COMPARISON OF LOWER BODY SEGMENT ALIGNMENT OF ELITE LEVEL HOCKEY PLAYERS TO AGE-MATCHED NON-HOCKEY PLAYERS

By

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COMPARISON OF LOWER BODY SEGMENT ALIGNMENT OF ELITE LEVEL HOCKEY PLAYERS TO AGE-MATCHED NON-HOCKEY PLAYERS.

A CAPSTONE PROJECT

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By

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Abstract

Lower body overuse and insidious onset injuries are thought to have an underlying biomechanical component which may be predisposing to injury. The purpose of this study was to compare lower body biomechanical characteristics for elite hockey players to matched controls. I hypothesize that elite hockey players have a greater degree of anterior pelvic tilt, greater varus knee angle, a higher foot arch and feet held in parallel more during gait than a matched non-skating population. Measures were taken of elite level, college aged, male hockey players and compared to cross country runners (ten subjects in each group) who served as controls for trunk angle, pelvic tilt angle, knee alignment, (varus/valgus angle), foot angle, arch index (arch height), hip, center of range of motion, hip external rotation, hip internal rotation, hip total range of motion (ROM), knee transverse plane ROM, and step width. The results obtained support the hypothesis for anterior pelvic tilt and foot angle during gait. Although knee angle was in the expected varus direction it was not significant and no differences were observed in the foot arch between the groups. All other measurements not directly related to the hypothesis were not significantly different with the exception of mean step width. The obtained results are important as recent literature describes a lower body posture of medial collapse into "dynamic valgus" as being predisposing to injury. Results show, on the spectrum from lower body varus to lower body valgus, hockey players are on the varus side of the spectrum in all attributes except arch height, which was similar in both populations. Since lower body alignment is thought to be coupled, this inconsistency appears contrary to the "medial collapse into dynamic valgus" model and may explain why foot orthotics and athletic shoes used as an injury intervention often fail.

Introduction

This manuscript represents an original biomechanical investigation done as a Masters of Arts capstone project. This project compares select biomechanical attributes between two populations of athletes, i.e., ice hockey players and cross-country runners, with the intent to gain a better understanding of some of the underlying biomechanical elements that may be involved in athletic overuse and insidious onset injuries, and in the process gain experience with a selection of measuring techniques.

Lower extremity overuse or insidious onset injuries (without a clear mechanism) represent a significant portion of injuries experienced with participation in sports and athletics [1-4]. The elements of lower extremity (body) posture include the lumbar spine, pelvis, hips, knees, ankles and feet, all linked in a kinetic chain. Through coupled motion, each element both influences and is influenced by the other elements in the chain of joint coupling [5]. Particular lower body postures during athletic participation may serve as a predisposing or a protective factor in the development of lower body overuse or insidious onset injuries [6].

Exploring the differences between populations of athletes has proven to be a useful tool in identifying the contribution to injury by differences in body postures as illustrated by the following two examples.

First, with the rise of athletic opportunities for women in organized sports the differences in injury epidemiology between men and women is apparent. According to National Collegiate Athletic Association injury surveillance data, women soccer players are twice as likely to sustain a knee anterior cruciate ligament tear than men in any given year [7]. Hewett *et al.*, put these figures much higher for female athletes, stating a "four- to six-fold higher incidence of knee injury over male athletes participating in the same sports" [8]. Much has been learned

about the factors involved in non-traumatic knee anterior cruciate ligament tears by studying the prevalent biomechanical difference between men and women including body posture [6, 8].

Second, studies done on major league pitchers have shown a shift in shoulder range of motion (ROM) in their pitching arm with regard to internal and external rotation ROM. The shoulder of the pitching arm gains external rotation with a corresponding loss of internal rotation compared to a normal rotation seen in non-pitchers. The arc of motion, the total of external rotation and internal rotation remains normal. Internal rotation is lost as external rotation is gained. The ROM shift is only demonstrated on the pitching arm side. The non-pitching arm demonstrates normal ROM. Pitchers who have a pronounced shift favoring external rotation in their throwing arm have a lower rate and severity of shoulder injury from throwing, showing this shift to be protective [9, 10]. Thus, differences in biomechanical characteristics arising from gender differences or specialization can have detrimental or protective effects.

Of the previously mentioned overuse or insidious onset lower extremity injuries patellofemoral pain (PFP) is a term used to refer to a number of medical conditions that cause pain around the front of the knee. These conditions include anterior knee pain syndrome, patellofemoral malalignment, and chondromalacia patella. These conditions may be the result of irritation of the soft tissues around the front of the knee [11-13].

PFP is one of the most common lower extremity conditions seen by clinicians in orthopedic practice [1, 12]. While patellofemoral problems are evident in a wide range of people, PFP is particularly prevalent in younger persons who are physically active. Based on the data of Taunton et al, approximately 2.5 million runners will be diagnosed with PFP in a given year [1, 12]. PFP also is a significant problem in the military, as it has been reported that 37% of recruits develop symptoms while participating in basic training [12]. Females are reported to be at higher risk for the development of PFP than their male counterparts [12]. The problem of PFP is

highlighted by the fact that 70% to 90% of individuals with this condition have recurrent or chronic pain [12].

While interventions for PFP show positive short-term outcomes, long-term outcomes are less positive. Eighty percent of individuals who completed a rehabilitation program for PFP still reported pain, and 74% had reduced their physical activity at a 5-year follow-up [12]. The lack of long-term success in treating this condition may be due to the fact that the underlying factors that contribute to the development of PFP are not being addressed [12].

The present study looks at factors that may underlie the development of lower extremity overuse injuries like PFP. The next section describes basic concepts that underlie the biomechanical features of the human body, with special emphasis on forces placed on the hip, knee, and ankle.

The coupling of motion of body segments mentioned above is an idea put forward in the literature [5, 14]. Coupling occurs primarily as two types: coupled linear motion and coupled angular motion. Linear motion occurs in a single plane, acting on a joint causing it to behave like a hinge, the body segments that share the joint are coupled at the joint. Coupling of angular motion involves rotation where segments sharing a joint causing each to rotate the other through shared ligamentous and muscular attachments.

With respect to linear motion, the joint angle formed at the hip shares a segment with the joints above in the trunk or spine and also shares a segment (femur) with the joint angle formed at the knee below. In this way a joint is couple with the joint above and the joint below. Linear motion occurs in the sagittal and frontal planes (Fig. 1).

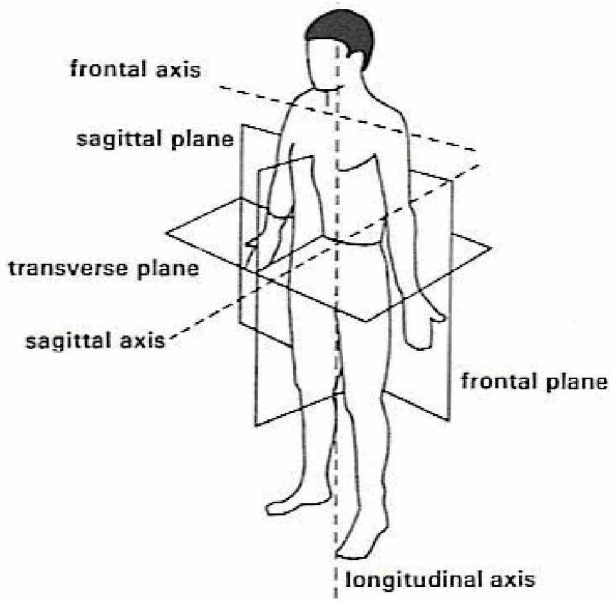


Figure 1. Cardinal planes and axes of body motion.

(from: http://bicarlsen.files.wordpress.com/2013/05/body-axes.png. Accessed May 18, 2015)

To understand the forces experienced by each joint during an activity with respect to linear motion, the interaction of the coupled joints and the ground reaction force vector can be calculated for simplified system (Fig. 2)[15]. The exertion of force on the body by the ground reaction force is seen as external and the body's exertion of force against the ground reaction force is seen as internal. These forces can be quantified as a force (F) x distance (r) = □□□□□ □□of rotation or torque (τ)□□□□□□3D)[15]. In single leg stance, where F is the ground reaction force (GRF) the vector that travels from the center of pressure at the foot toward the center of mass of the body, and r is the perpendicular distance between the GRF vector and the center of the joint [15]. The resulting force τ is torque experienced at the joint exerted by the GRF, an external force, which must then be countered by an internal force. As illustrated in Fig.3 the torque at each joint is affected by how they are aligned with respect to the GRF vector. Joints closer to the GRF vector experience less externally exerted force than those further away and the body needs to generate less internal force to counter the external force thus lowering the sum of overall force experienced by the joint and its components.

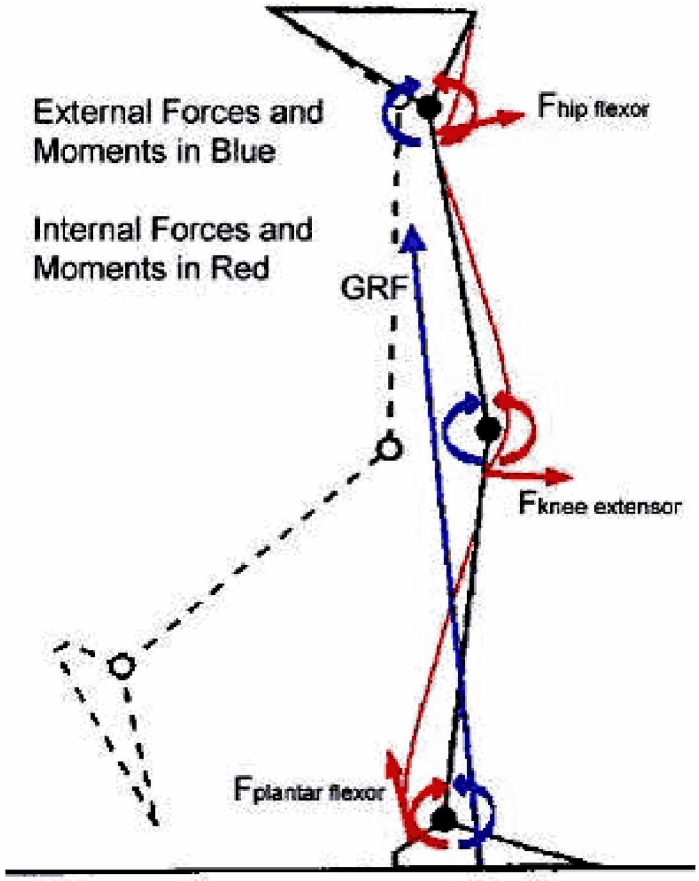


Figure 2. As in Figure 3 to follow, torque is a measure of turning force on an object such as a hip, knee or ankle joint. The torque at each joint is affected by how they are aligned with respect to the ground reaction force (GRF) vector. Torque experienced by the joint exerted by the GRF vector is calculated by the magnitude of the GRF vector multiplied by the perpendicular distance from the GRF vector to the joint or force (F) x distance (r) = torque (τ). The body needs to generate internal force (red) to counter the external torque (blue).

(from: http://www.oandp.org/olc/lessons/html/200606-14/images/Section3_plantarflexor.gif. Accessed May 18. 2015)

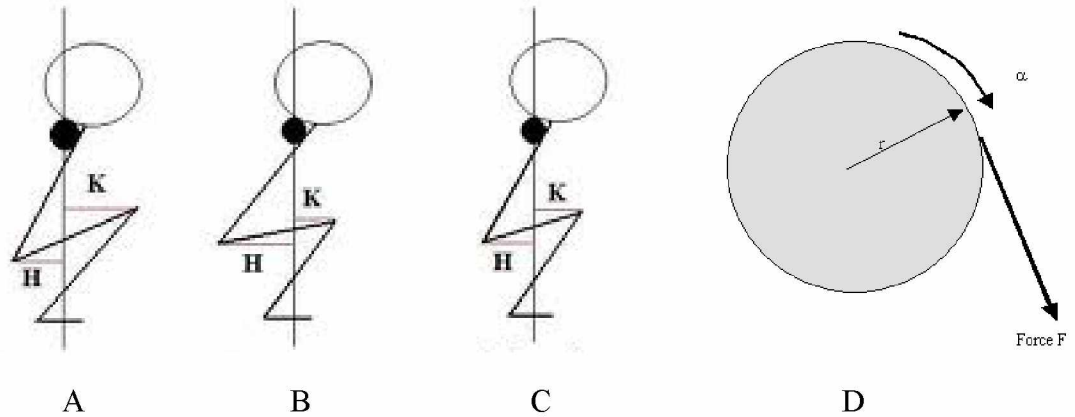


Figure 3. Torque is a measure of turning force on an object such as a hip or knee joint. The torque at each joint is affected by how they are aligned with respect to the ground reaction force (GRF) vector. D - Torque experienced by the joint exerted by the GRF vector is calculated by the magnitude of the GRF vector multiplied by the perpendicular distance from the GRF vector to the joint, force (f) x distance (r) = torque (τ). Joints closer to the GRF vector experience less torque than those further away; therefore, the body needs to generate less internal force to counter the torque, lowering the sum of overall forced experienced by the joint and its components. A, B and C, which symbolize a person doing a squat lifting exercise with a weight bar across the top of the shoulders. Feet are planted on the floor. The vertical line represents the GRF vector. In A the hips are closer to the GRF vector than the knees therefore, the knees experience the greater torque. In B the knees are closer to the GRF vector than the hips; therefore, the hips experience the greater torque. In C the hips and knee are equal distance from the GRF vector so they experience equal torque.

Right Fig. 3D (http://www.antonineeducation.co.uk/Image_library/Physics_5_Options/Applied_Physics/App_01 /Pulley_1.gif. Accessed April 13, 2015; left: Fig. 3A, 3B, 3C (http://tonygentilcore.com. Accessed April 10, 2015).

Coupling of linear motion is much simpler conceptually than coupling of angular motion, which will now be described. In the transverse plane coupled motion occurs with rotation of the segments on each side of the joints with each segment forming the axis of rotation. For illustrative purposes transverse plane rotation shares some similarity with the U-joints in an automotive drive train, which allows free linear movement of the engine/transmission, drive shaft and axle in some planes but only allows coupled rotation around the central axis (Fig. 4). Similarly, free linear motion is allowed in the frontal and sagittal planes of the lower body but in the transverse plane motion is restrained to some degree as coupled rotation. Rotation in the transverse plane occurs around a perpendicular vertical axis (Fig. 1) in which the longitudinal axis of the trunk, thighs and lower legs are these perpendicular axes (Fig. 5).

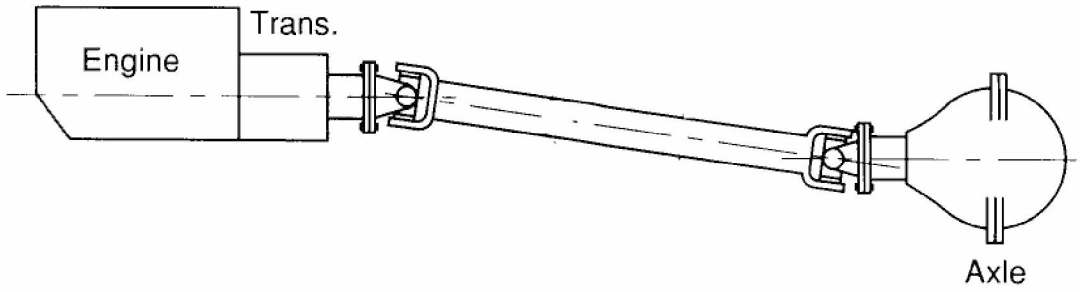


Figure 4. Automotive driveline and U-joint schematic. This system allows the engine/transmission, drive shaft and axle to move independently. Central rotational motion, coupled by the U-joints is preserved as the independent elements of the drive train movement.

(adapted from: http://www.4xshaft.com/driveline101.asp. Accessed May 18, 2015)

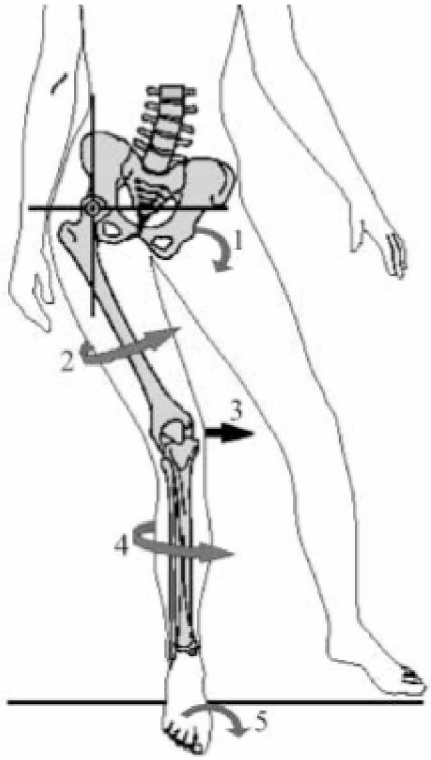


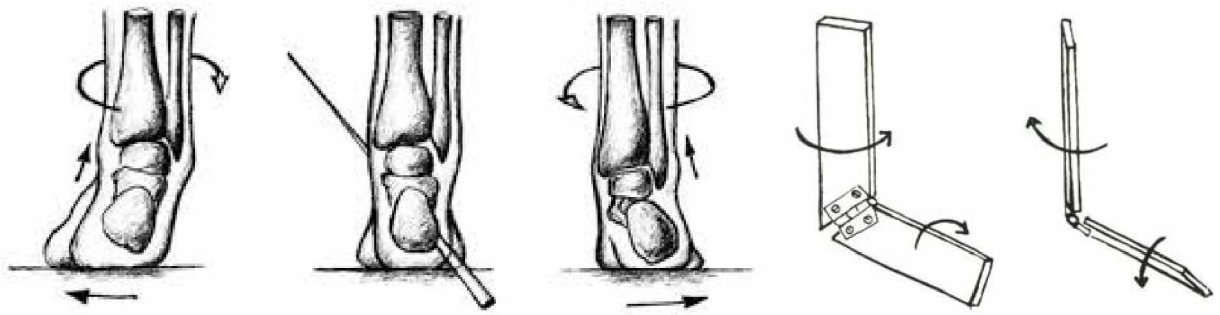
Figure 5. Dynamic valgus (labeled as arrow 3) occurs at the knee and is allowed by the coupled motion of internal rotation around the long axis of the thigh (labeled as arrow 2) and lower extremity above the ankle and foot (labeled as arrow 4). This motion is coupled with the tri-planer motion of pronation and supination at the ankle and foot (labeled as arrow 5). Dynamic valgus is thought to have an element of pelvic drop in the frontal plane (labeled as arrow 1). This process is called "medial collapse into dynamic valgus."

(adapted from: Powers, J Orthop Sports Phys Ther 33 (11):639-46)

Angular motion about the ankle is more complex still and involves changes to foot arch height and foot angle. With respect to linear motion, the ankle moves in the sagittal plane as a hinge joint into dorsiflexion and plantar flexion (Fig 6). However, with respect to rotation, transverse plane motion about a vertical axis above the ankle and foot is converted to and from tri-planer motion around an oblique axis by the joints of the mid and hind foot to become pronation and supination at the foot [16]. Internal rotation above the foot and ankle, at the foot becomes foot pronation, lowering the arch of the foot and increasing foot angle. Conversely, external rotation above the foot and ankle becomes supination at the foot, raising the arch of the foot (Fig. 7) [16]. Raising and lowering the arch of the foot without corresponding rotation of the tibia results in changes in the foot angle, the angle at which the foot projects anteriorly in the transverse plane. Raising the arch without tibial external rotation projects a smaller "foot angle" that is more parallel with midline. Whereas, a flattening of the arch without tibial internal rotation projects a larger "foot angle" that is more outwardly turned away from the midline (Fig. 8)[16].

Figure 6. Motion at the ankle foot complex can be described with four terms: plantarflexion were the foot moves in the plantar direction or dorsiflexion were the foot moves dorsally. Pronation and supination are the other two terms that describe ankle motion and are illustrated and described in Figure 7.

(http://upload.wikimedia.org/wikipedia/commons/thumb/4/4a/Dorsiplantar.jpg/419px-Dorsiplantar.jpg. Accessed May 18, 2015)



A B C D

Figure 7. Transverse plane rotation of the leg above the ankle is converted to tri-planer rotation around an oblique axis in the ankle and foot to become supination (high arch) and pronation (low arch) in the foot. Notice the tibia is on the right side of the foot making this an illustration of the right ankle and foot. B – a neutral ankle and foot posture. The rod represents the oblique axis about which rotation above the ankle is converted to supination and pronation in the foot. A – a supinated foot with external rotation above the ankle. C – a pronated foot with internal rotation above the ankle. D- a hinge on an oblique axis between two strips of wood is often used to illustrate the oblique axis that converts rotation of the lower leg to supination and pronation at the foot by the foot ankle complex.

(7A, 7B, 7C from: www.ptonthenet.com/images/articles/3877_Image3.jpg. Accessed May 18, 2015. 7D from: http://podo3000.eu/francais/travaux/l'equilibration%20par%20le%20pied.htm. Accessed May 18, 2015).

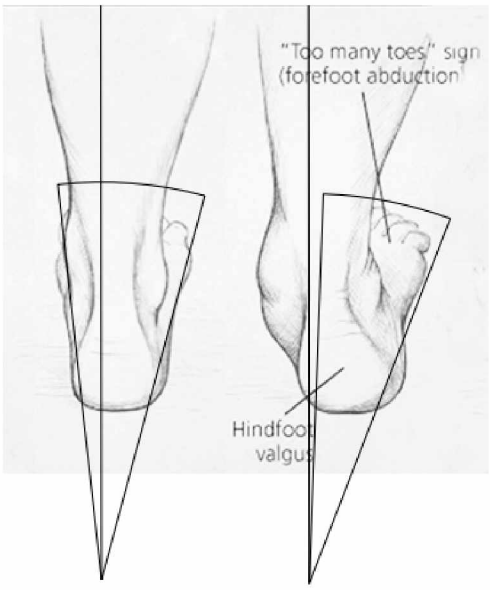


Figure 8. As the arch flattens, the hind foot or rear foot abducts into a valgus alignment and the forefoot moves lateral increasing the foot angle. Clinically, this is know as "too many toes sign."

(adapted from http://2.bp.blogspot.com/7MH67ruDBbE/UHRXFtxrDwI/AAAAAAAA AFU/-dNIhlhXn2v0/s1600/pttd3.jpg. Accessed April 19, 2015)

Motion about the knee has some complexity as well. The knee joint is considered a hinge joint, which at a gross level only allows flexion and extension occurring in the sagittal plane (Fig. 9). Knee alignment, knee varus or knee valgus, occurs in the frontal plane (Fig. 1) and varies within the population. Knee alignment is classified as neutral when the centerline of the thigh and the lower leg form a straight line when viewed in the frontal plane (Fig. 10B). Knee alignment is classified as valgus when this line forms an angle opening away from midline (Fig. 10C) and varus when this line forms and angle opening toward midline (Fig. 10A). As a hinge joint, the knee articulates in the sagittal plane (Fig. 1) and is not designed to articulate in the frontal plane into varus and valgus. However, the introduction of rotation of the thigh and tibia can dynamically change knee alignment when viewed in the frontal plane. Internal rotation of the thigh and tibia results in a "dynamic valgus" alignment of the knee (Fig. 11) [14]. Dynamic valgus alignment rotates the femoral patellar notch medially from neutral alignment causing the patella to ride lateral in the notch predisposing the knee to PFP (Fig. 11). Dynamic valgus also predisposes the knee to a non-traumatic anterior cruciate ligament injury [8, 14].

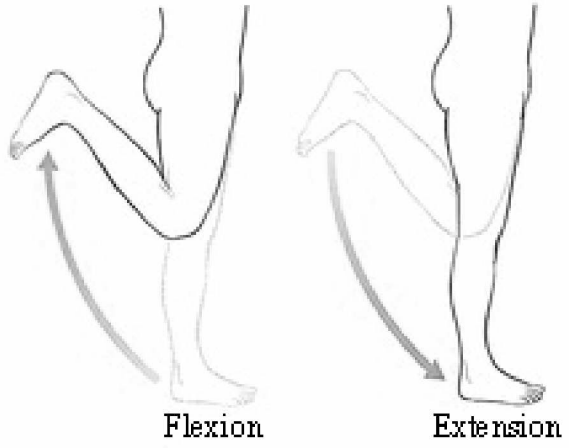


Figure 9. The knee is a hinge joint. Motion about the knee is generally described and flexion and extension. Some rotation of tibia on femur also occurs.

(http://o.quizlet.com/i/HFDijbidwaam732vJm3BkA_m.jpg. Accessed May 18, 2015)

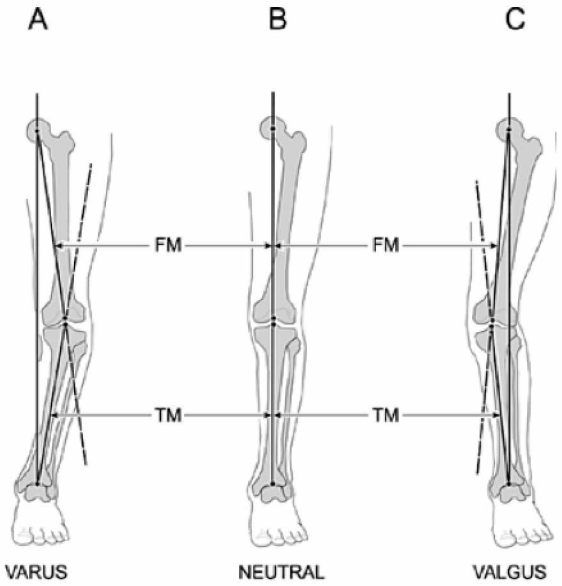


Figure 10. Descriptors of knee alignment in the frontal plane are: A - varus alignment where the angle formed by the midline of the femoral shaft (FM) and midline of the tibial shaft (TM) opens to the midline of the body, B - neutral alignment where FM and TM form a straight line, C- valgus alignment where the angle formed by FM and TM opens away from the midline of the body.

(Adapted from: http://pixshark.com/varus-vs-valgus.htm. Accessed May 11, 2015)

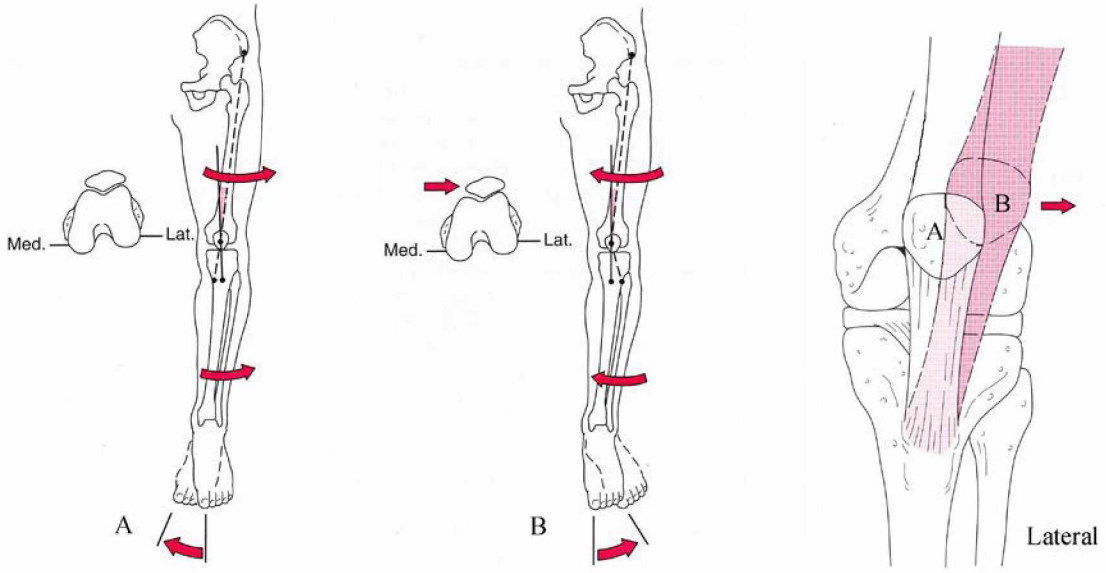


Figure 11. Static knee alignment in the frontal plane can be classified as neutral, varus or valgus (Fig. 10). A static neutral or varus knee can become dynamically aligned into valgus with medial collapse (Fig. 5) As the hip and tibia internally rotates from neutral alignment A into medial collapse B the patellar notch moves under the patella as the femur rotates making it ride lateral. This is illustrated by the transverse plane view to the left in A and B of the distal end of the femur at the knee and the knee frontal view at far right showing a lateral shift of the patella in the patellar notch caused by the femur rotating medial as the lower extremity collapses medially into a dynamic valgus alignment. (adapted from Magee [16])

Dr. Tom Wells, the Department Head and principal faculty of the former UAF Physical Education Department noticed and often commented on his perceived link between elite hockey skating and a particular lower body posture of: an anterior pelvic tilt, a varus knee angle and a high arched foot. To the casual observer Dr. Wells statement appears to be true, all of which results in feet being held more parallel during gait. "He has the classic hockey player walk." This is an observational study comparing lower body posture of two athletic populations: elite skaters "hockey athletes" and controls: athletes who may skate but not at an elite level, matched for age, gender and level of athletic participation. In the present study, it was hypothesized that elite hockey players would have a greater degree of anterior pelvic tilt, greater varus knee angle, a higher foot arch and feet held in parallel more during gait than a matched non-elite skating population.

Materials and Methods

This study was approved by the University of Alaska Fairbanks (UAF) Institutional Review Board (IRB), classified as exempt status IRB #308581-2, with Dr. Abel Bult-Ito as the Principal Investigator.

Lower body joint alignment angles were measured in standing posture to explore the linear relationship of each. To explore some of the properties of coupled rotational motion, a comparison of the available range of motion (ROM) of the two populations of subjects was explored. Available ROM in the transverse plane at the hips and knees and elements of tri-planer motion at the ankle and foot was measured and statistically compared. Comparison of ROM in the transverse plane may give a sense of how constrained angular motion coupling may be. Non-invasive measurement techniques were used to document the elements of lower body posture and motion of interest characterized by:

(1) Footprints – barefoot walking on poster paper with wet water base paint,

(2) Static pelvic tilt – determine right and left pelvic tilt using anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) as landmarks,

(3) Hip ROM in the transverse plane, internal and external rotation, and

(4) Knee ROM in the transverse plane, internal and external rotation.

Subjects

Study participants were recruited and selected from two populations of athletes based on convenience and their willingness to participate. Written informed consent was obtained using a form constructed to IRB specification. The final form used was approved by the IRB. The biomechanics of men differ from that of women [6, 7]. Therefore, only male subjects were enrolled in the study. The elite skating group consisted of ten members of a National American Hockey League team based in Fairbanks during the 2013-2014 hockey season. The positional make-up of the hockey group is five forward, four defensemen and one goalie. All ten of the non-skating athletes were members of the UAF cross country running team. Six of the runners from the cross country team were also members of the cross country ski team, changing teams as the seasons change from Fall to Winter. Ages ranged from 18 to 21 years old in the hockey players and 18 to 26 in the running subjects. In order to fill the number of subjects needed to represent the running group, one of the runners was the cross-country team graduate assistant coach, age 26. Subjects were instructed to report for data collection wearing running shorts.

Stride Analysis

The elements of stride are traditionally divided into spatial and temporal elements [17]. The

temporal elements of stride, those of cadence and velocity were not measured. The spatial elements of each subjects gait pattern were captured as footprints in paint for analysis. Footprints of each subject were captured on 1.25m x 2.75m sheets of poster paper, which allowed subjects to take 4 to 5 steps in a single trial. Footprints were obtained by having each subject step first onto a terry cloth towel saturated with black water based Tempera paint then continue on to walk on a sheet of poster paper at a self selected speed. To prevent slips and falls, the paint saturated towel was placed on a rubber-backed mat. Each sheet of footprints was hung and digitally photographed from 7.3m at a focal length of 86mm. Using tools available in "EasyDraw 3.9.6", a lite Computer aided design (CAD) software for a Macintosh computer, digital images of each sheet were scored for the following stride spatial elements [17]:

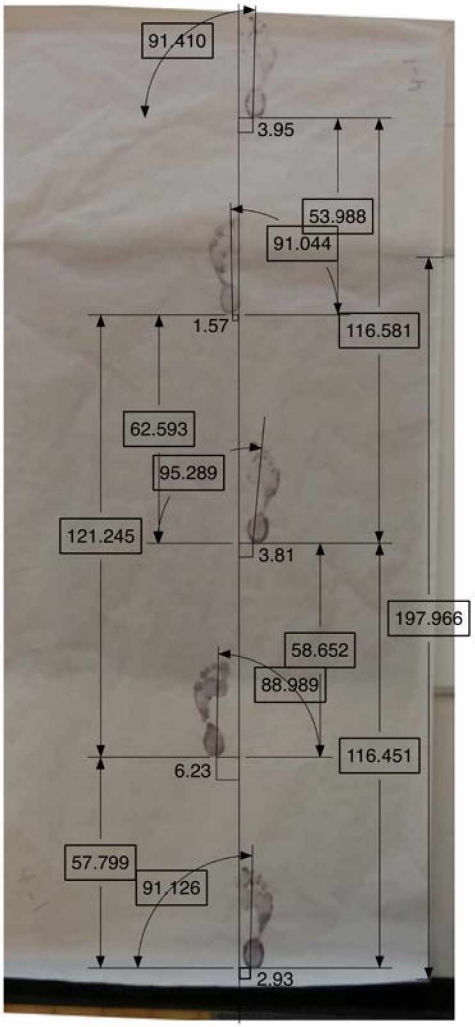
Step length - the distance between the point of initial contact of one foot and the point of initial contact of the opposite foot. In normal gait, right and left step lengths are similar.

Stride length - the distance between successive points of initial contact of the same foot. Right and left stride lengths are normally similar [17].

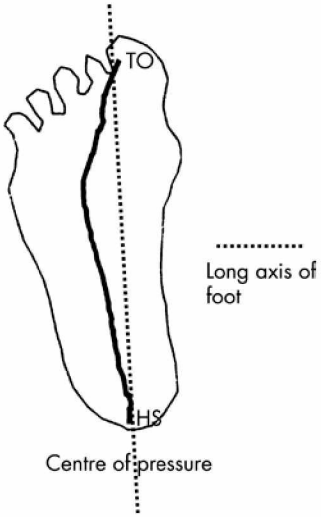
Base of Support – the sum of step width, the two perpendicular distances from the points of initial contact of the right and left foot to the line of forward progression.

Foot Angle - describes an angle between the line of forward progression [18] and a line representing the centerline of the foot made by drawing a line between the midpoints of the calcaneus and the second metatarsal head [19]. This measure is also called "foot placement angle" in some of the physical therapy literature [20]. The angle considered normal for men is about 7° [21]. The path traveled by the center of pressure from heel strike to toe off, which defines the line of foot progression, represents an approximation of this line used to estimate the foot angle [22]. In the present study it is measured and reported from as a line perpendicular to

the line of progress. Subtracting 90° is required to normalize the data with that reported in the literature (Fig. 12B) [19, 20].



A.



B.

Figure 12: A - An example of a subject's footprints in paint left on paper after the steps have been scored. The scoring procedure comprised the following steps. 1) The line of forward progression was drawn with regard to gait (the centerline between alternating left and right footprints. 2) At the heel of each footprint, a perpendicular line was drawn just behind the heel of each print and the center of each heel is marked on the line. 3) Measuring from the center of the heel to the line of forward progression gives the step width. 4) A line was then drawn from the center of the heel to the area between the first and second toe, this represents the line of foot progression, the line traveled by the center of pressure along the bottom of the foot from heel strike (HS) to toe off (TO) (see 12B). 5) The angle formed by the perpendicular line was used to establish step width and the line representing foot progression is the foot angle plus 90°, which is referred to as foot angle in this paper. 6) Step length was measured from heel to heel of the next footstep as they alternate sides, and stride length is measured from heel to heel of the next footsteps on the same side. B – The solid line is the path traveled by the center of pressure from heel strike to toe off which defines the line of foot progression. The solid line represents an approximation of this line used to estimate the foot angle.

Foot Arch Analysis

To numerically quantify arch height a representative right and left footprint was selected for each subject from the footprints captured in paint on poster paper. Each footprint was scored for arch index (AI) [23], the ratio of the middle third of the footprint to the total footprint area. A high arch will have less of the mid-foot in contact with the ground than a low arch, and thus AI will be represented by a lower number in higher arched individuals. This methodology is described by Cavanagh and Rodgers [23]. In the case of this study, water based poster paint was used instead of forensic ink. The footprint areas were determined using technology borrowed from geographic mapping, a dot grid, which is a common way of estimating area or the acreage represented on a map (Fig. 13; Appendix 2). The AI represents a ratio, therefore dot grid units cancel when the ratio is calculated. Classification is as follows: high arch < 0.21; normal arch 0.21 - 0.26; flat arch > 0.26 [23].

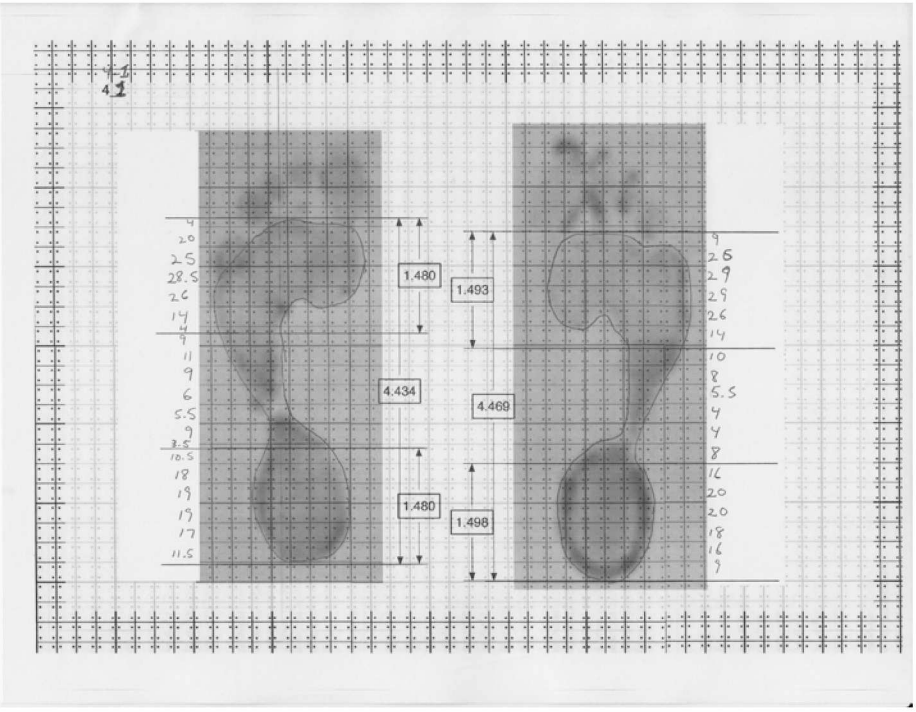


Figure 13. An example of poster paint footprints scored for arch index (AI). In this example the left AI is 0.20 and the right is 0.15. The AI [23] is the ratio of the middle third of the footprint to

the total footprint area. A high arch will have less of the mid-foot in contact with the ground than a low arch, and thus the AI will be represented by a lower number in higher arched individuals. Arch height is numerically quantified by selecting a representative right and left footprint for each subject from the footprints captured in paint on poster paper. Each footprint is superimposed on a dot grid (Appendix 2), then, outlined in pencil to define the fuzzy edge for dot counting. The footprint is equally divided into thirds. The dots in each row are counted in accordance with the protocol for geographic use of the dot matrix (Appendix 2). The number of dots counted in each row is written beside the row, then the dot counts are totaled for each footprint third. The AI is then calculated by dividing the dot count of the middle third by the dot total for all three thirds. The units cancel in the equation resulting a numeric ratio describing arch height.

Marker Placement

For standing posture photos, static pelvic tilt measurements and hip transverse plane range of motion, 1cm stick-on markers were placed on the following landmarks (Fig. 14):

(1) Sternal notch at the base of the neck,

(2) Anterior superior iliac spine (ASIS),

(3) Posterior superior iliac spine (PSIS) of the pelvis,

(4) Greater trochanter of the hip,

(5) Tibial tubercle just below the knee,

(6) Fibular head, superior lateral lower leg,

(7) Anterior ankle syndesmosis, and

(8) Lateral malleolus at the ankle.

Each subject removed their shirt and had their running shorts taped up at the sides to reveal the greater trochanters.

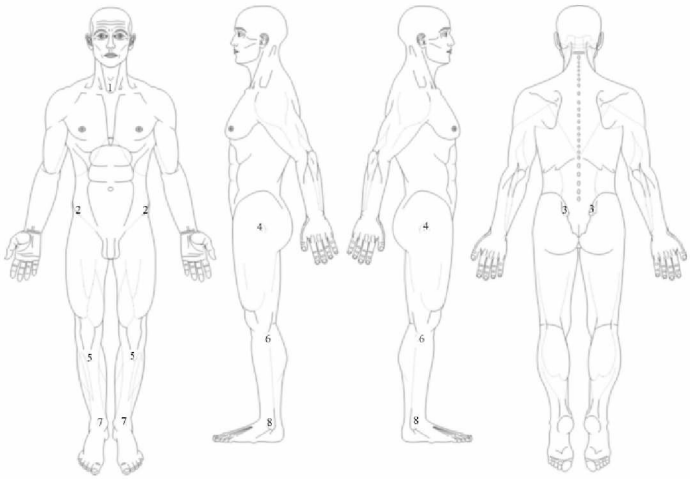


Figure 14: Marker placement of (1) Sternal notch, (2) Anterior superior iliac spine (ASIS), (3) Posterior superior iliac spine (PSIS), (4) Greater trochanter, (5) Tibial tubercle, (6) Fibular head, (7) Anterior ankle syndesmosis, and (8) Lateral malleolus.

(adapted from www.bodiesinbalanceleth.ca/?page=22212. Accessed May 17, 2015)

Standing Posture

With landmark stickers in place, each subject was placed facing forward in front of a posture grid. Digital still images were taken of each of the 4 aspects of the body by having the subject make a quarter turn after each aspect was photographed. Photos were captured and measurements made using a webcam and Kinovea 0.8.15 motion capture and measurement freeware software for Windows 7. The camera was placed at 90cm, approximately waist height, and 3.65m from the subject. The webcam was a Microsoft LifeCam Cinema, Part #: H5D-00013, H5D-00001 capturing at a resolution of 1280 x 720 pixels with a fixed focal length of 32mm. Only the anterior and two lateral aspects were scored to yield trunk angle, pelvic tilt and knee alignment.

Trunk Angle

Trunk angle is a measure of the orientation of the trunk in the sagittal plane. It is the angle formed between the trunk and the thigh (Fig. 15) [24]. Each right and left lateral view of the standing posture images was measured using EazyDraw.

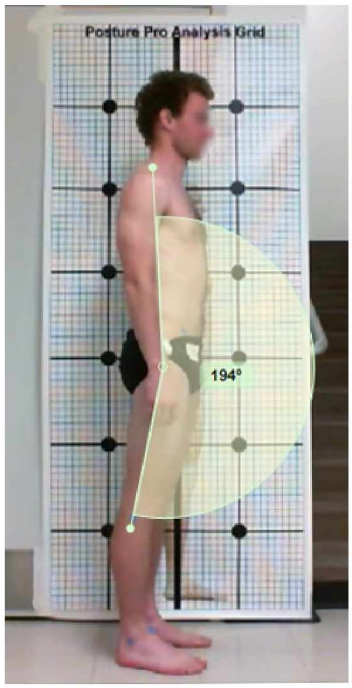


Figure 15. An example of a lateral aspect image scored for trunk angle. To score trunk angle, an angle was drawn on the left and right lateral images using Kinovea software. The apex of the angle was placed on the greater trochanter marker (Fig. 14). One ray of the angle centered at the shoulder on the acromion process and the other at the knee on the fibular head. The software provided a measurement of the angle formed in degrees. A hip angle of 180° is neutral. A hip angle greater than 180° is in extension and less that 180° is in flexion.

Pelvic Tilt

Pelvic tilt is a measure of orientation of the pelvis in the sagittal plane. More specifically, it is the angle formed between the horizontal plane and a straight line connecting the pelvis's ASIS and PSIS (Fig. 16) [24]. Each right and left lateral view of the standing posture images was measured using EazyDraw.

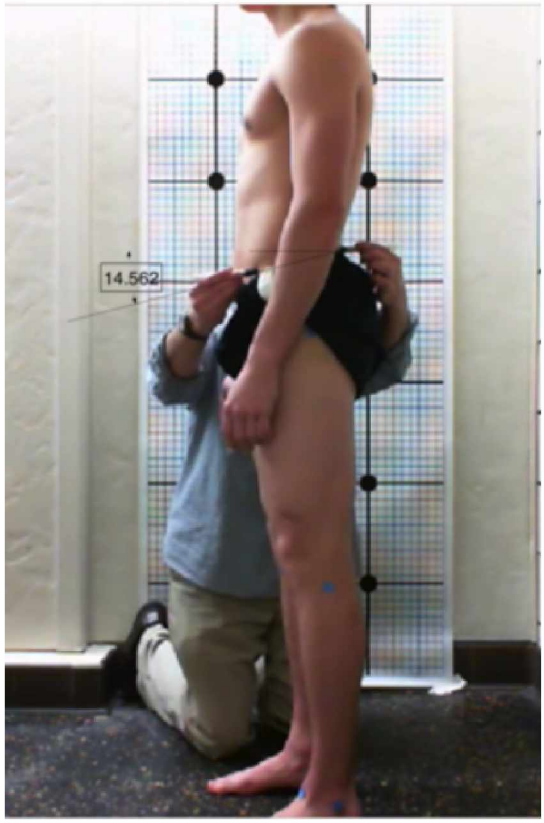


Figure 16. An example of a lateral aspect image scored for pelvic tilt. For each image, a marker wand is touched to the PSIS and ASIS (**Fig.** 14) indicating the location of each landmark on hip facing the camera. Images were taken using the same protocol for standing posture. The angle was drawn using EasyDraw software, previously described, with the apex at the PSIS and the bottom ray of the angle extended through the ASIS and the top ray is parallel to the horizon.

Knee Alignment

The anterior view of standing posture is used to score knee alignment in the frontal plane commonly referred to a varus or valgus alignment (Fig. 17) [16]. The angle is formed at the knee. The two rays of the angle are from ASIS at the hip to the tibial tubercle at the knee and the syndesmosis at the ankle to the tibial tubercle at the knee. The data reflect an angle measured clockwise in the right lower extremity and counterclockwise in the left.

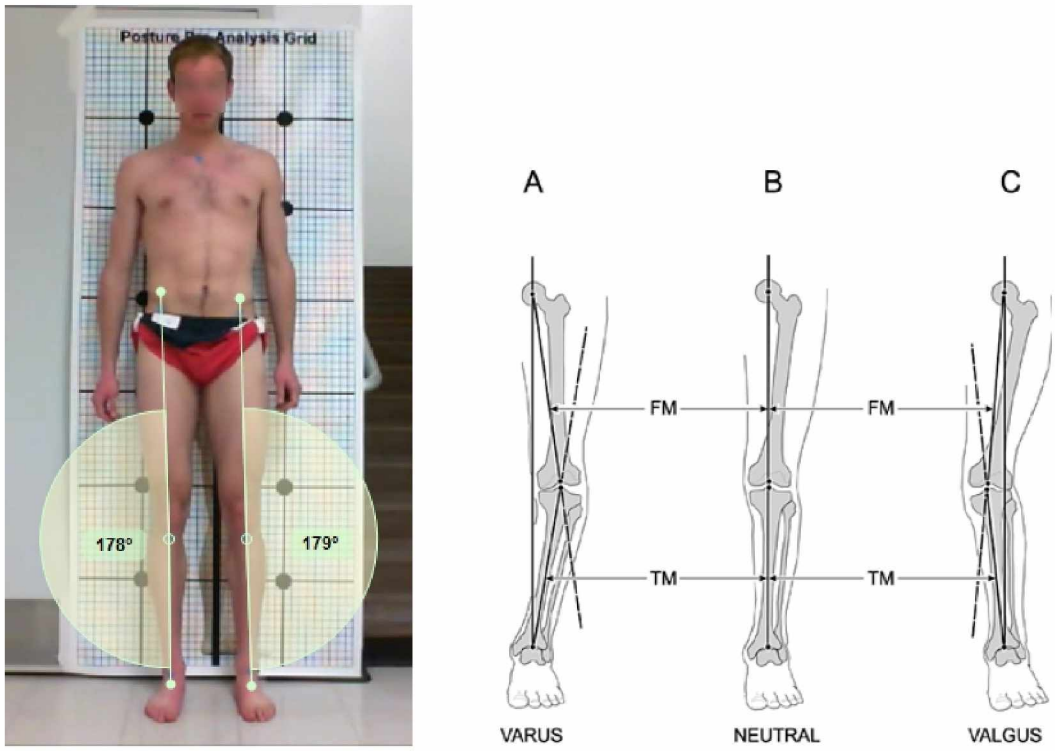


Figure 17. Left: An example of a frontal aspect image scored for knee angle. To score knee angle, an angle is drawn on the left and right lower extremity using Kinovea software previously described. The apex of the angle is placed at the tibial tubercle marker (Fig. 14). One ray of the angle centered at the ASIS of the hip and the other at the ankle at the anterior syndesmosis. The software provided a measurement of the angles formed in degrees. A knee angle of 180° is neutral. A knee angle greater than 180° is varus alignment and less than 180° is valgus alignment (Fig. 10). Right: Descriptors of knee alignment in the frontal plane are: A - varus alignment where the angle formed by the midline of the femoral shaft and midline of the tibial shaft opens to the midline of the body, B - neutral alignment where the angle formed by the midline of the femoral shaft and midline of the tibial shaft forms a straight line, C- valgus alignment where the angle formed by the midline of the femoral shaft and midline of the tibial shaft opens away from the midline of the body [16].

(Adapted from: http://pixshark.com/varus-vs-valgus.htm. Accessed May 11, 2015)

Knee Transverse Plane Range of Motion

To measure the available knee ROM in the transverse plane, i.e., the total of the internal and external rotation, subjects were placed sitting in a chair with knees at 90°, feet on the poster paper resting on the floor (Fig. 18) [16]. Keeping the knee at 90° and the tibia in a vertical position, each foot was internally rotated and traced onto the poster paper then externally rotated and traced again. The forefoot moves medial to lateral while the heel rotates in place. Digital

images were produced from the poster paper tracing using the methods previously described for footprints on poster paper [16]. The angle between the midline of each tracing was measured using Kinovea software giving the angle in degrees between extreme internal and extreme external rotation.

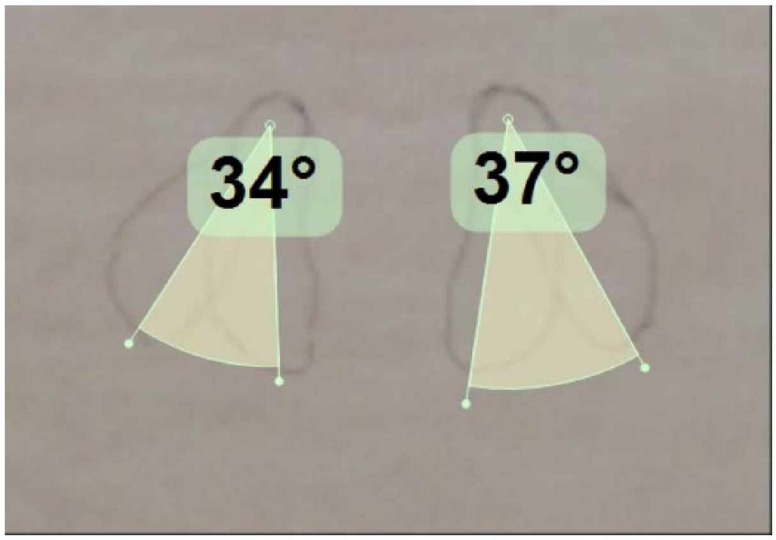


Figure 18. An example of a subject's footprints traced onto poster paper after it had been scored for knee transverse plane motion. Subjects were sitting in a chair with knees at 90°, feet on the poster paper resting on he floor (Fig. 17) [16]. Keeping the knee at 90° and the tibia in a vertical position, each foot was internally rotated and traced onto the poster paper and then externally rotated and traced again. Digital images were produced from the poster paper tracing using the methods previously described for footprints on poster paper. The angle between the midline of each tracing was measured using Kinovea software, previously described, giving the angle in degrees between extreme internal and extreme external rotation.

Hip Transverse Plane Range of Motion

To measure available hip ROM in the transverse plane, i.e., the total of the internal and external rotation, subjects were placed face down on the exam table with knees and feet hanging over the end (Fig. 19) [16, 25]. The webcam and Kinovea software previously described was set up at the end of the table to capture motion in the lower extremity in the transverse plane on video. With the subject face down the pelvis was stabilized with downward pressure by the examiner,

forcing both ASISs into the table preventing motion at the pelvis. Each knee was bent separately to 90° and externally rotated to end range then internally rotated to end range. The video frames capturing end range of external and internal rotation are converted to still images and measured using EasyDraw software.

Figure 19. An example of video frames captured at maximum hip internal and external rotation for scoring hip transverse plane ROM. To measure available hip ROM in the transverse plane, i.e., the total of the internal and external rotation, subjects were placed face down on the exam table with knees and feet hanging over the end. The webcam and Kinovea software previously describe was set up at the end of the table in the same plane as the table to capture lower extremity motion in the transverse plane. With the subject face down the pelvis was stabilized with downward pressure by the examiner, forcing both ASISs into the table preventing motion at the pelvis. Each knee was bent separately to 90° and externally rotated to end range then internally rotated to end range. The video frames capturing end range of external and internal rotation were converted to still images and measured using EasyDraw software as describe above for pelvic tilt. The apex of the angle was centered at the knee with one ray running through the tibial tubercle to through the anterior syndesmosis. The other ray was parallel to the horizon.

Data Analysis

For stride analysis, some subjects had a larger number of footprints either on the left or right side. To prevent bias from the side with the higher number of footprints, an average for each side was calculated to remove that bias, then, an overall average for each subject was calculated.

For statistical analysis, one number for each characteristic representing the left and right average for each subject is used. Once averages were calculated statistical analysis was done using the statistical software package "Wizard 1.5.1" for Macintosh computers available from the Apple App Store. For each measure, the hockey player and runner groups were statistically compared using a Mann-Whitney U test and the z values and p values reported, as well as the means ± standard errors of the mean (SEM) for each group. The data was not normally distributed.

Results

The resulting statistical data is summarized in Table 1 and is organized and presented in three parts based on the conclusion that can be drawn from each data set: (1) posture and alignment data, (2) available transverse plane ROM data, and (3) step width average data.

Table 1. Mean ± SEM, z, and p of hockey players and controls of trunk angle, pelvic tilt angle, knee angle, foot angle, arch index, hip center of range, hip external rotation, hip internal rotation, and hip total ROM. The statistical evaluation for differences between the hockey players and runners is represented by the Mann-Whitney U test z values and corresponding p values.

Characteristic	**Mean Hockey ± SEM**	**Mean Control ± SEM**	z_{18} =	**p <**
Trunk angle	185.85° ± 1.22°	187.01° ± 1.10°	0.796	0.426
Pelvic tilt angle	**11.96° ± 1.35°**	**7.42° ± 1.41°**	**2.117**	**0.034**
Knee alignment, (varus/valgus angle)	183.05° ± 0.76°	181.35° ± 0.79°	1.556	0.120
Foot angle	**90.14° ± 0.82°**	**92.57° ± 0.87°**	**1.965**	**0.049**
Arch index (arch height)	0.250 ± 0.015	0.245 ± 0.013	0.302	0.762
Hip, center of range of motion	80.35° ± 2.05°	78.34° ± 2.09°	0.151	0.880
Hip, external rotation	38.65° ± 2.81°	32.99° ± 2.82°	1.058	0.290
Hip, internal rotation	122.05° ± 3.03°	123.69° ± 2.36°	0.680	0.496
Hip, total ROM	83.39° ± 4.15°	90.69° ± 3.11°	1.739	0.082
Knee transverse plane ROM	45.85° ± 2.29°	42.70° ± 3.94°	1.022	0.307
Step width (cm)	7.12 ± 0.74	5.03 ± 0.63	1.814	0.070

1. Posture and Alignment

Trunk angle, pelvic tilt, knee alignment, foot angle and arch index, the data elements of posture and alignment are of interest with regard to the stated study hypothesis and these data largely support the hypothesis: elite hockey players had a significantly greater degree of anterior pelvic tilt and feet held more parallel (Table 1) compared to age and gender matched non elite skating population (control group). Although elite hockey players tended to have greater varus knee angle than the control group, this did not reach statistical significance. The two athlete groups did not differ in the height of the foot arch. The hockey group tended to have a lesser trunk angle than the control group (Table 2) but this was not statistically significant. Trunk angle was included in the data collection but was not explicitly a part of the hypothesis statement. The trunk is difficult to model biomechanically and not an element often seen in contemporary lower extremity biomechanics literature [26].

2. The Available Transverse Plane Range of Motion (ROM)

Elite hockey players did not differ significantly from the control group for hip center of range motion, hip internal and external rotation, or knee transverse plane ROM (Table 1). The elite hockey players tended to have a smaller hip total ROM compared to the control group (Table 2), but it was just short of statistical significance. Overall, these results show that these two groups of athletes have similar available transverse plane ROMs.

3. Step Width Average

As a point of interest, it was noticed during the stride analysis that the walking base, the perpendicular distances from the points of initial contact of the right and left foot to the line of forward progression appeared to differed between the two groups. The elite hockey players tended to have a larger step width compared to the control group (Table 2), but it was just short of statistical significance.

Discussion

The hypothesis that elite hockey players have a greater degree of anterior pelvic tilt, greater varus knee angle, a higher foot arch and feet held in parallel more during gait than a matched non-elite skating population was supported by the results for anterior pelvic tilt and foot angle during gait. Although the varus knee angle was in the expected direction it was not significant and no differences were observed in the foot arch between the groups. All other measurements not directly related to the hypothesis were not significantly different.

Previous studies have shown that lower extremity biomechanics, i.e., posture and alignment are involved in the development of lower body overuse or insidious onset injuries [1-3] and in the variability of risk with regard to sustaining a non-traumatic anterior cruciate ligament (ACL) injury [27]. Medial collapse illustrated in Figure 5, (pelvic drop, coupled to leg internal rotation, coupled to valgus knee alignment, couple with a flattening of the arch) has been implicated in both patellofemoral pain and non-traumatic ACL injury [6, 8, 11-14, 27].

Patellofemoral Pain Research

Patellofemoral Pain (PFP) was introduced earlier in the paper with the idea of being able to put the present study in perspective with regard to current literature; showing how elements of linear and angular motion coupling may relate to insidious onset injuries like PFP and why the aspects of those elements were chosen to be included in the present study.

In 2009 the first International Patellofemoral Pain Research Retreat was held in Baltimore, MD. Subsequently three more have been held in 2011, 2013 and 2015. The proceedings of the first three retreats have been published in the sports medicine literature with the 2015, Manchester, England meeting proceedings in the process of being published. An important underlying theme of all three retreats for which the proceeding are available, is explicitly stated in the proceedings of the 2nd retreat held in Ghent Belgium [12], "while it was generally agreed that the etiology of PFP is multifactorial in nature, it was the contention that the root causes of this condition are not well understood." For the purpose of the retreat causal factor are divided into (A) proximal factors: the hip, pelvis and trunk; (B) local factors: patellofemoral joint mechanics and surrounding tissues; and (C) distal factor: foot and ankle mechanics. All of these elements are included in the present study and are organized in this section along a parallel theme looking at influences: of proximal factors (the hip), local factors (the knee), and distal factors (the ankle and foot).

A. Proximal Factors

Research continues to build consensus that proximal mechanics are altered in women with PFP. This often is observed as excessive hip adduction and/or internal rotation. These altered mechanics have not been reported as consistently in men. Emerging evidence suggests that trunk mechanics differ between individuals with PFP and those without it [11]. The proximal factors are present in PFP are also the same factors involved in increased risk of a non-traumatic

knee ACL tear in women [27]. In the present study it was found that proximally, hockey players have a posture with decreased trunk flexion and anterior pelvic tilt compared to controls which likely exposes them to less risk of PFP, whereas the control runner group may be more at risk when participating in the same activity [1, 14, 28].

B. Local Factors

Locally, "… the relationship between structure and biomechanics is not known. It is possible that structural abnormalities coupled with poor biomechanics will increase the likelihood of PFP. On the other hand if structure is normal, then the biomechanics may not matter. As of yet, no study has examined patellofemoral joint structure and mechanics in the same cohort …" [12]. The present study found that hockey players are slightly more varus aligned in the frontal plane than controls. However, this difference is not significant.

C. Distal Factors

Consensus at the Vancouver retreat was that the importance of foot arch mechanics remains unclear [11]. "Greater tibial internal rotation, but not foot mechanics measured with a multi-segment foot model, was observed in people with PFP compared with a control group. Alterations in tibial rotation may provide a potential link between PFP and distal factors [11]." In the present study, hockey player's held their feet more parallel in gait than controls. Hockey players were expected to have a higher arch than controls, which was not supported by the data.

Summarizing PFP literature relevant to the present study is important because understanding alignment and coupled motion is a precursor to understanding the underlying mechanisms of PFP and the related risk of non-traumatic ALC injury. Understanding alignment and coupled motion is also paramount to the design of successful treatment strategies of insidious onset and overuse lower extremity injuries like PFP. The present study adds to the baseline knowledge of

lower body alignment and motion coupling with regard to hockey players and their runner controls.

In the consensus work outlined above it was stated the influence of foot mechanics on the lower body kinetic chain remains unclear. Speaking to this uncertainty with regard to interventions aimed at the foot and ankle, two recent papers shed some light on the topic.

In a 2014 paper published in JOSPT titled *Injury-reduction effectiveness of prescribing running shoes on the basis of foot arch height: summary of military investigations*, Knapik et al. summarize research done by the military services: the Army, Air Force, and Marine Corps as follows [29].

Prior to 2007, efforts to minimized running injuries during basic training, the military services generally followed the recommendations of the shoe companies. As the science emerged in the late 1980s and continuing into the 2000s, running shoes were classified largely on their intended purpose and related to plantar shapes. The assumption was that plantar shapes reflected of foot arch height and plantar shape could be used to select a type of running shoe that was appropriate to the individual with the goal of reducing the likelihood of injury.

"Individuals with a foot shape reflecting a low arch were presumed to have greater rear-foot and mid-foot mobility that allowed the foot to pronate excessively during the stance phase of running. For these individuals, "motion-control" shoes were recommended, because it was assumed that these shoes could control excessive foot motion [4, 29]."

"Individuals with a plantar shape reflecting a high arch were assumed to have rigid or inflexible feet that impacted the ground with greater force and did not pronate sufficiently. These

individuals were directed toward “cushioned” shoes, which presumably increased shock absorption by providing for more pronation and cushioning to soften ground impact [4, 29].”

“Individuals with a foot shape reflecting a normal arch height were assumed to impact the ground with less force and to have an appropriate amount of foot pronation. A “stability” shoe, which was presumed to have moderate cushioning and motion-control characteristics, was recommended for these individuals [4, 29].”

In 2007, studies by the Army, Air Force, and Marine Corps using recruits undergoing basic training were conducted independently; however, the design of the 3 studies was identical. Recruits were randomized into either an experimental or control group and trained side by side in the same military units.

The recruits in the experimental group were assigned motion-control, stability, or cushioned running shoes, based on their plantar shape, which represented a low, medium, or high foot arch, respectively. Controls were assigned a stability shoe regardless of foot shape.

The results showed that there was little difference in injury rates between the control group where all subject were given a stability shoe and experimental group where subjects were given shoes based on foot shape as recommended by the shoe manufacturers.

Figure 20. The wet test. (Adapted from Knapik [29].) Three steps: 1) Place a piece of paper, that is large enough to accommodate the size of your foot, on a flat, hard floor; 2) Wet the bottom of your foot and stand up on the piece of paper, making an imprint with your foot The foot should be damp enough to make an imprint, but not so wet that the imprint of the foot is obliterated; 3) Match your footprint, as best you can, to one of the three most common foot types pictured above [4].

Table 2. Categories of Running Shoes

Cushioned	Motion Control	Stability
Designed to reduce impact forces.	Designed to limit excessive pronation.	Cross between cushioned and motion control shoes, with different models providing varying degrees of both.
Recommended for runners who impact the ground in a neutral position, underpronators, or runners with pes cavus or a wet test high arch	Recommended for moderate to severe overpronators and some runners with pes planus or a wet test flat arch.	Recommended for runners exhibiting mild or no overpronation or a wet test normal arch.

(Adapted from Knapik [29].)

Beno Nigg, at the University of Calgary Human Performance Laboratory, now late in his career as a shoe science researcher published a paper this year in the British Journal of Sports Medicine titled *Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter'.* In this paper he writes: once thought to be the prime predictors of running injuries, there is a lack of conclusive evidence regarding

the relationship between impact characteristics and ankle pronation to the risk of developing a running-related injury. Based on this lack of evidence, “two new paradigms are suggested to elucidate the association between footwear and injury. These two paradigms, 'the preferred movement path' and 'the comfort filter', suggest that a runner intuitively selects a comfortable product using their own comfort filter that allows them to remain in the preferred movement path. This may automatically reduce the injury risk and may explain why there does not seem to be a secular trend in running injury rates [30].”

The present study, when taken as a whole where populations of athletes are viewed on a spectrum, hockey players represent a population where the lower extremity posture trended away from “medial collapse into dynamic valgus” at the hips and knees whereas, in comparison to hockey players, runners trend closer to a posture on the medial collapse side of the spectrum at the hips and knee. While there were alignment differences at the hips and knees there was no difference in arch height between the two populations suggesting foot arch coupling is not tightly constrained in the “medial collapse into dynamic valgus” model, where pelvic drop, coupled to leg internal rotation, coupled to valgus knee alignment is coupled with a flattening of the arch (Fig. 5). Powers, in his clinical commentary states “the knee is designed to absorb rotational forces through its transverse plane motion” [14]. However, he does not offer any references to support this statement. From the results of the present study it appears rotational forces may be absorbed at the knee with a degree of uncoupling as rotation passing up and down the kinetic chain, through the knees, allowing some independent rotation to occur. Thus allowing arch height to change independently of knee and hip alignment, supporting Powers claim. Foot angle also differs between the two populations; hockey player had a foot angle more parallel to the line of progression or direction of travel. Arch height, a coupled variable, may be

adjusted over time to give an optimum foot angle for the sport. As the arch flattens foot angle increases and vice versa (Fig. 5, 7 and 8).

With regard to injury risk, previous studies have also shown biomechanical differences in relation to differences in injury risk between populations of athletes such as the differences between men and women playing the same sport [6-8, 14, 27]. This is the first study that looked for differences in biomechanical characteristics matched for age, sex and experience in athletes participating in two different sports. The present study shows that there are biomechanical differences in alignment between hockey players and runners who are otherwise matched. Injury epidemiology of the two sports is very different. Hockey injuries tend to be traumatic [28] whereas running injuries tend to be overuse [1] making it difficult to relate or compare injury risk to alignment as has been done in the single sport studies.

Limitations based on use of Skin Markers and two-dimensional video technique.

In the present study, skin markers were used as anatomical landmarks for digital photography and subsequent measurement. The markers were located on the subject with the aid of palpation. Since markers were anchored to the skin with adhesive, the markers were subject to movement of the skin as the subject moved. Skin marker movement has been identified as a source of error in the literature and can be significant. The following table summarizes the data from two papers on the subject, which compare the stability of skin markers placement compared to metal pin markers anchored in the subject's bone [31, 32]. In the present study, error from skin movement is likely to be minimal since marker were largely placed with subject in the position in which they were sequentially digitally photographed and scored.

Table 3. Skin markers vs bone pins. The numbers represent the difference between measurements taken from surface skin markers recorded by video and measurements taken from bone pins recorded by x-ray. RMSE is root mean square error.

Knee Joint Rotations	Running (Reinschmidt [32])	Cutting (Benoit [31])
Adduction/Abduction	6.6° (RMSE)	13.1° (absolute)
Internal/External Rotation	7.9°(RMSE)	5.4° (absolute)
Flexion/Extension	9.0°(RMSE)	4.2° (absolute)

(adapted from: MedSport - University of Michigan Sports Medicine Program slide presented at the American Society for Sports Medicine, July 2014)

Measurement error comparisons from two-dimensional (2D) video and three-dimensional (3D) video analysis have been done and are documented in the literature [25, 33, 34]. The results are similar between 2D and 3D analysis for frontal plane motion where the 2D camera is perpendicular to the frontal plane. In the present study the cameras were placed perpendicular to the plane of motion being measure. Therefore, we can expect the measurement error contribution by using 2D video and digital photography over 3D to be minimal.

Limitations of Sample Size

The number of subjects "n" was based on the number of subjects conveniently available, limited to 10 in each group. In the present study a number of the findings of experimental effect were just short of significance. There are a number of statistical methods that could be used to estimate the ideal sample size using the results of this study as a pilot to gauge the magnitude of effect for future work.

Conclusions

The present study supported alignment and posture differences at the pelvis, hips, knees and feet between elite hockey athletes and the runners who served as controls. The differences were mostly consistent with the stated hypothesis. The foot arch was not different, which suggests that foot arch coupling is not tightly constrained in the "medial collapse to dynamic valgus" model, where pelvic drop, coupled to leg internal rotation, coupled to valgus knee alignment is couple with a flattening of the arch (Fig. 5). This is important as foot orthotics [35] and athletic shoe design [29, 30] are used as a treatment intervention designed to change alignment of the lower extremity by changing arch height and motion. The finding of this study reinforces recent work done by Nigg [30] and the military services [29] which erodes the perceived value of using foot orthotics and athletic shoes as a treatment modality and may explain the injury intervention failures that often occur using foot orthotics or athletic shoes to change lower extremity mechanics.

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Appendix 1 Raw Data Tables

Posture and Alignment Data Table

Hockey/Control	Identity	Side	Position	Pelvic tilt angle	Knee Varus Valgus Angle	Average Foot Angle plus 90°	Arch Index
Hockey	1_1	Left	Forward	9.86	182	86.446	0.220430108
	1_1	Right	Forward	3.367	183	89.7415	0.214285714
Hockey	1_2	Left	Forward	11.405	185	90.1185	0.241042345
Hockey	1_2	Right	Forward	10.606	184	84.687	0.234398782
Hockey	1_3	Left	Defenseman	20.145	185	86.4535	0.256993007
Hockey	1_3	Right	Defenseman	23.847	183	92.30333333	0.241197183
Hockey	1_4	Left	Forward	7.923	186	94.78366667	0.235194585
Hockey	1_4	Right	Forward	9.826	184	94.573	0.266101695
Hockey	1_5	Left	Goalie	11.863	181	89.63	0.327027027
Hockey	1_5	Right	Goalie	11.197	182	87.026	0.344490934
Hockey	2_1	Left	Forward	5.057	188	91.577	0.288961039
Hockey	2_1	Right	Forward	12.859	184	95.496	0.268876611
Hockey	2_2	Left	Defenseman	14.324	186	88.67	0.208400646
Hockey	2_2	Right	Defenseman	13.215	186	95.911	0.246467818
Hockey	2_3	Left	Defenseman	10.147	181	86.4345	0.238848921
Hockey	2_3	Right	Defenseman	9.474	181	90.543	0.289617486
Hockey	2_4	Left	Forward	14.562	180	93.7365	0.276408451
Hockey	2_4	Right	Forward	14.818	182	88.322	0.296774194
Hockey	2_5	Left	Defenseman	13.601	179	87.7155	0.185840708
Hockey	2_5	Right	Defenseman	11.078	179	88.5445	0.127155172
Control	3_1	Left		14.435	180	92.453	0.252173913
Control	3_1	Right		9.461	181	93.246	0.259581882
Control	3_2	Left		5.22	184	93.385	0.215619694
Control	3_2	Right		1.552	188	87.29466667	0.228360958
Control	3_3	Left		2.871	181	88.777	0.228571429
Control	3_3	Right		0.434	176	88.0105	0.233176839
Control	3_4	Left		12.414	178	94.8395	0.266475645
Control	3_4	Right		9.77	179	95.6035	0.273529412
Control	3_5	Left		7.309	183	95.22	0.224948875
Control	3_5	Right		10.386	183	96.3745	0.195378151
Control	4_1	Left		6.226	177	90.0165	0.196660482
Control	4_1	Right		5.554	180	92.60833333	0.145488029
Control	4_2	Left		4.26	181	86.98166667	0.331606218
Control	4_2	Right		2.868	183	93.953	0.319783198
Control	4_3	Left		0.167	182	94.48333333	0.259689922
Control	4_3	Right		9.204	183	99.131	0.269449715
Control	4_4	Left		8.108	182	91.741	0.272300469
Control	4_4	Right		6.758	179	95.58133333	0.254125413
Control	4_5	Left		12.825	181	89.0745	0.230905861
Control	4_5	Right		18.566	186	92.66033333	0.250384025

ROM data table/step width average

Hockey/ Control	Identity	Position	Side	Knee Trasverse Plane ROM	hip ROM	Center of Hip ROM	hip ER angle	hip IR angle	Step Width Average
Hockey	1_1	Forward	Left	43	70.364	73.698	38.516	108.88	4.8875
Hockey	1_1	Forward	Right	30	84.676	68.889	26.551	111.227	4.8875
Hockey	1_2	Forward	Left	47	84.324	74.062	31.9	116.224	6.7925
Hockey	1_2	Forward	Right	41	80.424	73.77	33.558	113.982	6.7925
Hockey	1_3	Defenseman	Left	45	92.688	80.488	34.144	126.832	6.49
Hockey	1_3	Defenseman	Right	58	69.183	80.6025	46.011	115.194	6.49
Hockey	1_4	Forward	Left	63	87.888	74.463	30.519	118.407	3.472
Hockey	1_4	Forward	Right	59	82.988	83.287	41.793	124.781	3.472
Hockey	1_5	Goalie	Left	47	116.217	82.9315	24.823	141.04	7.37
Hockey	1_5	Goalie	Right	38	113.551	80.7955	24.02	137.571	7.37
Hockey	2_1	Forward	Left	34	78.327	90.0465	50.883	129.21	8.825
Hockey	2_1	Forward	Right	46	88.479	97.4875	53.248	141.727	8.825
Hockey	2_2	Defenseman	Left	41	89.748	73.308	28.434	118.182	9.5975
Hockey	2_2	Defenseman	Right	40	85.624	76.755	33.943	119.567	9.5975
Hockey	2_3	Defenseman	Left	55	75.633	90.0745	52.258	127.891	10.605
Hockey	2_3	Defenseman	Right	50	59.813	78.7455	48.839	108.652	10.605
Hockey	2_4	Forward	Left	47	84.669	84.9795	42.645	127.314	8.575
Hockey	2_4	Forward	Right	42	87.702	85.342	41.491	129.193	8.575
Hockey	2_5	Defenseman	Left	50	59.717	85.6095	55.751	115.468	4.47
Hockey	2_5	Defenseman	Right	41	75.853	71.7035	33.777	109.63	4.47
Control	3_1		Left	40	102.901	73.1815	21.731	124.632	7.045
Control	3_1		Right	49	101.037	66.3385	15.82	116.857	7.045
Control	3_2		Left	37	87.115	80.2865	36.729	123.844	4.486
Control	3_2		Right	34	88.081	91.0215	46.981	135.062	4.486
Control	3_3		Left	43	93.69	82.159	35.314	129.004	7.5975
Control	3_3		Right	54	87.744	81.776	37.904	125.648	7.5975
Control	3_4		Left	44	87.47	70.88	27.145	114.615	7.6025
Control	3_4		Right	49	81.349	75.9385	35.264	116.613	7.6025
Control	3_5		Left	42	89.457	67.3295	22.601	112.058	4.075
Control	3_5		Right	49	87.738	63.675	19.806	107.544	4.075
Control	4_1		Left	39	88.052	79.221	35.195	123.247	3.698
Control	4_1		Right	29	80.992	87.612	47.116	128.108	3.698
Control	4_2		Left	30	81.903	88.8615	47.91	129.813	5.554
Control	4_2		Right	32	79.791	76.1665	36.271	116.062	5.554
Control	4_3		Left	37	90.896	82.775	37.327	128.223	2.45
Control	4_3		Right	27	94.099	82.8025	35.753	129.852	2.45
Control	4_4		Left	61	113.669	75.4585	18.624	132.293	2.404
Control	4_4		Right	85	112.04	83.288	27.268	139.308	2.404
Control	4_5		Left	35	78.13	76.919	37.854	115.984	5.854
Control	4_5		Right	38	87.667	81.1175	37.284	124.951	5.854

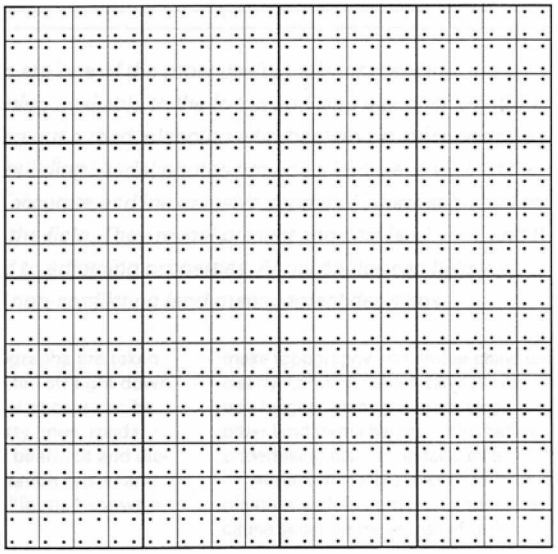
Appendix 2

Dot Grid for Measuring Map Areas

Dot grid with map scales and equivalents for a 64 dot per-square-inch acreage grid.

To use this grid, photocopy the figure on a transparent overlay sheet available from any copy center.

DOT GRID



(64 dots per square inch)

How to Use the Dot Grid

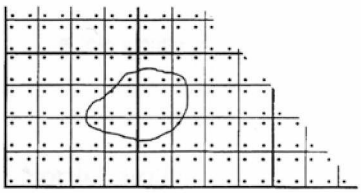
Place grid over area to be measured. Count all dots that fall within the measurement area. Dots which fall on lines are counted as one-half dots. To compute total acreage, multiply dot total by conversion factor for your photo's scale.

MAP SCALES AND EQUIVALENTS

Equivalent Scale	Inches Per Mile	Acres Per Square Inch	Converting Factor Each dot equals:
1" = 660'	8.00	10.00	0.156 acres (about 1/6 acre)
1" = 1,000'	5.28	22.96	0.359 acres (about 1/2 acre)
1" = 1,320'	4.00	40.00	0.625 acres (about 2/3 acre)
1" = 2,000'	2.64	91.83	1.435 acres (about 1 1/2 acre)

EXAMPLE:

A section of a dot grid is placed over an irregular shape. Nineteen dots fall within the object's boundaries. Two fall on the line and are counted as one-half each. The total number of dots is 19 + (2 x ½) = 19 + 1 = 20. Multiply this total by the acreage conversion factor.



Virginia Tech, College of Natural Resources and Environment, Forest Courses, Module 4. "Dot Grid for Measuring Map Areas." VT.edu.

(from: http://web1.cnre.vt.edu/forestcourses/Module4/dot_grid.pdf, Accessed May 17, 2015)