2011

ACL Injuries in Montgomery County, OH: Moving toward the Development of a Prediction Model

Kelly Estes
Wright State University - Main Campus

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Kelly Estes
MD-MPH Candidate
Wright State University Boonshoft School of Medicine

Acknowledgements

I would like to thank Dr. Sabrina Neeley for serving as my advisor and editor during the creation of this manuscript.

Special thanks to Dr. Tarun Goswami from Wright State University's Department of Engineering for his assistance with data interpretation and continued guidance with this research.

Finally, thanks to my husband, Josh, who has supported me through the five-year MD track.

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Abstract

Anterior cruciate ligament (ACL) tears are one of the most frequent soft tissue injuries of the knee. A torn ACL leaves the knee joint unstable and at risk for further damage to other soft tissues manifested as pain, dislocation, and osteoarthritis. A better understanding of the dimensional details of knee joints suffering ACL tears and a prediction model for individuals susceptible to tears is needed. Using a cross-sectional study design, magnetic resonance images (MRIs) of 72 patients with knee injuries were evaluated from an orthopedic surgery group practice. The status of the ACL was the main variable of interest, creating two groups of comparison, ACL tear and ACL non-tear joints. Epidemiological risk factors and digital measurements were compared in both groups leading to empirical data correlations. Positive smoking status and the length of the ACL in the sagittal plane were found to be significantly more likely in the ACL tear group. The modifiable variable, BMI and ACL measurements in the sagittal plane were used towards the development of a prediction model to establish the critical dimensions for non-tear and tear ACLs. The further development of this equation might allow for identification of individuals at high risk for ACL tear and direction of these individuals towards targeted ACL intervention programs.

Introduction

The anterior cruciate ligament (ACL) is a major stabilizer of the knee joint. The increasing prevalence of ACL tears in the past decade likely correlates with an increase in individuals participating in moderate physical activity (National Center for Chronic Disease Prevention & Health Promotion, 2009). Griffin et al. (2000) have estimated that there are 80,000-250,000 ACL injuries annually in the United States. The highest incidence occurs in the 15-25 year old age group and in those who play sports involving pivoting of the knee joint such as European football, basketball, European handball, and volleyball. A deficiency of the ACL either due to a contact mechanism or a non-contact collapse of the knee joint, will eventually lead to premature and disabling osteoarthritis.

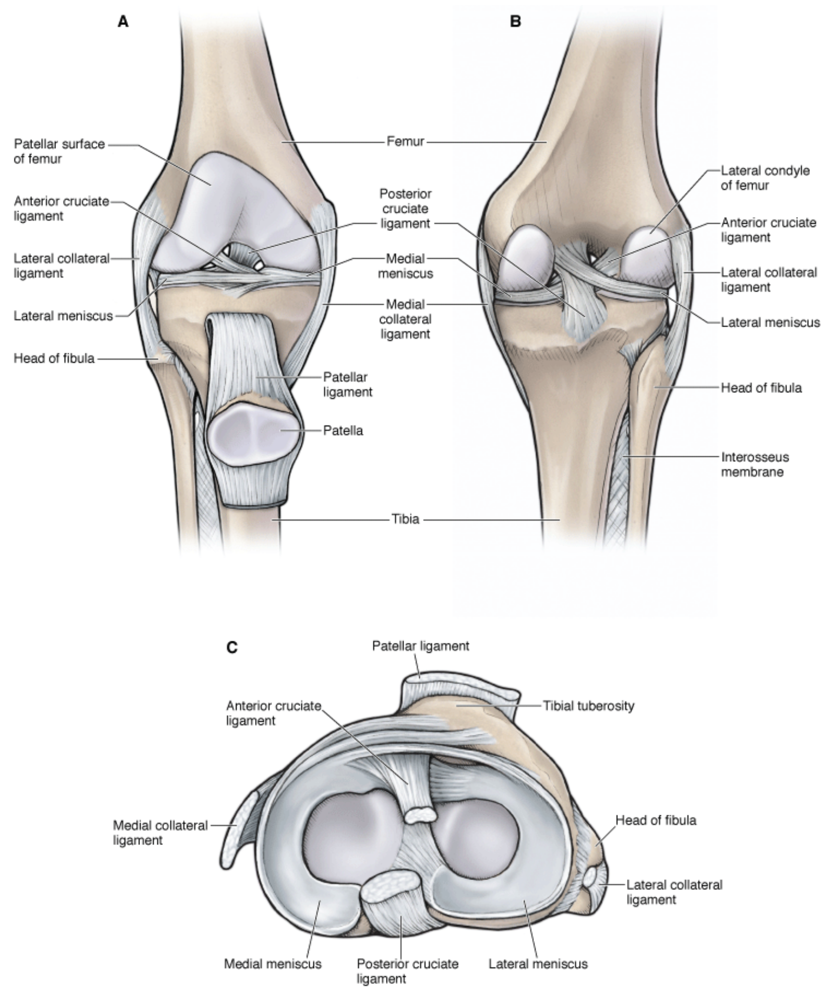
It has been estimated the financial burden of posttraumatic osteoarthritis in the United States is $3.06 billion dollars each year (Brown, Johnston, Saltzman, Marsh, & Buckwalter, 2006). The Centers for Disease Control (1996) estimates that 100,000 ACL reconstructions surgeries are performed each year. However, posttraumatic degenerative arthritis has been found to occur despite surgical ACL reconstruction (Daniel et al., 1994; Ferretti, Conteduca, De Carli, Fontana, & Mariani, 1991; Fithian et al., 2005; Lohmander, Ostenberg, Englund, & Roos, 2004; Myklebust & Bahr, 2005; von Porat, Roos, & Roos, 2004). When comparing radiographs of females aged 26-40 who sustained an ACL tear during adolescence with matched controls, there is a higher prevalence of radiographic osteoarthritis and reported functional limitations in those who have a history of an ACL tear (Lohmander et al., 2004). These women are likely to qualify for knee replacements at an early age, an effective treatment for knee osteoarthritis. However, patients receiving a knee replacement prior to age 65 have a 3-fold higher risk of needing a revision operation in their lifetime (Knutson, Lewold, Robertsson, & Lidgren, 1994). Surgery and the accompanying anesthesia are not without risks. This treatment also does not address the emotional, mental and economic costs of an ACL tear.

Previous research has attempted to better understand functional anatomy of the knee, biomechanics of ligament injury, mechanisms of ACL failure, the clinical course following an ACL tear, and the best method of treatment. Despite ongoing research in each of these areas, the complexity of identifying individuals at greatest risk for ACL tears and the best way to prevent an ACL tear are far from understood. Detection of individuals who are at higher risk for an ACL tear would result in less surgical intervention, less rehabilitation, and less decrease in productivity and time away from work, exercise and sport participation.

Literature Review

Anatomy of the ACL

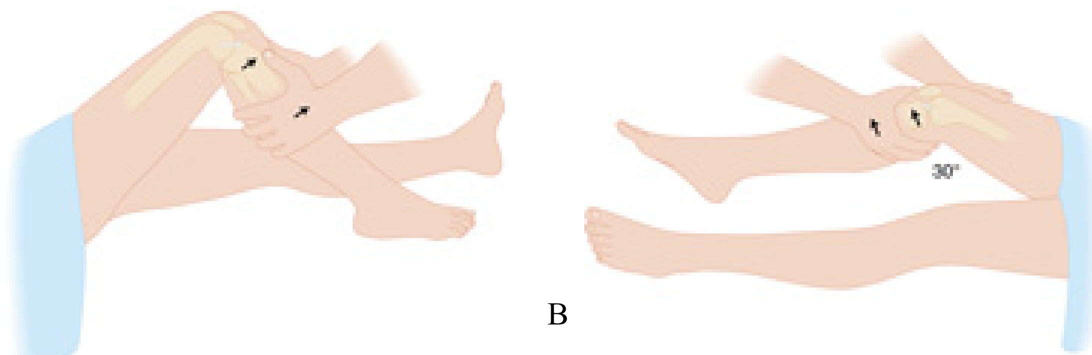
The knee complex is made of articulations between the femur and the tibia and the femur and the patella. These two joints allow for complex motion producing flexion, extension, and minimal rotation. The knee capsule is made up of several ligaments that form the outer support of the knee complex. The anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL) are the two ligaments within the knee capsule that create areas of laxity and strength to result in dynamic range of motion. The major ligaments and support structure of the knee are shown in Figure 1.



Source: Morton DA, Foreman KB, Albertine KH: *The Big Picture: Gross Anatomy:* www.accessmedicine.com

Figure 1. The knee complex. The ACL runs in a diagonal direction from the lateral femur to the medial tibia (Morton, D.A., Foreman, K.B., & Albertine, K.H., 2011). A. Anterior view of the right knee joint capsule with the patella reflected inferiorly. B. Posterior view of the knee joint. C. Superior view of the right knee joint.

The ACL can be divided into distinct functional bundles that represent the varying tension of the fibers through range of motion of the knee. The most widely accepted view is the classification of fibers into two bundles, anteromedial and posterolateral bundles (Girgis, Marshall, & Monajem, 1975; Palmer, 2007). The bundles are named based on their position of insertion into the tibia. The bundles have a clinical application as well as a functional significance. A positive anterior drawer sign (Figure 2a) is thought to more highly correspond to a torn anteromedial bundle, whereas a positive Lachman sign is thought to indicate a tear more likely in the posterolateral bundle (Figure 2b) (Furman, Marshall, & Girgis, 1976). Overall, the Lachman test has a higher sensitivity and specificity (sensitivity, 84–87%; specificity, 93%; positive LR = 12.4, negative LR = 0.14 as compared to the anterior drawer with sensitivity, 48%; specificity, 87%; positive LR = 3.7, negative LR = 0.6.) (Gonzales & Nadler, 2011). During extension of the knee, the posterolateral bundle is stretched and the anteromedial bundle is relaxed. The opposite occurs during flexion when the femoral attachment of the ACL moves into a horizontal position, resulting in stretch of the anteromedial bundle and relaxation of the posterolateral bundle (Amis & Dawkins, 1991).



A B

Figure 2. A. Anterior drawer sign. With the patient’s knee is flexed to 90°, the examiner pulls tibia in anterior direction. B. Lachman’s test. The patient’s knee is flexed to 30° and the examiner pulls the tibia in an anterior direction. Either test is considered positive if laxity is felt as compared to the contralateral knee.

The overall course of the ACL is to run in an anterior, medial, and distal direction from the femur to the tibia. The femoral ACL attachment lies at the posterior segment of the inner surface of the lateral femoral condyle (Arnoczky, 1983). The fibers fan out (Smith, Livesay, & Woo, 1993) as they cross the midline and attach in front of and lateral to the medial intercondylar tubercle (Arnoczky, 1983; Girgis et al., 1975). There may be some fibers of the ACL that blend and attach to the anterior and posterior horns of the lateral meniscus as well.

The ACL is covered in a synovial membrane, which makes the ACL an intra-articular structure. The average length of the ACL ranges from 22 mm to 41 mm, with a mean of 32 mm. The average width of the ACL ranges from 7 mm to 12 mm (Amis & Dawkins, 1991; Kennedy, Weinberg, & Wilson, 1974; Odensten & Gillquist, 1985). These measurements were all collected during studies using cadavers. More recently, digital measurements using magnetic resonance imaging (MRI) were evaluated for their accuracy (Cohen et al., 2009). Cohen et al. measured the two bundles of the ACL on sagittal and coronal planes of fifty MRIs. These values were then compared to a measurement taken during surgery on ten knees that had undergone both MRI and knee arthroscopy. The agreement between the MRI and intraoperative measurements indicates that MRI measurements of the ACL are clinically reliable (Cohen et al., 2009).

Biomechanics of the ACL

The ACL functions to limit the anterior translation and internal rotation of the tibia on the femur, and can also limit hyperextension and both valgus (inward) and varus (outward) stresses on the knee. There have been many methods of studying the mechanism of injury such as video analysis, interviews with injured subjects, cadaver studies, clinical studies, and mathematical modeling. The majority (70-84%) of injuries are non-contact in nature; no physical contact with equipment, other individuals, or any other type of object that may cause a direct blow has occurred (Alentorn-Geli et al., 2009). The typical mechanism of ACL injury occurs when internal rotation and abduction of the tibia occurs in the flexed position of the knee, often leading to a valgus or inward collapse (Olsen, Myklebust, Engebretsen, & Bahr, 2004). The most devastating force in this sequence is the anterior translation force when the knee is flexed around

20-30º (Boden, Dean, Feagin, & Garrett, 2000; Yu & Garrett, 2007). The noncontact mechanism taken into context with the young age of the average individual to suffer an ACL tear is atypical for ligamentous sports injuries and prompts further research into the mechanism of ACL tears.

Slauterbeck, Hickox, Beynnon, and Hardy (2006) constructed a model (Figure 3) to describe the relationship between risk factors and the pathway to ACL injury. This model predicts that all factors will eventually affect the mechanical load placed on the ACL or the magnitude of the ACL load at failure. The model in Figure 3 places the risk factors in a hierarchy with sex hormones as the underlying cause. This common root serves as one possible explanation for the higher incidence of ACL injury in females.

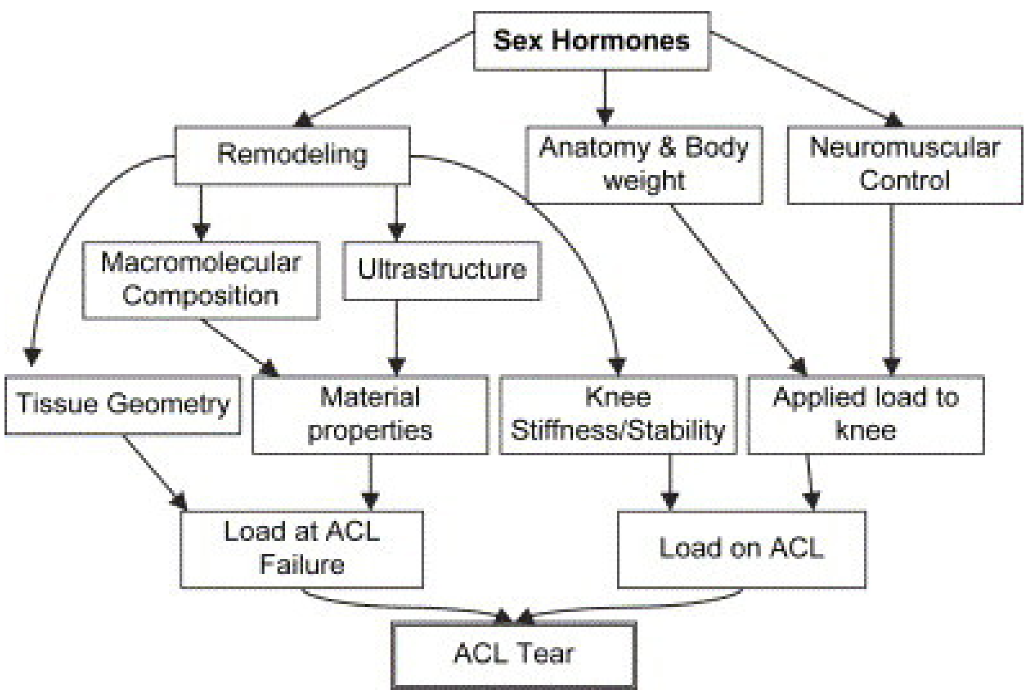


Figure 3. Model describing factors affecting ACL injury (Slauterbeck, Hickox, Beynnon, & Hardy, 2006).

Risk Factors for ACL Injury

Female athletes have a 3-5 times higher risk of ACL injury than their male counterparts, hypothesized to be due to a variety of reasons. Extrinsic factors have been suggested, such as weather, training, coaching, surface, footwear, and technique (Gwinn, Wilckens, McDevitt, Ross, & Kao, 2000; Shelbourne, Davis, & Klootwyk, 1998). Intrinsic factors have also been studied such as ligament laxity (Nicholas, 1970; Uhorchak et al., 2003), hormone differences (Ruedl et al., 2009; Wojtys, Huston, Boynton, Spindler, & Lindenfeld, 2002), and anthropometric variations (Arendt & Dick, 1995). Ruedl et al. (2009) hypothesized use of oral contraceptives as a potential protective factor in ACL injury. However, after surveying recreational skiers with a non-contact ACL injury compared to age-matched controls, use of oral contraceptives did not show a protective effect (Ruedl et al., 2009).

Gender variations of the femoral notch morphometry have been studied as one possible explanation for an increased rate of ACL tears in females. Multiple studies have correlated intercondylar notch stenosis, or narrowing, with ACL injury (Anderson, Lipscomb, Liudahl, & Addlestone, 1987; LaPrade & Burnett, 1994; Shelbourne et al., 1998; Souryal, Moore, & Evans, 1988; Souryal & Freeman, 1993), however gender alone has not been consistently correlated with femoral notch stenosis. Several studies have proposed that a smaller, biomechanically weaker ACL may be found in a smaller notch (Anderson, Dome, Gautam, Awh, & Rennirt, 2001; Charlton, St. John, Ciccotti, Harrison, & Schweitzer, 2002; Davis, Shelbourne, & Klootwyk, 1999; Muneta, Takakuda, & Yamamoto, 1997; Souryal et al., 1988). The correlation between notch width and ACL size is controversial. Davis, Shelbourne, and Klootwyk (1999) found a positive correlation, suggesting that a narrow ACL width represents a weaker, more susceptible ACL. However, other studies have found that the size of the notch did not correlate with the size of the ACL (Anderson et al., 2001; Muneta et al., 1997).

Souryal et al. (1988) used plain radiographs to calculate notch width index (NWI) based on a measured ratio of femoral notch width to femoral bicondylar width (see Figure 5 and the methods section for a description of NWI calculation). Patients in this study who had sustained bilateral ACL injuries had a statistically smaller NWI than did patients without ACL injuries. Further studies have confirmed this relationship (LaPrade & Burnett, 1994; Souryal & Freeman, 1993).

Most studies have shown that there is a difference in NWI between males and females (Shelbourne, Facibene, & Hunt, 1997; Shelbourne et al., 1998; Souryal & Freeman, 1993). Few studies have shown that gender does not correlate with NWI (LaPrade & Burnett, 1994). Chandrashekar, Slauterbeck, and Hashemi (2009) found that female cadavers had smaller ACLs in length, cross-sectional area, volume, and mass when compared to male cadavers. When comparing the microanatomy, females had lower fibril concentration and lower percent area of collagen fibrils than men (Chandrashekar, Slauterbeck, & Hashemi, 2009). The most reasonable explanation for the increased risk of ACL tears in a small notch is impingement of the ACL on the roof of the notch during tibial external rotation and abduction (Dienst et al., 2007; Park, Wilson, & Zhang, 2008).

The data on the relationship between BMI and ACL injury is inconsistent. Two studies have found that an increased BMI poses an increased risk for ACL injury (Brown, Yu, Kirkendall, & Garrett, 2005; Uhorchak et al., 2003), while two have found no relationship (Knapik et al., 2001; Ostenberg & Roos, 2000).

Smoking has not been studied as a risk factor for ACL tears. Previous studies have shown the effects of smoking on the musculoskeletal system, specifically in relation to wound healing, bone metabolism, pain tolerance, and postoperative infection (Adams, Keating, & Court-Brown, 2001; Hoogendoorn, Simmermacher, Schellekens, & van der Werken, 2002; Kinsella, Rassekh, Wassmuth, Hokanson, & Calhoun, 1999; Kwiatkowski, Hanley, & Ramp, 1996; Towler, 2000).

However, the role of smoking in the incidence of injuries is seldom considered. Lincoln, Smith, Amoroso, and Bell (2003) found a relationship between smoking and long-term disability among persons with meniscal injuries. These authors suggested the poor vascular supply of the menisci in combination with the biological effects of smoking lead to an impaired inflammatory and reparative response.

ACL injury has been defined according to a model of risk mechanisms. This model describes ACL injury as the end result of the combination of a predisposed athlete (internal risk factors) in a situation of higher risk (external risk factors) during an event in which the ACL cannot withstand the applied load (Bahr & Krosshaug, 2005). The model highlights the role of both qualitative (history of previous injury, skill level, etc.) and quantitative (body weight, intercondylar notch width, etc.). The basic model from Bahr and Krosshaug (2005) was expanded to describe the interplay of risk factors involved in ACL injury during the Hunt Valley II meeting, a gathering of experts in the area of ACL injury research. This updated model, shown in Figure 4, was based on a combination of an epidemiologic model (Meeuwisse, 1994) and a biomechanical model (McIntosh, 2005). Internal risk factors, such as age, gender, health status, anatomy, and skill level establish a baseline risk level leading to a predisposed athlete. This can be considered the first layer of risk in the injury causation model.

The predisposed athlete then becomes exposed to external risk factors such as coaching technique, protective equipment used in their sport, and environmental conditions. This defines the second layer of risk, resulting in a susceptible athlete. The final step leading to injury is the occurrence of an inciting event. This could be the particular playing situation, the behavior of those playing the sport, the player biomechanics, or a combination of these events that directly lead to ACL injury.

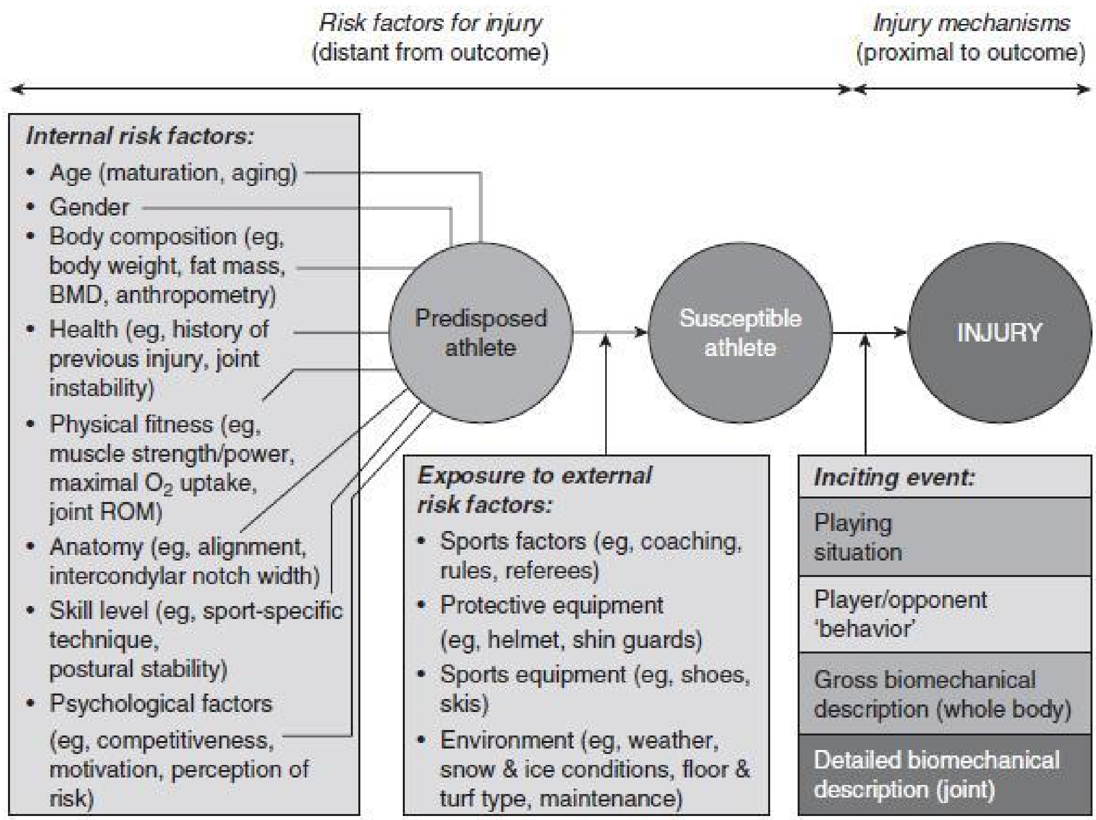


Figure 4. Injury causation model for ACL injury (Griffin et al., 2006).

Prevention Strategies

It is important to investigate the relative contribution of less modifiable factors, however prevention and treatment should focus on the modifiable areas of ACL injury. Currently, there is no method available to accurately and practically screen athletes at increased risk for an ACL tear. Screening at the level of the coach, athletic trainer, or team physician with a simple, objective test administered as part of the preparticipation exam would target a large population of high-risk athletes susceptible to knee injury.

ACL tear prevention programs have been shown to decrease the rate of knee injuries (Gilchrist et al., 2008; Heidt, Sweeterman, Carlonas, Traub, & Tekulve, 2000; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Wedderkopp, Kaltoft, Holm, & Froberg, 2003). Internal risk factors such as body composition, physical fitness, and psychological factors and external factors such as coaching, sports equipment, and environment are all possible targets for prevention. The most successful programs involve some combination of stretching, strengthening, aerobic conditioning, agility training, plyometrics, and risk awareness skills. It is not known by which mechanism such prevention programs are effective, however post-program data has shown improvements in balance, strength, and coordination (Griffin et al., 2006). The prevention programs have promising results, however more rigorous studies of their effect need to be undertaken. Few studies have been randomized, controlled, or have sufficient populations sizes to really come to a powerful conclusion about their results. Most programs only test female athletes, compliance is rarely reported, and age is seldom factored into the results. Further information is needed about the appropriate age to start a program, the length of time and intensity that is required to be effective, not only to reduce the risk of ACL tears, but also to reduce risk factors for ACL tears.

There are no studies to date that have attempted to develop a method of predicting ACL injuries based on anatomical measurements in combination with demographic variables**.** A better understanding of the anatomical and demographic susceptibility factors for ACL tears is needed. The ability to identify individuals who are at higher risk for ACL tears would help to better understand the mechanism of injury and target populations who would benefit from an ACL tear prevention program.

The purpose of this study was to use the multiplanar imaging and soft tissue visualization strengths of MRI to measure dimensions of the knee joint. The measurements were analyzed to determine whether significant relationships exist between demographic variables, width and length of the ACL, NWI, and ACL injury. The trends identified were then used towards the development of a prediction model for ACL injury. The following hypotheses were tested:

(1) the NWI would be smaller for females as compared to males,

(2) increased body mass index (BMI) would be an increased risk factor for ACL injury,

(3) a relationship between modifiable risk factors and ACL measurements would be able to describe individuals who are at greater risk for ACL injury.

Materials and Methods

After receiving approval from the Miami Valley Hospital and Wright State University institutional review board, the 2006-2009 surgery records were retrospectively reviewed for knee procedures taking place at Miami Valley Hospital of two full-time orthopedists. Patients having knee procedures who received an MRI during their diagnostic workup qualified for the study. A cross-sectional study design was used with ACL status as the main variable of interest. All MRI scans were performed on a 1.5 Tesla General Electric (Milwaukee, Wis.) Signa MRI scanner. T1-weighted images in 4mm-thick cuts were evaluated based on the integrity of the image.

MRI measurements were digitally obtained using IDX Imagecast iPACS Viewer developed by IDX Systems Corporation by placing the cursor at the appropriate position and tracing the length of the object being measured. The femoral condyle width and the notch width measurements were taken in the same T1 coronal cut, which together form the NWI (Figure 5). This method was reproduced as described by Domzalski, Grzelak, and Gabos (2010). The sagittal ACL measurements of width and length were taken in the cut in which the full length of the ACL was in view (Figure 6). This value was extrapolated in the MRIs containing an ACL tear or partial tear. The sagittal ACL width was measured at the midpoint. The coronal ACL width was measured in the slice in which the ACL crossed the posterior cruciate ligament (PCL), in which the ACL midsubstance could best be visualized (Figure 7). The Notch Width Index (NWI) was calculated using the following formula:

Notch Width Index (NWI) = femoral notch width /femoral condyle width (**Equation 1**)

Data was statistically analyzed using Chi-square tests and one-way ANOVA. A p-value less than 0.05 was considered statistically significant.

Figure 5. Sample MRI showing how NWI is calculated. First, femoral condyle width (dashed line), was drawn at the level of the insertion of the popliteus in the lateral condyle of the femur, parallel to the joint line, formed by the distal femur condyles. Then, on the same line, femoral notch width (solid line), was drawn based on the most interior margins of the femoral condyles. NWI was then calculated using Equation 1.

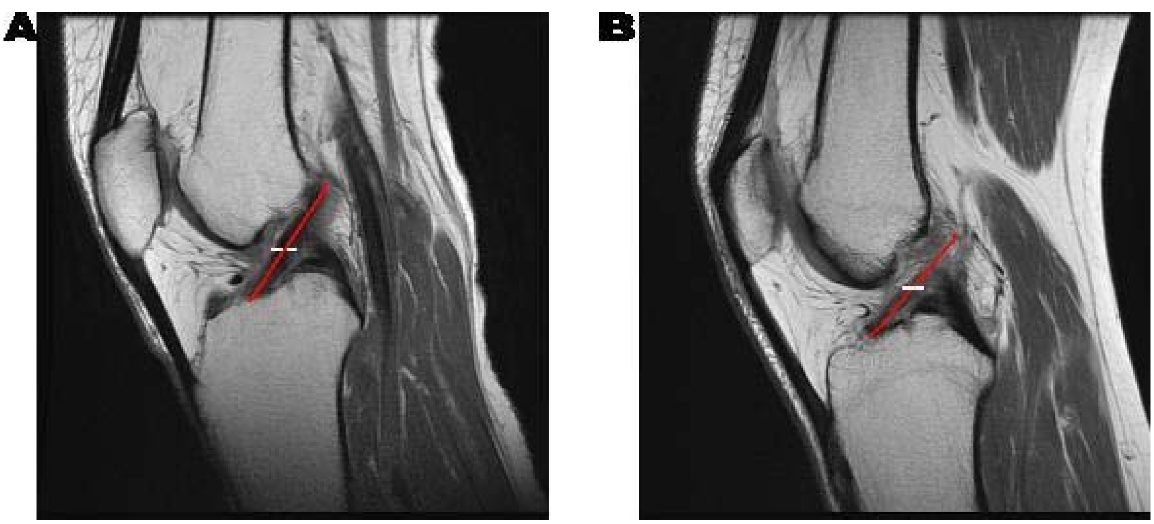


Figure 6. Measurement of sagittal ACL width (white line), taken at the midsubstance, and measurement of sagittal ACL length (red line) from femoral to tibial attachment sites. Sample from non-tear in panel A and sample from tear group in panel B.

Figure 7. Measurement of frontal ACL width in non-tear (A) and tear (B) groups.

Remaining calculations were made using population data (Greater Dayton Area Hospital Association, 2011) based on number of emergency room visits to Miami Valley Hospital in 2009. Because this data was only available for 2009, the 2009 data was multiplied by four to provide an estimate over the four-year period in which this data was obtained. Data were statistically analyzed using Chi-square tests and one-way ANOVAs. A p-value less than 0.05 was considered statistically significant.

The cumulative years of life lived with disability (YLDs) were calculated rather than the more commonly used, disability-adjusted life years, because of the simplicity of the former calculation. YLD was calculated using the formula YLD = I x DW x L, where I is the number of incident cases, DW is the disability weight in the range 0-1, and L is the average duration of disability (measured in years).

Results

The demographic information is presented in Table 1. The mean age of the tear population was 29±11 years old (range 12-59) and for the non-tear group the mean age was 35±15 (range 12-76). This difference in age between the tear and non-tear groups was statistically significant. There were no statistically significant differences (α=0.05) between tear and non-tear groups for gender, side of injury, mechanism, or BMI. A cutoff of 25 was used to separate the BMI between those of normal weight (BMI < 25) and those who are overweight and obese (BMI ≥ 25). There were 14 (44%) smokers and 16 (50%) non-smokers in the tear group and 7 (18%) smokers and 32 (80%) non-smokers in the non-tear group. There was a statistically significant difference in smoking status between those in the tear group and those in the non-tear group (p = 0.010).

Table I. Demographics of tear and non-tear groups.

Demographic		**Tear (%)**	**Non-tear (%)**	**Test Variable**	**P Value**
Total number of cases		32	40		
Gender	Male	21	28	Chi = 0.157	0.801
	Female	11	12		
Side	Right	15	22	Chi = 0.640	0.479
	Left	17	17		
Age	Average (years)	29	35	T = -2.082	0.041*
	Range (years)	12-59	12-76		
Smoking	Yes	14	7	Chi = 6.605	0.010*
	Unknown	2	1		
Mechanism	Contact	12	9	Chi = 2.761	0.100
	Noncontact	14	26		
	Unknown	6	5		
BMI	< 25	8	11	Chi = 0.164	0.692
	Unknown	10	10		

BMI – Body Mass Index (wt in kg/ ht in m^2)
*Statistically significant

The incidence of knee injuries was then calculated using the value of 117,612 emergency room visits to Miami Valley Hospital in 2009. This was extrapolated to estimate the four-year visit total of 470,448. Given the total of 72 MRIs that were done in this group of patients, this makes the incidence rate of knee injury at Miami Valley hospital 15 per 100,000 each year. This is higher than the overall rate of 0.8-2.5 per 100,000 for the United States (Griffin et al., 2000).

The cumulative YLD was calculated for the study group (n=32) alone using the formula YLD = I x DW x L. The number of cases, I was 32. According to the World Health Organization, the disability weight (DW), for knee osteoarthritis is 0.129 (World Health Organization, 2004). The Average duration of disability (L) was calculated to be 51 after subtracting the average age of ACL injury in the tear group, 29, from the average life expectancy of females in the United States, 80 (National Center for Chronic Disease Prevention & Health Promotion, 2009). It was found that in this population 210 cumulative years were lost to disability as a result of an ACL tear. This correlates to 6.57 years of life lived with disability per person.

MRI measurements were compared between torn and non-torn individuals, males and females, and those of normal weight (BMI < 25) and those who were overweight and obese (BMI > 25) (see Table 2). The length of the ACL in the sagittal plane was significantly different between torn and non-torn (p = 0.033), as well as, between males and females (p = 0.000). The NWI was also significantly different between torn and non-torn individuals (p = 0.028).

Table 2. Average measurement values in mm comparing torn and non-torn ACL groups, males and females, and those of normal weight and those overweight.

	ACL Status		**P Value**	**Gender**		**P Value**	**BMI**		**P Value**
	Torn	Non-torn		Female	Male		<25	≥ 25	
APW	6.91	7.05	0.752	6.82	7.07	0.603	7.29	6.92	0.535
SW	7.08	6.58	0.341	6.77	6.81	0.946	6.38	6.98	0.409
SL	36.99	39.73	0.033*	34.98	40.17	0.000*	37.53	39.33	0.238
NWI	0.25	0.27	0.028*	0.27	0.26	0.252	0.26	0.27	0.418

APW=ACL width in anterior-posterior slice, SW=ACL width in sagittal slice, SL=ACL length in sagittal slice, NWI=notch width index
*Statistically significant (α=0.05)

The MRI measurements were analyzed to identify possible relationships between measurements and tear status of the ACL. Demographic variables from the population and MRI measurements were compared in order to identify trends. BMI was compared to sagittal ACL length/width in the non-tear (Figure 9A) and tear (Figure 9B) groups. In both groups, the BMI peaked with the ACL measurements, suggesting that BMI is a function of the sagittal length/width ratio.

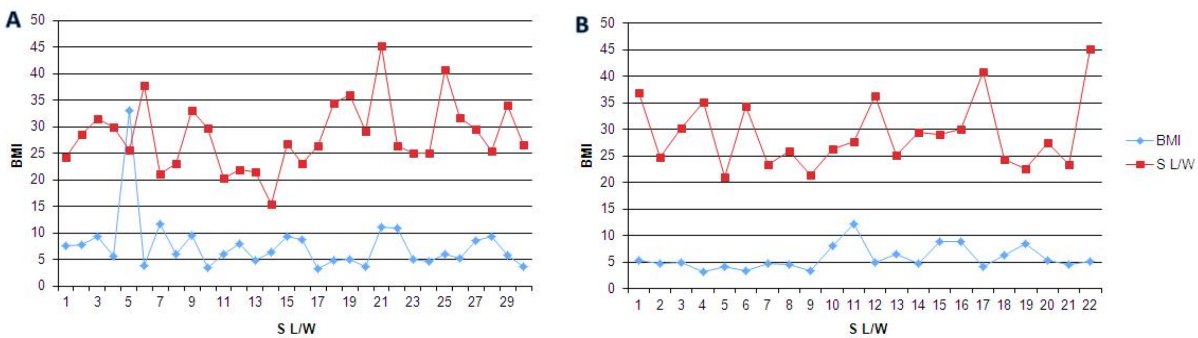


Figure 9. A- BMI plotted against sagittal ACL length/width in the non-tear group. **B**- BMI plotted against sagittal ACL length/width in the tear group.

The MRI measurement, sagittal ACL length/width, was compared to a ratio of BMI normalized by sagittal ACL length/width in the non-tear (Figure 10A) and tear (Figure 10B) groups. Both non-tear (A) and tear (B) groups in Figure 10 show the data scatter which can be fit with a power law equation. An attempt was made to develop a prediction model for each case. The prediction models establish critical ACL dimensions for a particular BMI. The prediction models produced R^2 value greater than 76%.

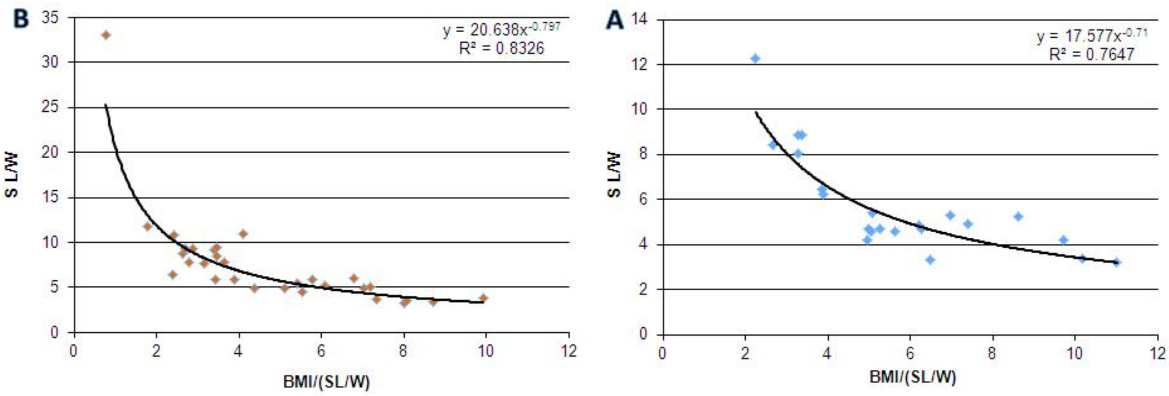


Figure 10. A- Sagittal length/width plotted against BMI/(sagittal ACL length/width) in the non-tear group. **B**- Sagittal length/width plotted against BMI/(sagittal ACL length/width) in the tear group.

Discussion

The increasing rate of physical activity and sports injuries around the world has prompted investigation into the factors that increase an individual's susceptibility to injury. This study confirms the relationship between the size of the ACL and dimensions of the intercondylar notch using MRI measurements, previously described by Dienst et al. (2007).

The first hypothesis predicted the NWI to be smaller in females as compared to males. There was no statistical difference in NWI between males and females overall; however, the NWI was found to be statistically smaller between the tear and non-tear groups. Although the ACL width measurements were not significant between tear and non-tear groups, the length of the ACL in the sagittal plane was statistically smaller between tear and non-tear groups. The length of the ACL measured in the sagittal plane was also found to be statistically significant between males and females overall, despite ACL status. Although previous work measured smaller ACL length, volume, and cross-sectional area in female cadavers (Chandrashekar et al., 2009) the length of the ACL has not previously been investigated as a risk factor for ACL tears.

The NWI was found to be significantly different between tear and non-tear groups, which confirms previous studies that have found a relationship between a smaller notch and ACL tears (Anderson et al., 1987; LaPrade & Burnett, 1994; Shelbourne et al., 1998; Souryal et al., 1988; Souryal & Freeman, 1993). These findings suggest a shorter ACL may play a role in ACL injury and may predispose female athletes to a higher rate of ACL injury. The underlying mechanism may be related to a lower collagen fibril concentration and lower percent area of collagen fibrils in women compared to men. Further research is needed to describe this theory as an explanation for the gender difference in ACL tear rates.

In this population, the ACL width was similar in the sagittal and frontal plane, comparable to other results about which plane measures a wider ACL (Harner et al., 1995; Odensten & Gillquist, 1985). There was not a statistically significant difference in BMI between the tear and non-tear groups, disproving the second hypothesis of this study. However, when comparing BMI with the size of the ACL, the shape of the BMI line was found to peak and trough with the ACL sagittal length/width ratio line in both ACL torn and non-torn MRIs This finding suggests that BMI is a function of the ACL sagittal length/width measurement.

The third and final hypothesis predicted a relationship between modifiable risk factors and ACL measurements. An ACL risk prediction model has yet to be developed to identify individuals at high risk of ACL injury. We compared BMI and ACL measurements in the sagittal plane in tear and non-tear groups to describe individuals who are at greater risk for ACL injury. The following relationships could be described.

Tear Group: $L/W = 17.58\,[BMI/(L/W)]^{-0.71}$ $R^2 = 0.7647$ **(Equation 2)**

Non-tear Group: $L/W = 20.64\,[BMI/(L/W)]^{-0.8}$ $R^2 = 0.8326$ **(Equation 3)**

These equations may be manipulated to generate critical derivations involving ACL dimensions for a particular BMI or vice versa.

$L = [17.58\ (BMI)^{-0.71}\ (W)^{0.29}]^{(1/1.71)}$ (**Equation 4**)

$L = [20.64\ (BMI)^{-0.8}\ (W)^{0.2}]^{(1/1.8)}$ (**Equation 5**)

$(BMI)^{-0.71} = 0.056\ (L/W)^{0.29}$ (**Equation 6**)

Where L equals the length of the ACL in the sagittal plane and W equals the width of the ACL in the sagittal plane. Equations 2 and 3 are an example of how a modifiable variable could be used to determine the critical dimensions for torn or non-torn ACLs based on BMI data. Derivations can be made from each equation for individual cases, such as to determine the critical length or width of the ACL in the sagittal plane.

These equations have the potential for important public health implications. The anatomical features of the notch and the dimensions of the ACL are not readily modifiable, however BMI is a modifiable variable. This means that an individual's ACL length and width could be measured or estimated with a clinical correlate and a desired BMI would be produced using the prediction model equation. The calculated BMI corresponds to the maximum target value for the individual to maintain in order to decrease risk of ACL injury. In addition to preventing primary ACL injury, this prediction model could be used to prevent a second ACL tear. After female athletes tear their ACL and undergo surgical reconstruction, they have a 1 in 4 risk of tearing their ACL again (Paterno et al., 2010). The prediction model could be used by physical therapists to identify a target BMI for athletes based on the dimensions of the ACL. Future directions involve analyzing other risk factors for ACL injury in a similar fashion, perhaps to develop a multivariate model. Such a prediction model could be used to counsel individuals regarding their risk for an ACL injury.

An unexpected finding in the population currently studied was a significant difference between smoking status between tear and non-tear groups, with smokers being more likely to suffer an ACL tear. Despite the studies of the effects of smoking on the musculoskeletal system, the association between smoking and the incidence of ACL tears has not been studied. The increase in ACL tears in patients who are smokers provides a teaching point for providers educating athletes on smoking cessation. This trend does not necessarily mean that cigarette smoking is a risk factor for an ACL tear. Perhaps the role of cigarette smoking in delayed healing caused more individuals with ACL tears to seek medical evaluation. The role of cigarette smoking in ACL injury should be investigated in a more rigorous study before specific recommendations and conclusions can be drawn.

The 1,694 YDL calculated for the ACL tear population describes the number of healthy years that are lost due to an ACL tear. This is especially meaningful considering that osteoarthritis has been shown to occur in individuals despite having had surgical reconstruction (Daniel et al., 1994; Ferretti et al., 1991; Fithian et al., 2005; Lohmander et al., 2004; Myklebust & Bahr, 2005; von Porat et al., 2004). A focus on prevention of ACL tears is the best method to prevent lifelong disability in a young and active population.

Preventing ACL Injury

A primary goal of health care is to prevent disease before it occurs and to identify risk factors early enough to provide intervention prior to injury. Ideally, such screening tests should be inexpensive and easy to administer. At this time, there is no evidence-based screening test to prevent ACL tears. There is a systematic method for designing the approach to prevent a sports injury known as the "sequence of prevention" (van Mechelen, Hlobil, & Kemper, 1992). The sequence involves identifying and describing the sports injury, outlining the mechanisms which play a part in the occurrence of the injury, introducing measures to reduce the future risk or severity of the injury, and finally evaluating the measure in the intended population. The ACL tear has been thoroughly studied and this research has been summarized above, satisfying the first two steps of the sequence. However, there has yet to be a validated laboratory or clinical screening tool to screen for ACL tears.

Common screening tests used today are blood pressure for heart disease, blood glucose for diabetes, and mammogram for breast cancer. These tests have been evaluated based on their sensitivity, specificity, ability to decrease disease burden, and cost-effectiveness. There are four endpoints to be considered when assessing the potential gain from a screening test (Martin, 2008). These endpoints can be applied to develop a screening test for athletes at risk for ACL injury.

First, the number of subjects who need to be screened in order to alter the outcome in one individual needs to be determined. For example, in the case of blood pressure, it is estimated that 18 males older than 60 would need to be screened with sphygmomanometry and then pharmacologically treated to prevent one cardiovascular event (Staessen et al., 2000). Second, further research needs to be done to evaluate the absolute and relative impact of screening on disease outcome. This calculation would determine the number of athletes who would be spared from surgical intervention, psychological stress, or disabling osteoarthritis if they were screened over a determined time period. Third, the cost per year of life saved needs to be calculated. Screening tests that cost less than 30,000-50,000 per year of life saved are considered “cost-effective” (Mark & Wong, 2011). Lastly, the screening technique is typically found to be useful if the average life expectancy for the population is increased. However, in this situation it is more appropriate to consider the number of years lived with disability (YLD). In order for the screening test to be clinically useful, it must not only extend life, but should extend a productive life in which the individual can be considered an active member of society. These statistics are best calculated from a rigorous meta-analysis compiling many ACL trials, which is not currently available in the literature.

The results of this study contribute to the growing field of the biomechanics of ACL injury. A prevention model could be developed to identify individuals who are at high-risk for ACL injury based on anatomical measurements and modifiable demographic variables. These individuals could then be referred to participate in an ACL tear prevention program to target specific risk factors for knee injury. MRI is not the ideal tool for screening, mostly due to high cost and a lengthy logistical process. If the trends identified here can be validated in a more robust study, perhaps there is a clinical correlation that could serve as a marker to identify these risk factors that were discovered on MRI. For example, using a surface anatomy measurement to represent the sagittal ACL length that was found to be significantly shorter in length in individuals with an ACL tear.

Limitations

The cumulative incidence rate (15 per 100,000 each year) underestimates the number of knee injuries that occur in the Dayton area. Considering the method in which MRIs were obtained, only those patients who presented to the emergency department or their primary care physician, and were then referred to an orthopedic surgeon to receive an MRI are represented in this sample. This study only involved one physician group in the area; therefore perhaps this value should be considered a cumulative incidence rate of knee injuries for this orthopedic practice.

Years of life lived with disability calculation is limited because members of the non-tear group were suffering a knee injury. This calculation was meant to describe those suffering from an ACL tear.

The cross-sectional design of this study has its own inherent limitations. The conclusions made based on the data gathered show an association between variables. The causality of events cannot be determined using this study design. The chart review method questions the reliability of the variables such as BMI, which is frequently based on a patient's own estimation of their weight.

Finally, the measurement of the intact ACL on MRI can be technically difficult and the torn ACL even more so. The torn ACL can disrupt the dimensions of the knee complex, leaving a measurement of the boney attachment sites on the femur and tibia a poor representation of the intact ACL. A more reliable method of the "torn" ACL measurement would be to MRI the contralateral knee of an individual who has suffered an ACL injury. This is one potential future direction for further investigation of the trends identified here.

Conclusion

This MRI study suggests that smoking and a shorter ACL length may play a role as risk factors for ACL tears. Trends in the digital measurements have shown a relationship between the size of the intercondylar notch and the width and length of the ACL in the sagittal plane. BMI was found to be a function of the width and length of the ACL in the sagittal plane. The development of a prediction equation involving the relationship between width and length of the ACL in the sagittal plane and BMI was suggested. A prediction model of this type could serve as the foundation for the critical dimensions for non-torn and torn ACLs. The trends identified here could lead to a more practical method of identifying individuals at high risk for an ACL tear. If demographic data in combination with digital measurements taken from MRI could predict ACL injury, it may be possible to take similar measurements of human surface anatomy as a more practical method of predicting injury. This might allow the identification of individuals at high risk for ACL tears and serve as a referral point for targeted interventions to prevent ACL injury.

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Appendix I

Public Health Competencies

1. Analytic/Assessment Skills
    a. Defines a problem
    b. Determines appropriate uses and limitations of both quantitative and qualitative data
    c. Identifies relevant and appropriate data and information sources
    d. Applies data collection processes, information technology applications, and computer systems storage/retrieval strategies
    e. Recognizes how the data illuminates ethical, political, scientific, economic, and overall public health issues

2. Policy Development/Program Planning Skills
    a. Collects, summarizes, and interprets information relevant to an issue

3. Communication Skills
    a. Communicates effectively both in writing and orally, or in other ways
    b. Advocates for public health programs and resources
    c. Effectively presents accurate demographic, statistical, programmatic, and scientific information for professional and lay audiences

4. Community Dimensions of Practice Skills
    a. Collaborates with community partners to promote the health of the population

5. Basic Public Health Sciences Skills
    a. Identifies the individual's and organization's responsibilities within the context of the Essential Public Health Services and core functions
    b. Defines, assesses, and understands the health status of populations, determinants of health and illness, factors contributing to health promotion and disease prevention, and factors influencing the use of health services
    c. Identifies and applies basic research methods used in public health
    d. Applies the basic public health sciences including behavioral and social sciences, biostatistics, epidemiology, environmental public health, and prevention of chronic and infectious diseases and injuries
    e. Identifies and retrieves current relevant scientific evidence
    f. Identifies the limitations of research and the importance of observations and interrelationship