexion angle (Deg)</td>
<td>20.89 ± 5.96</td>
<td>16.99 ± 5.64*</td>
</tr>
<tr>
<td>Knee flexion angle at PATSF (Deg)</td>
<td>31.72 ± 10.76</td>
<td>26.93 ± 9.93</td>
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<tr>
<td>Maximum knee flexion angle (Deg)</td>
<td>75.25 ± 5.00</td>
<td>71.84 ± 6.60*</td>
</tr>
<tr>
<td>Knee extension moment at PATSF (BW*BH)</td>
<td>0.012 ± 0.044</td>
<td>0.028 ± 0.038</td>
</tr>
<tr>
<td>Maximum knee extension moment during landing (BW*BH)</td>
<td>0.054 ± 0.038</td>
<td>0.063 ± 0.039</td>
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<tr>
<td>Initial knee abduction angle (Deg)</td>
<td>3.16± 2.57</td>
<td>2.98 ± 2.18</td>
</tr>
<tr>
<td>Knee abduction angle at PATSF (Deg)</td>
<td>5.05±3.25</td>
<td>4.83± 3.82</td>
</tr>
<tr>
<td>Maximum knee abduction angle (Deg)</td>
<td>10.77 ± 6.72</td>
<td>12.15 ± 5.02</td>
</tr>
<tr>
<td>Knee adduction moment at PATSF (BW*BH)</td>
<td>0.001± 0.048</td>
<td>-0.003 ± 0.035</td>
</tr>
<tr>
<td>Maximum knee adduction moment during landing (BW*BH)</td>
<td>0.053± 0.037</td>
<td>0.053 ± 0.027</td>
</tr>
<tr>
<td>Pre-landing VM EMG (MVC)</td>
<td>0.71 ± 0.32</td>
<td>0.57 ± 0.27</td>
</tr>
<tr>
<td>Pre-landing VL EMG (MVC)</td>
<td>0.76 ± 0.39</td>
<td>0.51 ± 0.37</td>
</tr>
<tr>
<td>Pre-landing ST EMG (MVC)</td>
<td>0.36 ± 0.19</td>
<td>0.36 ± 0.15</td>
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<tr>
<td>Pre-landing BF EMG (MVC)</td>
<td>0.45 ± 0.17</td>
<td>0.33 ± 0.09**</td>
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<tr>
<td>Landing VM EMG (MVC)</td>
<td>1.71 ± 0.51</td>
<td>1.48 ± 0.62</td>
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<td>Landing VL EMG (MVC)</td>
<td>2.17 ± 1.07</td>
<td>1.66 ± 0.76</td>
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<tr>
<td>Landing ST EMG (MVC)</td>
<td>0.31 ± 0.21</td>
<td>0.32 ± 0.15</td>
</tr>
<tr>
<td>Landing BF EMG (MVC)</td>
<td>0.44 ± 0.22</td>
<td>0.34 ± 0.13</td>
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</table>
Figure 4. Knee flexion/extension angle during stance phase.

Figure 5. Tibial shear force during stance phase.
Figure 6. Knee flexion/extension moment during stance phase.

Figure 7. BF EMG during 100 ms pre-landing.
DISCUSSION

The purpose of this study was to investigate the effects of one-month detraining on the knee biomechanics in a stop-jump task in collegiate female volleyball players. It was hypothesized that subjects would demonstrate greater biomechanical risk factors for non-contact ACL injuries after one-month detraining. Detraining effects are common in athletes and can be caused by competition schedule, onset of injury, retirement, and season interval. The detraining effects in the current study were induced by a one-month season interval during which subjects conducted self-selected exercise instead of following any designed training regimen. The detraining effects were successfully simulated because the average training duration was 2.6 hours/week during the season interval compared to 20 hours/week training regimen during the competition season.
The significant decrease in jump height (p=0.001) during a stop-jump task further suggested that the detraining protocol in this study effectively created decreased performance. These results agreed with Izquierdo et al\textsuperscript{25} who observed decreases in both strength and power output of leg extensor muscles after 4 weeks detraining. On the other hand, Myer et al\textsuperscript{41} found 6 weeks neuromuscular training improved muscle strength and increased jump height. Mujika and Padilla\textsuperscript{37} indicated that for highly trained athletes, eccentric force and sport-specific power may suffer significant declines after 4 weeks of inactivity. Stop-jump tasks, which require a large lower extremity power exertion in order to reach maximum jump height, are commonly experienced by volleyball players during spiking. In the current study, the decrease in jump height could be largely due to a decline in muscle strength and power for lower extremity muscles.

The results suggested detraining increased the sagittal plane risk factors of ACL injury. Smaller knee flexion angle at initial foot contact with ground (p=0.042) and smaller maximum knee flexion angle during stance phase were found at the time of post-detraining (p=0.042) as compared with pre-detraining. A trend to have a smaller knee flexion angle at PATSF (p=0.052) was also observed. Studies demonstrated that sagittal plane kinematics had excellent repeatability within a test day as well as between days, so it is unlikely that the effects of detraining on decreased knee flexion angles was due to measurement variability.\textsuperscript{13} Nunley et al\textsuperscript{44} found patella tendon-tibia shaft angle and knee flexion angle were inversely correlated with each other. The results suggest that with a given quadriceps muscle force, decreasing knee flexion angle would increase the anterior shear force at the proximal end of tibia by increasing the patella tendon-tibia shaft angle. Markolf et al\textsuperscript{32} showed anterior shear force was the most direct ACL loading of cadaver knees and the loading increased as knee
flexion angle decreased. Less knee flexion during athletic tasks were repeatedly found in females compared with males and were suggested to be a potential cause of gender disparity in ACL injury rates. Malinzaka et al.\textsuperscript{30} found that female recreational athletes tend to have less knee flexion angles in comparison to men during the stance phase of side-cutting and cross-cutting movements. Salci et al.\textsuperscript{47} found female volleyball players demonstrated less knee flexion angle during spike and block landings. These results combined together support the theory that one-month detraining, which induced less knee flexion angles, might predispose athletes into a higher risk situation to sustain ACL injuries.

Decreased pre-landing BF EMG activity (p=0.002) and a trend of decreased pre-landing VL EMG activity (p=0.054) were found at the time of post-detraining compared with pre-detraining. Nagano et al.\textsuperscript{43} found a higher hamstrings/quadriceps ratio for the 50 ms time pre-landing phase in males than in females during single limb drop landing. Chappell et al.\textsuperscript{5} observed the quadriceps EMG increased about 50 milliseconds before landing for both males and females. They also found increased quadriceps and hamstring EMG and reduced knee flexion angles during the pre-landing phase in females than in males. As the main function of BF is to flex the knee, its decreased pre-landing EMG could be associated with reduced knee flexion angles at initial foot contact with the ground. Although a trend of decreased pre-landing VL EMG was not consistent with a decreased knee flexion angle, the decrease of muscle coactivation on the lateral side of knee may cause a decrease in joint stiffness.\textsuperscript{19} However, significant differences were not found in all knee muscle EMG during the landing phase. Studies\textsuperscript{33, 60} showed that the pre-landing motion before foot-ground contact was associated with peak knee motion during landing and an initial knee flexion angle greater than 20° was encouraged in technique training programs.\textsuperscript{45} After one-month detraining,
initial knee flexion angles dropped from 21° to 17°, followed by an approximately 4° decrease in knee flexion angle at PATSF and maximum knee flexion angle during stance phase. The results suggested that the decreased knee flexion angle at PATSF and decreased maximum knee flexion angle could be caused by the smaller initial knee flexion.

Chappell et al\textsuperscript{6} showed that decreased relative strength simulated by exercise-induced muscular fatigue resulted in decreased knee flexion angle in a stop-jump task. Meanwhile, the central nervous system has been suggested to store patterns that control motion and these patterns are learned with time and repetition.\textsuperscript{19} It was possible that during the competition season, which included high risk circumstances such as intense training programs and competition, not only were athletes’ muscles strengthened, but also athletes gradually adopted motor control patterns to protect them from injuries. After one-month detraining, subjects’ muscle strength may have decreased as well as awareness of adopting safe movement control patterns. Therefore, the decreased knee flexion angle caused by detraining could be due to the combination of decreased muscular strength and loss of optimal motor control patterns.

Besides sagittal plane mechanisms, abnormal frontal plane movement control has also been proposed as a cause for non-contact ACL injuries. Markolf et al\textsuperscript{32} found that the addition of valgus and varus moments to anterior shear force could significantly increase ACL strain as compared to only anterior shear force loading. Hewett et al\textsuperscript{18} found a larger knee abduction angle and moment in ACL injured athletes than in uninjured athletes. The results of this current study showed that detraining did not have significant effects on frontal plane control patterns. In contrast to knee sagittal plane movement, determinants of frontal plane motion were much more complex. The knee valgus angle is largely associated with hip
adduction and internal rotation, knee flexion, and tibial external rotation. Coactivation of quadriceps and hamstring muscles were proposed to support varus-valgus moments by increasing joint stiffness. Hip abduction and external rotation strength were also suggested to play an important role in control of frontal plane knee motion. While studies indicated that larger frontal motion in females than in males could be a cause for gender disparity in ACL injuries, our results suggested that one-month detraining did not change the frontal plane motion in highly trained volleyball players.

Changes in sagittal motor control patterns after detraining suggest the importance of preseason conditioning for athletes to recover both sport-specific performance and proper motor control strategies before they start a high level of competition. Heidt et al found that 7-week preseason conditioning training which included treadmill and plyometric training induced a lower percentage of ACL injuries in high school players in the following season. Myer et al showed 6 weeks of neuromuscular training resulted in significant increases in performance in terms of maximum squat repetitions, single-leg hop distance, and vertical jump as well as lower extremity biomechanics such as increased knee flexion-extension range of motion. Furthermore, Hewett et al completed a prospective study to investigate the effects of 6-week neuromuscular training on knee injury rate. They found untrained female athletes had a 3.6 times higher incidence of knee injury than trained female athletes and 4.8 times higher than male athletes. On the other hand, poor conditioning was found to be associated with increased knee injuries. Therefore, instead of participating in intense competition, implementing a proper training program after detraining to regain appropriate motor control patterns becomes important in preventing ACL injuries. It was shown that the incidence rate for ACL injuries was higher during competition than during practice. Studies
also suggested that biomechanical risk factors for ACL injuries became more pronounced when the effects of reaction and fatigue were introduced. Asking athletes after detraining to be exposed to a scenario with high risk factors could increase their probability of suffering ACL injury.

The use of volleyball players is a limitation to generalize the findings of this study. Future studies with a larger sample size and diversity of sports are needed to confirm the generalization of the results to other ACL high risk sports. One month detraining duration was used due to the timing limitation of the winter season interval. Although one month was shown to be enough to induce significant muscular and physiological changes in highly trained athletes, longer durations of detraining must be investigated to thoroughly understand the detraining effects on ACL risk factors. In addition, normalized EMG was used as a measure of muscle activation. However, muscle force is dependent upon muscle activation, muscle cross-section area, fiber type, force-velocity, and force-length relationships. Solely EMG measurements were not sufficient to explain kinematic changes as a function of changes in muscle force. Future studies with musculoskeletal models are needed to interpret the results of changes in kinematics after detraining.

In conclusion, one-month detraining significantly decreased jump height, initial and maximum knee flexion, and pre-landing BF EMG of collegiate female volleyball players. The decreased BF muscle activation could be the cause of the decreased initial knee flexion angle which consequently resulted in a decreased maximum knee flexion angle. The decreased knee flexion angle indicates a possible increased strain on the ACL and thus an increased risk for ACL injury. Proper neuromuscular training programs should be
implemented for highly trained volleyball players after detraining to recover their
performance and motor control patterns for preventing ACL injuries.

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CHAPTER III

GENERAL CONCLUSION

Detraining effects are common in athletes and can be caused by competition schedule, onset of injury, retirement, and season interval. In the current study, the detraining effects were induced by a one-month season interval. The significant decrease in jump height during a stop-jump task further suggested that the detraining protocol in this study effectively created decreased performance. The decrease in jump height could be largely due to a decline in muscle strength and power for lower extremity muscles.

Smaller knee flexion angle at initial foot contact with ground and smaller maximum knee flexion angle during stance phase were found at the time of post-detraining as compared with pre-detraining. Previous studies demonstrated that with a given quadriceps muscle force, decreasing knee flexion angle would increase the anterior shear force at the proximal end of tibia by increasing the patella tendon-tibia shaft angle. These results combined together support the theory that one-month detraining, which induced less knee flexion angles, might predispose athletes into a higher risk situation to sustain ACL injuries. While studies indicated that larger frontal motion in females than in males could be a cause for gender disparity in ACL injuries, our results suggested that one-month detraining was not enough to change the frontal plane motion in highly trained volleyball players.

Decreased pre-landing BF EMG activity and a trend of decreased pre-landing VL EMG activity were found at the time of post-detraining compared with pre-detraining. As the main function of BF is to flex the knee, its decreased pre-landing EMG could be associated with reduced knee flexion angles at initial foot contact with the ground. Studies showed that the pre-landing motion before foot-ground contact was associated with peak knee motion during
landing. The results suggested that the decreased knee flexion angle at PATSF and decreased maximum knee flexion angle could be caused by the smaller initial knee flexion.

Studies showed that decreased relative strength simulated by exercise-induced muscular fatigue resulted in decreased knee flexion angle in a stop-jump task and the central nervous system has been suggested to store patterns that control motion and these patterns are learned with time and repetition. It was possible that after one-month detraining, subjects’ muscle strength may have decreased as well as awareness of adopting safe movement control patterns. Therefore, the decreased knee flexion angle caused by detraining could be due to the combination of decreased muscular strength and loss of optimal motor control patterns.

Changes in sagittal motor control patterns after detraining suggest the importance of preseason conditioning for athletes to recover both sport-specific performance and proper motor control strategies before they start a high level of competition. Asking athletes after detraining to be exposed to a scenario with high risk factors could increase their probability to suffer ACL injury.

The use of only volleyball players is a limitation to generalize the findings of this study. Future studies with a larger sample size and diversity of sports are needed to confirm the generalization of the results to other ACL high risk sports. One-month detraining duration was used due to the timing limitation of the winter season interval. Longer durations of detraining must be investigated to thoroughly understand the detraining effects on ACL risk factors. In addition, future studies with musculoskeletal models are needed to interpret the results of changes in kinematics after detraining.

In conclusion, one-month detraining significantly decreased jump height, initial and maximum knee flexion, and pre-landing BF EMG of collegiate female volleyball players.
The decreased BF muscle activation could be the cause of the decreased initial knee flexion angle which consequently resulted in a decreased maximum knee flexion angle. The decreased knee flexion angle indicates a possible increased strain on the ACL and thus an increased risk for ACL injury. Proper neuromuscular training programs should be implemented for highly trained volleyball players after detraining to recover their performance and motor control patterns for preventing ACL injuries.
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Thanks to my advisor, Dr. Jason Gillette, and my committee members, Dr. Tim Derrick and Dr. Gary Mirka. Your kind personalities and professional academics taught me how to use science to benefit the society and improve people’s life.

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You guys made me feel I was at home even though my real home was on the other side of earth.

Thanks to other professors and friends who helped me during these invaluable two years. It is an unforgettable experience in my life and I will always be a Cyclone.
APPENDIX A
EXTENDED RESULTS

Figure a. Knee adduction/abduction angle during stance phase.

Figure b. Knee adduction/abduction moment during stance phase.

Figure c. VM EMG during 100ms pre-landing.

Figure d. ST EMG during 100ms pre-landing.
Figure e. VL EMG during stance phase.  
Figure f. VM EMG during stance phase.  
Figure g. ST EMG during stance phase.  
Figure h. BF EMG during stance phase.
Title of Study: The Effects of Season Interval on Strength, Balance and Lower Extremity Biomechanics in a Stop-Jump Task in Collegiate Female Volleyball Players

Investigators: Boyi Dai, Jason C. Gillette, Timothy R. Derrick, Gary Mirka, Christopher J. Sorensen

This is a research study. Please take your time in deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION

The purpose of this study is to evaluate the effects of season interval on strength, balance and lower extremity biomechanics in a stop-jump task in collegiate female volleyball players. The goal of this study is to find if season interval could increase the potential risk factors of Anterior Cruciate Ligament injuries. You are being invited to participate in this study because you are a collegiate female volleyball player between 18 and 29 years old.

DESCRIPTION OF PROCEDURES

If you agree to participate in this study, you will participate in two strength, balance and stop-jump tests. One of the tests is before winter season interval and another one is after winter season interval. Each testing session will last about 1 hour and 30 minutes. During the study you may expect the following study procedures to be followed:
For the first test, you will be asked to come to the Biomechanics Laboratory. Questions about inclusion and exclusion criteria will be asked verbally by investigators. Questions will be asked as follow: Are you between 18 and 29 years old? Did you have a lower extremity injury that prevented participation in physical activity for >2 weeks over the previous 6 months? Do you possess any cardiovascular, respiratory, neurologic or other conditions that prevented you from participating at maximal effort in sporting activities? Have you ever suffered an ACL injury?

If you meet the criteria for this study, investigators will verbally explain the experiment and allow you ample opportunity to ask questions about the study.

Your age will be asked. Your height, weight and anthropometric measurements including thigh length, thigh circumference, calf length, calf circumference, ankle height, ankle width, foot length and foot breadth will be recorded. Your lower extremity strength including hamstring and quadriceps strength will be measured using hand-held dynamometry. A hand-held dynamometry is a strength scalar often used in physical clinic. Strength data will be collected when you exert power on one side of the dynamometry and investigators hold another side of the dynamometry. Three repetitions of the strength tests will be conducted for you.

Spherical markers will be placed on your shoulder, legs, and feet using double-sided adhesive discs. The location of these reflective markers will be recorded using an eight-camera video tracking system. You will be asked to conduct a series of balance tests in which you will stand upright on your dominant leg on the force platform with eye closed. Each trial will last for 20 seconds with knee of the contralateral limb will be flexed and held at about 90
degrees and not permitted to contact the support limb. Your arms will be folded in front of the chest. Three repetitions of the balance tests will be conducted for you.

After the balance test, pregelled surface electrodes will be placed on your skin over the muscle bellies of the hamstring muscle group which are the vastus lateralis, rectus femoris and vastus medialis oblique. Pregelled surface electrodes will also be placed over the muscle bellies of the quadriceps muscle group which are semimembranosus, biceps femoris and semitendinosus muscles. A ground electrode will be placed over the tibial tuberosity.

Pregelled surface electrodes are used to monitor the general picture of muscle activation. Surface electrode is a small device that is adhered to skin to simply record the muscle activity instead of giving muscle electric stimulation or involving input of amount of energy. A ground electrode is be used as a reference where is supposed to have no muscle activities. Pregelled surface electrodes means there will be gel on the electrodes to optimize the electrical conduction from the muscle to the electrodes. The quadriceps is a large muscle group on the front of the thigh. The hamstring is a large muscle group on the back of the thigh. The vastus lateralis muscle locates on the lateral part of the quadriceps. The rectus femoris muscle locates on the middle part of the quadriceps. The vastus medialis oblique muscle locates on the medial part of the quadriceps. The biceps femoris muscle locates on the lateral part of the quadriceps. The semitendinosus muscle locates on the middle part of the quadriceps. The semimembranosus muscle locates on the medial part of the quadriceps.

Basically, pregelled surface electrodes will be put on the lateral, middle and medial parts on the front and back of thigh of your dominant leg. Three trials of isometric maximum voluntary contractions will be performed for quadriceps and hamstring muscle groups.
Then you will be asked to conduct a series of stop-jump tasks. The stop-jump tasks will consist of a 3-step approach run followed by a 1-footed takeoff, a 2-footed landing with each foot on a separate force plate, and a 2-footed takeoff for maximum height. A jump height tester will put near the force platform and you will be asked to touch the tester as high as possible in order to simulate the spiking maneuver in volleyball. Three repetitions of stop-jump will be conducted for you.

During the season interval, you will be asked to record any injury that happens to you and any exercise you do. After the season interval, you will be asked to come to the Biomechanics Laboratory again to test your lower extremity strength, balance and lower extremity biomechanics in a stop-jump task with the same procedure used at baseline testing.

**RISKS**

While participating in this study, you may be exposed to several risks of injury. Minor discomfort or skin irritation may occur from the double-sided adhesive discs. As a precaution, the amount of time that the reflective markers are attached to your skin will be minimized as much as possible. Additionally, some muscle or joint discomfort may occur while performing the repetitive jumping or following participation. Ankle or knee injuries may happen in the stop-jump. Therefore, you will be given enough time to warm up and stretch. You can also try stop-jump for several times before the formal test. You may become fatigued while performing the repetitive jumping. Therefore, you will have at least one minute of rest between each drop vertical jump trial and will be asked if you require additional recovery time. There is a possibility of mechanical injury due to a fall, so there will be a spotter nearby to provide physical assistance if needed.
BENEFITS
If you decide to participate in this study there may be no direct benefit to you. It is hoped that the information gained in this study will benefit society by providing information on understanding if season interval is a contributing factor of Anterior Cruciate Ligament injuries. A general goal is to using the results of this study to develop a best combination of resistance training, balance training and flexibility training at different periods of the season to not only enhance athletes’ physical capability but also reduce the risks of Anterior Cruciate Ligament injury.

ALTERNATIVES TO PARTICIPATION
The only alternative is to not participate in this study.

COSTS AND COMPENSATION
You will not have any costs and will not be compensated for participating in this study.

PARTICIPANT RIGHTS
Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide to not participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled.

CONFIDENTIALITY
Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal
government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy your records for quality assurance and data analysis. These records may contain private information. To ensure confidentiality to the extent permitted by law, the following measures will be taken. The motion analysis is numerical and does not contain video that could identify the participant. Your data will be kept confidential by using alphanumeric identifiers that are unrelated to your name. Your name and information/data will be kept in separate secure locations. Your informed consent document will be kept in a locked file cabinet in Boyi Dai’s office in Forker Building. The research team will keep private all research records that identify you to the extent allowed by law. When the results of the study are reported, the combined information that has been gathered will be presented. If the results are published, your identity will remain confidential.

QUESTIONS OR PROBLEMS

You are encouraged to ask questions at any time during this study.

For further information about the study contact Boyi Dai at 515-441-2974 or Jason C. Gillette at 515-294-8310.

If you have any questions about the rights of research subjects or research-related injury, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office of Research Assurances, Iowa State University, Ames, Iowa 50011.

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PARTICIPANT SIGNATURE
Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant’s Name (printed) ________________________________

_________________________________________  __________________________

(Participant’s Signature)  (Date)

INVESTIGATOR STATEMENT

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

_________________________________________  __________________________

(Signature of Person Obtaining  (Date)

Informed Consent)