

Using Motion Sensor Technology to Manage Risk of Injury in a Strength and Conditioning Program for Female Collegiate Athletes

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ABSTRACT

Background of Study: Females generally have a 6-8 times higher risk for lower extremity injury compared to male counterparts due to biomechanical differences and/or poor landing strategies. In recent years, a great deal of focus has been placed on prevention and reduction of non-contact lower extremity injuries. This has spurred the development of assessment methods to determine how athletes move and tools with which those motions are measured. Efforts have been made to measure and quantify movement strategies, which have given rise to multiple movement tests and measurement devices. One approach is the use of wearable technologies used in conjunction with a movement screening. **Objective:** Demonstrate a practical approach of using wearable technologies to guide training regimens in a population of female athletes that would be considered at risk for lower extremity injuries. **Methods:** A cohort of Division I female volleyball athletes were screened using wearable technology then assigned an intervention based on screening results. Comparisons were made between injury rates during the season when the intervention was applied compared to previous seasons. **Results:** All lower extremity injury rates were reduced after the intervention was applied. **Conclusions:** The use of wearable technology aids in quantifying movement to then assign a strategic intervention to reduce injuries in an at risk athletic population.

Key words: Early Intervention, ACL Injuries, Knee Injuries, Female Athletes, Wearable Electronic Devices

INTRODUCTION

Non-contact lower extremity injuries have become common in athletic populations and account for 80% of all injuries (Andernord et al., 2015; K. Ford et al., 2015). Furthermore, sports that have higher incidence of dynamic loading have been shown to have a greater risk for injury (Ageberg & Roos, 2016; Andernord et al., 2015; K. Ford et al., 2015). Two of the most common knee injuries are anterior cruciate ligament (ACL) rupture and patellofemoral joint (PFJ) dysfunction. It is estimated that 350,000 reconstructions are performed annually in the USA (Andernord et al., 2015; K. Ford et al., 2015). Of those ACL reconstructions, 79% develop knee osteoarthritis and 20% sustained a re-injury of the ipsilateral or contralateral side (Ageberg & Roos, 2016; Andernord et al., 2015; K. Ford et al., 2015). Many of these injuries are non-contact indicating the mechanisms of injury may be modified. Females are at a higher risk for lower extremity injury due to many anatomic factors and biomechanical strategies used during the weight acceptance phase of dynamic tasks such as running, cutting and jumping. Due to the rising costs of injury management,

the ability to minimize injury has become an area of recent investigation. Despite the presence of numerous assessments, none have been shown to be a conclusive assessment of movement patterns for estimating injury predisposition in athletic populations. Many of the current assessments that are utilized are collected by human observation and given a numeric value based on the assessor's interpretation of the movement. Many of these movement assessments are not dynamic, and only assess motion that is static and controlled (Bushman et al., 2016; K. Ford et al., 2015). The purpose of this paper is to provide an overview of an evidence based practice to evaluate and quantify movement patterns of NCAA Division I female collegiate volleyball players using a dynamic motion assessment tool and prescribe exercise interventions to modify injury predictive movements.

Factors Affecting Non-contact Lower Extremity Injury

Biomechanical assessments have shown that as the knee accelerates into a valgus position, the tensile load on the ACL increases. Hyperextension, excessive valgus, and ab-

duction moments can further attribute to knee and ACL loading. For example, runners with decreased hip abductor and hip extensor strength exhibit greater hip and knee frontal plane and transverse plane motion (Ekstrom, Donatelli, & Carp, 2007). Furthermore, tensile load on the ACL is greatest when tibial torsion and knee extension occurs, which then increases both knee valgus and internal rotation (Ekstrom et al., 2007). Activation of the quadriceps without proper hamstring activation may also contribute to an increased tensile load in the ACL. Therefore, increased anterior translatory forces with abduction moments and valgus instability have all been shown to increase incidence of injury to the knee joint (Ekstrom et al., 2007). Improper valgus knee alignment combined with hip internal rotation during landing can cause damage to the patellofemoral joint, contribute to meniscal tears, and ruptures of the static restraints (Ekstrom et al., 2007).

There are several anatomic and non-modifiable factors that affect knee injuries such as a wider Quadriceps angle (Q-Angle) and a narrow femoral notch; however, surgical intervention is necessary to negate their influences. Strength, muscle activation, and control of the hip musculature play a critical role in controlling dynamic lower extremity valgus. It has been noted that the gluteus medius is the primary abductor of the hip and it receives assistance from the gluteus minimus and piriformis to control frontal plane motion. The gluteus maximus is the primary hip extensor and external rotator that controls the sagittal plane (K. R. Ford, Myer, & Hewett, 2010). With properly targeted exercise, frontal and sagittal plane motion for neuromuscular control can be modified. Muscular activation patterns can be improved to provide additional assistance for knee stability during dynamic tasks such as activating the gluteus maximus prior to weight acceptance to decrease knee valgus angles (Ageberg & Roos, 2016; Borotikar, Newcomer, Koppes, & McLean, 2008; Brazen, Todd, Ambegaonkar, Wunderlich, & Peterson, 2010; Decker, Torry, Wyland, Sterett, & Steadman, 2003; K. Ford et al., 2015). Patients who complain of patellofemoral pain have decreased hip abduction, external rotation, and knee extension strength when compared to controls (Ekstrom et al., 2007; Omi et al., 2018). Furthermore, the decreased ability to control eccentric hip internal rotation and adduction may lead to greater dynamic lower extremity valgus that is correlated with PFJ pain (Ekstrom et al., 2007; Omi et al., 2018).

Factors Affecting Female Athletes

Dynamic lower extremity valgus is defined as a combination of motions and rotations in the lower extremity to include hip adduction, hip internal rotation and knee abduction; this also includes tibial external rotation and anterior tibial translation combined with ankle eversion. In sports it represents a knock-kneed posture during load acceptance in double and single leg tasks. Knee abduction moments have been observed to be a significant predictor for future ACL injury risk with 73% sensitivity and 78% specificity for female athletes (Ekstrom et al., 2007; K. Ford et al., 2015). Frontal knee plane motion, along with hip internal and external rotation was found to have predictive validity for a second ACL ligament injury following a reconstruction and rehabilitation

(Ekstrom et al., 2007; K. Ford et al., 2015). Furthermore a recent investigation showed that high knee abduction moment combined with hip weakness and improper lower extremity biomechanics was predictive of both PFJ pain and ACL injury risk (Ekstrom et al., 2007).

Overall, female athletes have a much higher risk than male athletes for non-contact lower extremity injuries. In high school and college, females have a nine-fold and five-fold increased risk for knee injuries, respectively (Ekstrom et al., 2007). It has also been reported that females have higher incidence of pathology due to improper landing mechanics and hip girdle weakness (Ekstrom et al., 2007). High knee abduction moment was predictive of both PFJ pain and ACL injury risk in young female athletes (Ekstrom et al., 2007). Females have been shown to have increased dynamic lower extremity valgus and thus an increased risk for ACL injury and PFJ pathology (Ekstrom et al., 2007). During adolescence, females show no change in hip strength when compared to the male counterparts showing longitudinal increases in hip strength throughout during this time period. This weakness, in addition to joint morphology differences between sexes such as wider pelvis, increased Q angle, and a narrow femoral notch, may lead to altered landing mechanics and movement strategies during loading phases of movement.

By identifying the weak muscle group(s) and inefficient movement patterns that are produced by these deficiencies, poor movement strategies during weight acceptance can be prevented, thus reducing lower extremity injury or re-injury. Altered neuromuscular control strategies during landing may be a potential factor related to lower extremity and ACL injuries in female athletes. In a study of 315 participants, young females showed reduced knee flexion angles at initial contact and lower hip extension torques with landing than compared to males of a similar age (Ekstrom et al., 2007; K. Ford et al., 2015). It has been suggested that there are sex specific landing strategies during vertical jump drop testing. Decker et al. (Decker et al., 2003) showed a decrease in eccentric muscle action to absorb landing forces at the hip in females. Additionally, patients who had undergone ACL reconstruction had greater hip abduction moments during the stance phase of gait that may provide increased protection for the ACL (Decker et al., 2003). These mechanisms play a significant role in neuromuscular control strategies for controlling and compensating for knee loading (Decker et al., 2003).

Factors impacting knee stability include amount of frontal plane motion, fatigue with single limb performance, trunk stability, limb symmetry, and the degree of lateral displacement of the pelvis during squatting (Dingenen et al., 2016; K. Ford et al., 2015). Injury prevention programs should be geared towards prevention of these aberrations within complex athletic movement. Strong evidence supports the use of prevention programs to reduce risk by 52% for females and 85% in males (Ekstrom et al., 2007; K. Ford et al., 2015). In 2013, Hoskikawa et al. (Hoshikawa et al., 2013) observed a significant improvement in PFJ pain and dynamic alignment when programs incorporate strengthening and improving neuromuscular control of the hip and core musculature. Furthermore, these movement corrective exercises, when performed

with video feedback, have been shown to alter knee and hip biomechanics. ACL injuries have been shown to be preventable when one uses specific training variables as a part of the injury prevention program (K. Ford et al., 2015; K. R. Ford et al., 2010). These variables include early intervention, teaching proper biomechanics, compliance, dosage, feedback, and type of exercise (K. Ford et al., 2015). ACL injury incidence decreased to 44% when patient compliance was greater than 66%. This included patients performing the intervention several times per week and lasting 20-30 min in duration. Lastly, this program must be performed with either visual or verbal feedback during pre-season, in-season, and post season. This program should be made up of a variety of exercises to include plyometrics, neuromuscular reeducation, and strengthening (K. Ford et al., 2015).

By evaluating each of these items using sophisticated tools and methods, we can better understand which movement deficiencies may exist within a single athlete. Excessive frontal plane movement can increase the athlete's risk for lower extremity injury however, by controlling that movement via muscular stabilization, we can reduce that risk (Hewett et al., 2005). Fatigue has also been shown to correlate to changes in movement strategy with increased frontal plane movement (Nessler, Denney, & Sampley, 2017). Therefore, one must train an individual to anticipate motor changes within a fatigued state. Trunk and hip girdle stability, although often overlooked, can influence lower extremity valgus and how the athlete's center of mass is placed to transmit force through the lower extremity (Nessler et al., 2017). Hip girdle weakness, especially in the hip abductors, can alter coronal plane mechanics thus changing the angle with which the foot comes into contact with a surface (K. R. Ford et al., 2010). Weaknesses within the lower extremity cause changes in limb symmetry index (LSI), and there can be displacement of the center of mass causing an asymmetrical presentation. This LSI is readily observed with post-operative ACL patients during a double limb squat. This LSI is a percentile measurement comparing the limb symmetry of the affected side to the unaffected side. Asymmetries and weakness can cause a lateral pelvic displacement that affects the squatting motion (Nessler et al., 2017).

Squatting is essential for the development of lower extremity strength. Variations within weight distribution and lateral displacement during the squat results in an altered force distribution that can impact joint structures (Nessler et al., 2017). Single limb squatting can be used to evaluate knee and hip girdle eccentric control, single limb loading, and proprioceptive control. Hoshikawa et al. (Hoshikawa et al., 2013) showed a statistically significant increase in cross-sectional area of the trunk musculature by implementing an exercise program consisting of 5 exercises. Additionally, he was able to demonstrate an increase in hip extension peak torques during squatting and jumping following the intervention. In addition to injury prevention, improvement in strength via specific strengthening of the hip and trunk muscles may improve athletic performance. Trunk and hip muscle strength has been correlated to maximal power and accuracy in athletic performance (Ekstrom et al., 2007). Ekstrom and colleagues (Ekstrom et al.,

2007) displayed a significantly greater gluteus medius EMG activation with the side plank exercise. They were able to correlate increased EMG activation for the following: gluteus maximus and hamstrings using the quadruped arm and leg extension lift exercise, vastus medialis oblique with the lateral step up exercise, longissimus thoracis and multifidus using the unilateral bridge exercise and side bridging exercises, and external obliques and rectus abdominals using the side bridge and prone bridging exercises. Therefore, there are exercises that have been shown to elicit greater EMG activity in the hip and trunk muscles and should be used to increase strength within those muscle groups.

Using Inertial Measurement Units to Quantify Movement

In recent years, interest has grown around wearable sensor technology that quantifies movement. The use of inertial measurement units (IMU) have become a popular method to apply wearable technology into the screening process of athletes to quantify movement rather than using subjective scoring. One such system (ViPerform, Dorsa VI, USA) is a 3D motion sensor system that utilizes wearable sensors that contain a rotameter, inclinometer and a magnetometer. This system has been previously shown to be a reliable and valid tool in measuring knee valgus and varus movements as well as movements of the trunk (Charry, Umer, & Taylor, 2011; Hu, Charry, Umer, Ronchi, & Taylor, 2014). The system measures 3 planes of motion and relays information via a portable radiofrequency (RF) device to a computer program, and utilizes a software system to analyze the movement. The wearable sensors, software and sophisticated algorithms objectively measure movement and muscle activation at 200 Hz. The sensors then relay a RF signal to a computer that produces a graphic representation of the movement a participant is performing. Simultaneous video monitoring and recording occurs while the sensors quantify the movement while a trained practitioner is required to analyze. The software utilizes a movement assessment, The Athletic Movement Index[®] (AMI) quantifies motion across 7 movements (Table 1) and provides a total movement score. The 7 movements for the AMI include plank, side plank (bilaterally), squat, single leg (SL) squat, SL hop and SL hop for distance, and ankle lunge. Once the movements are performed the RF device sends the information to the computer to give a total score and athletes are given a score that can be rated a low, moderate, or high risk for lower extremity injury. Based on that category, they are assigned exercises depending on the skill level the program assigns.

METHODS

Participants and Design

As a component of the routine preseason physical examination, a cohort of ten Division I female volleyball athletes (height 178.05 ± 4.60 cm, body mass 77.51 ± 10.29 kg) took part in a baseline movement assessment using the inertial movement screening described above. Comparison were made between the previous year injury data and the year of the intervention.

Procedures

Prior to performing each assessment, athletes were outfitted with 3D wearable sensors (Dorsa VI). For the plank, side plank and squat, sensors were placed at T10 and L5/S1. During single limb tests, sensors were placed on the right and left mid tibia. The sensor placement was based on a template design per Dorsa Vi's specifications (Charry et al., 2011; Hu et al., 2014). Exercises were repeated during the evaluation process creating a total of 85 repetitions during one assessment session in order to mimic the fatigue that an athlete may feel towards the end of an athletic encounter (Table 1). At the conclusion of testing all athletes, the 3D data and video was reviewed with the team athletic trainer and strength coach. The trained evaluator that performed the evaluation then assigned each athlete to level I - level III of the ACL Play It Safe Program (Tables 2-4) based on a predetermined set of criteria for each level assignment. The ACL Play It Safe Program consists of 2 distinct routines - a pre-practice routine (performed as a warmup) and a post-practice routine (fatigue state training). The program was performed during the season with the pre-practice routine done prior to practice and the post practice routine being done at the conclusion of practice. The exercises were performed under the direction of the team strength coach and done at least three times per week. Each athlete performed these exercises throughout the season and compliance was tracked via the strength coaches' attendance log.

Statistical Analysis

Injury data was tracked through the athletic training electronic medical record over two consecutive academic years. Only those that were a part of the roster during both years were used in the analysis. Paired sample t-test were then used to compare injury rates from the previous year when no intervention was conducted to the year in which the evaluation and intervention was performed. All statistical analyses were performed in SPSS version 22 (IBM, Chicago, IL). Significance was set using an alpha level of $p < 0.05$.

RESULTS

During the course of the intervention, the cohort had a 100% compliance rate. After the intervention there was a 67% reduction in hip injuries, 37% reduction in knee injuries, a 50% reduction in lower leg injuries, and 67% reduction in thigh injuries as compared to the injury rates from the previous year. Though the number of injuries were reduced there were no statistically significant differences when comparing year to year.

DISCUSSION

Noted changes in movement strategy can be measured with a comprehensive dynamic movement assessment using IMU technology. If poor movement strategy predisposes individuals to injury, then positive changes to movement strategy will improve injury rates. This notion is supported in the literature with hip focused exercise routines in athletes. Previous evidence suggests that hip focused exercise can prevent knee injuries in collegiate basketball players (Hewett, Ford, Myer, Wanstrath, & Scheper, 2006; Nessler, 2013). In a study by Omi et al. (Omi et al., 2018) overall ACL injury incidence was reduced from 0.25/1000 to 0.1/1000 in an 8 year intervention by introducing a hip focused injury prevention training. This was a clinically and statistically significant reduction in injury rates (Nessler, 2013). If an athlete performs the exercises they are assigned based on their individual results, there is a high probability they will show improvement on the overall battery of tests. It can be inferred that when a dynamic movement assessment is paired with hip focused strengthening interventions, there can be an improvement in scores that may be responsible for a decrease in injury rates. This may also be due to the fact that the interventions focused on a single limb intensive training program. Previous research has shown that when single limb training is the focus, changes movement strategy can occur. Thus, the use of single limb training that was included in the ACL Play It Safe interventions may have contributed to the reduction in injuries seen within the cohort.

Injury prevention programs can be very useful in preventing lower extremity non-contact injuries that are re-

Table 1. AMI Viperform™ test exercise protocol

Ami viperform test movement	Duration	Sets and repetitions
Prone plank	60 second hold	1 set; 1 repetition
Double limb squat	1-2 second pause for data collection	1 set; 20 repetitions
Right Side plank	60 second hold	1 set; 1 repetition
Left side plank	60 second hold	1 set; 1 repetition
Right Single leg squat	1-2 second pause for data collection	1 set; 10 repetitions
Right single leg hop	1 second pause for data collection	1 set; 10 repetitions
Right single leg quadrant hop	1 second pause for data collection	1 set; 8 repetitions
Right side ankle lunge in ½ kneeling	10 second hold	1 set; 3 repetitions
Left Single leg squat	1-2 second pause for data collection	1 set; 10 repetitions
Left single leg hop	1 second pause for data collection	1 set; 10 repetitions
Left single leg quadrant hop	1 second pause for data collection	1 set; 8 repetitions
Left side ankle lunge in ½ kneeling	10 second hold	1 set; 3 repetitions

Table 2. Level 1 (high risk category) exercise interventions

Exercise	Sets and repetitions
Dynamic lunge stretching	2 sets x 10 yards
Dynamic Sumo squat stretching	2 sets x 10 yards
High Knee dynamic stretching	2 sets x 10 yards
Single leg hop exercise	2 sets x 10 repetitions
Single leg tossing a ball	2 sets x 10 repetitions
Single leg dead lift with band resistance	2 sets x 10 repetitions
Sidestepping with band resistance	2 sets x 10 yards
Plank on elbows	2 sets x 30 seconds
Left Side plank on elbows	2 sets x 30 seconds
Right Side plank on elbows	2 sets x 30 seconds

Table 3. Level 2 (moderate risk category) exercises interventions

Exercise	Sets and repetitions
Dynamic lunge stretching	2 sets x 10 yards
Dynamic Sumo squat stretching	2 sets x 10 yards
High Knee dynamic stretching	2 sets x 10 yards
Single leg hop exercise (anterior and posterior hops)	2 sets x 10 repetitions
Single leg tossing a ball (with partner on balance pad)	2 sets x 10 repetitions
Single leg dead lift with band resistance	2 sets x 10 repetitions
Sidestepping with band resistance	2 sets x 10 yards
Plank on elbows (on balance pad)	2 sets x 30 seconds
Left Side plank on elbows (on balance pad)	2 sets x 30 seconds
Right Side plank on elbows (on balance pad)	2 sets x 30 seconds

lated to poor mechanics and lower levels of strength. Such programs have been shown to be successful with specific guidelines. First, the program must be measurable with technology that gives precise quantifiable data that can be tracked over time. Second, the program should be hip focused and strengthen the motions of the hip as well as perform neuromuscular reeducation exercises to improve landing strategy. The programs must ensure good compliance and be followed for more than three years to demonstrate significant changes in a group. A single limb, postural and hip stabilization focused program must be used to address the deficiencies. These tests can be implemented pre and post season with the interventions performed throughout the season and as part of a comprehensive strengthening program. With these tests, measures, and interventions, there can be a positive change in movement scores, injury rates, and performance. There is a great deal more that can be investigated in the use of IMU technology and movement screening. Future investigations using technology as previously described in association with movement assessments with randomized clinical controlled trials would greatly add to the understanding in this area. Additionally, comparisons of a variety of movement

Table 4. Level 3 (low risk category) exercise interventions

Exercise	Sets and repetitions
Dynamic lunge stretching	2 sets x 10 yards
Dynamic Sumo squat stretching	2 sets x 10 yards
High Knee dynamic stretching	2 sets x 10 yards
Single leg hop exercise (forward/backward/medial/lateral)	2 sets x 10 repetitions
Single leg tossing a ball (with partner on unstable surface)	2 sets x 10 repetitions
Single leg dead lift with band resistance	2 sets x 10 repetitions
Sidestepping with band resistance	2 sets x 10 yards
Plank on elbows (on balance pad)	2 sets x 630 seconds
Left Side plank on elbows (on balance pad)	2 set x 60 seconds
Right Side plank on elbows (on balance pad)	2 sets x 60 seconds

assessments in their ability to provide greatest predictive validity for injury should be examined. Furthermore, wearable inertial measurement units can be a useful aid in quantifying the information, making it trackable for practitioners.

CONCLUSION

The main finding of the observational analysis were that an intervention guide by IMU technology was able to reduce the number of lower extremity injuries in a cohort of athletes that is typically considered at risk. The use of the IMU technology allows for a more precise measurement then subjective testing that have previously been used to categorize movement scores. This allows for a better understanding of which interventions would fit the needs of the individual athlete. This is important as practitioners and clinicians continue to try and identify methods to reduce the incidence of lower extremity injuries.

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