Validation of Running Symmetry Using Trunk Mounted Accelerometry: Clinical Trial and Case Study

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Submitted to the Graduate Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Masters of Science
in
Human Nutrition, Food, and Exercise

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Abstract

Trunk-mounted monitoring equipment like GPSports SPIHPU units are designed to use global positioning (GPS), accelerometer and heart rate monitoring to evaluate the physical demands of an activity. A medical staff might also consider markers such as running symmetry in evaluation of injury occurrence and rehabilitation. A running symmetry is a ratio of the synchronization of the right and left lower limbs during the gait cycle. An asymmetry due to, a pathology or musculoskeletal injury, results in abnormal loading on the foot that may be detected by trunk-mounted accelerometry. The aim of this study is to evaluate the ability of SPIHPU units to detect running asymmetry. Subjects wore the HPISPU units (100Hz, 16g tri-axial accelerometer, 50Hz magnetometer) while engaged in various running activities. In the first study, artificially inducing a leg length discrepancy led to a difference between running symmetry scores. This discrepancy was confirmed using individual accelerometers attached to the lower leg near the foot. Next, varying running speed did not result in differences in running symmetry. However, the SPIHPU units did detect a running asymmetry between fatigued and non-fatigued conditions. Finally, two case studies showed that the units could identify asymmetry immediately after a lower leg injury and during rehabilitation of anterior cruciate ligament reconstruction surgery. The results of this study show that the HPUSPI units can be reliably used to monitor running symmetry and to detect asymmetrical gait patterns.
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Chapter 1

Purpose and Significance
Introduction:

With the growth of technology and analytics programs, sports science is in a position where more quantitative data can be collected and interpreted on a day-to-day basis [1]. We are also in a time where professional athletes are some the highest earning professionals in our society. Their contracts are given in the expectation they will make certain contributions to the common goal of winning a team championship. Cristiano Ronaldo earned approximately $53 million during the 2015-2016 season. During this time, he played in 48 matches for Real Madrid FC [2]. This means that he made over $1 million for every game he played, showing just how valuable one athlete can be to an organization.

This financial impact can be further analyzed using the case of Wayne Rooney. By multiplying games lost to injury (GLI) and salary owed per week. During a 9-month window Rooney was injured off and on for 3 months and missed 36% of matches played during this period. During that same time Rooney was making £250,00 per week grossing £7.5 million over the 9-month window [3,4]. Therefore, Manchester United paid £2.7 million, or 36% of £7.5 million, to a player who was physically unable to perform (PUP). Luke Shaw, making £70,000 per week, missed over 7 months, 86%, of the same 9-month window [3,4]. The time on the PUP list cost the team only £1.8 million. This example shows how players with larger salaries can impact the financial aspect of performance more than GLI alone. GLI is just the beginning of the financial burden placed on an organization when a player is unfit to participate in team activities as additional costs are incurred for medical treatments and rehabilitation, lost ticket sales and potential post-season participation.

After injury, it is almost guaranteed that some rehabilitation program will be established which may be extensive if surgery is required [5]. With one session of physical
therapy costing around $250, a 2-week session could cost thousands in additional expenses [6]. Specialists may be outsourced to administer alternative treatments like cryotherapy, adding another cost to the athlete who is unable to provide his or her skill set to the organization. The key to maximizing “profit” of the athlete is to minimize the time spent away from their job putting a focus on quick rehabilitation time. If the rehab process is rushed proper healing may not take place leading to re-injury and additional time PUP [7].

In addition to minimizing injuries teams are interested in quantifying as many variables as possible and turning to analytics to identify strong and weak aspects of the roster. The movie Moneyball gave a good representation of how sports analytics can be utilized to maximize all the pieces of a team and reach the ultimate goal of winning the championship [8]. The use of higher levels analytics as shown by the 2002 Oakland A’s in which the team was able to eliminate major contracts and fill the loss of productivity with cheaper contracts can lead to great benefits for an organization. These smaller contracts allowed the A’s to correct additional deficiencies and see beyond stats like hitting and home runs alone. The key to all of their success was being able to calculate trends in team performance and identify solutions to maximize performance while remaining in the limits of a league salary cap [8].

As we progress through this period of technological revolution, production of smaller and more accurate monitoring devices are being made available to the public sector, creating a stronger market for wearable technology [9]. Technologies like Global Positioning System (GPS) and accelerometry can be utilized in many fields ranging from phone apps to external systems such as those produced by companies like GPSports and Catapult [10,11].
These types of equipment accurately and reliably collect quantitative variables like total distance or body impact to be analyzed [12,13]. GPSports newest wearable, SPI HPU unit (Figure 1), is growing in popularity amongst major sports teams including several English Premier League (soccer), NFL (football) and NBA teams (basketball) [14]. These small compact units allow for the daily collection of over 100 variables describing the training load exerted on a specific individual in a non-invasive manner. The unit utilizes an external heart rate strap, worn below the xiphoid process, GPS, accelerometer, and magnetometer.

In addition to collecting velocity and heart rate variables, this technology allows the user to utilize accelerometry variables, like impact force, running or gait symmetry and body load, as a metric for evaluating total training load. Gait symmetry is defined as the equal values of gait variable on both sides, such as acceleration or ground reaction force [15,16,17]. Equal peak ground reaction forces experienced during right and left foot strike is considered “symmetrical” whereas differenced on foot strike forces is described as “asymmetrical”. Gait symmetry is also referred to as running or walking symmetry. An asymmetrical gait may also be referred to a walking or running imbalance. Using a symmetry index allows for left and right gait data to be quantified into a percent difference. In this methodology a score of zero would represent perfect symmetry while values above and below zero would represent asymmetry in the right or left direction where higher scores represent more asymmetry[18,19].

Utilizing gait symmetry, one can monitor improper loading of the body and identify when these abnormalities occur. Studies have shown that as subjects are fatigued changes in gait occur, which increases one’s risk of injury by reducing stability [20,21]. If a situation
arises in which an athlete is showing abnormal gait symmetry, physicians can act proactively to administer treatment to restore gait function before injury may occur. Risk of major injuries to the joints of the lower extremities can be reduced via the reduction of abnormal loading forces seen in gait asymmetry [22,23]. Lower leg injury often results in gait asymmetry which is reduced during recovery and rehabilitation. Thus, this metric could also be used to monitor injury recovery and make “return to play” determinations.

There have been studies that examined accelerometers and their capacity to quantify human gait [24,25,26]. All of these studies utilized ground reaction force from a force plate or video derived accelerations to validate accelerometer data. Trunk-mounted accelerometry has only been used in a few studies with force plate or video monitoring used to validate the findings of these studies. The main issue that arises when using such validation tools is the lack of applicability in a real world setting. By requiring a subject to perform exercise on an instrumented treadmill or to have complete foot strikes on an individual force plate some deviation from the natural gait pattern can occur [27].

In addition to the perturbed gait these monitoring tools are large and require a team of researchers to conduct data collection in a laboratory setting [28,29]. This requires an athlete to take additional time to have their gait symmetry tested outside of the natural environment [30]. Another limit is that only one subject could be evaluated at a time whether that be by instrumentation in the lab or via visual exam in the clinic [31]. One study looked at how running kinematics changed during long distance running and concluded that as subjects became fatigued vertical acceleration of the tibia increased at heel strike [32]. This increased acceleration would cause an increased force to be delivered
up the kinetic chain requiring the body to dissipate such forces in an abnormal manner, leading to an increased injury risk.

An experimental design that validates trunk-mounted accelerometers in a manner directly translatable to field-based sports and clinical setting does not exist currently. Thus, this study focuses on the accelerations endured between the foot and ground in a real world setting by utilizing a non-invasive monitoring system that can be used on a day-to-day basis during everyday activities performed outside of the laboratory.

**Statement of the Problem:**

Current methodology used to quantify running symmetry outside of the laboratory is visual inspection of an athlete by a physician. Inside the laboratory clinicians typically instrument athletes and conduct short bouts of locomotion in heavily controlled settings. By utilizing trunk mounted accelerometry, gait symmetry can be assessed in a variety of real-world conditions. Although a running symmetry can be identified via the GPSports SPI HPU technology, these values have not been compared against lower limb mounted, bilateral accelerometry. This is problematic as acceleration data obtained from a trunk-mounted accelerometer is influenced by the damping effects of knee, hip and vertebral column flexion and extension (e.g. dampening). In addition, there are no data showing change in running symmetry with varied exercise intensity or during a rehabilitation program. Thus, the three aims of this project are provided in the below section.
Specific Aims:

Aim 1: Determine the ability of the GPSports SPIHPU trunk-mounted units to detect running asymmetry during artificially induced running imbalance and compare those values to ankle-mounted sensors.

Hypothesis: Ankle mounted accelerometers and trunk mounted units will show similar changes in gait symmetry under conditions of an artificially induced asymmetry.

Objective: Show that by applying peak accelerations to a symmetry equation, a running symmetry score is produced that is similar to those produced by the GPSports proprietor algorithm.

Aim 2: Identify how exercise intensity (i.e. running velocity) and fatigue affect running symmetry.

Hypothesis: More intense exercise prescriptions will result in the development of an increased gait asymmetry when comparing the first 100m to the final 100m of a 1600m effort.

Objective: Confirm that running symmetry is affected by varying work out intensities due to fatigue.

Aim 3: Use case studies on known lower leg injuries to verify that injury-induced gait asymmetries can be detected with the trunk mounted accelerometer.

Hypothesis: An athlete suffering an acute lower leg injury and an athlete undergoing rehabilitation following anterior cruciate ligament reconstruction surgery will show gait asymmetries during running.
**Objective:** Adapt code used in previous experiment to calculate a running symmetry during an exercise prescription and compare to existing running imbalance.

**Significance:**

By utilizing trunk-mounted accelerometer data and a symmetry index, gait symmetry can be quantified under real-world setting like the field of play or clinical environment. Trunk mounted accelerometry provides a non-invasive means to quantitatively evaluate a running symmetry. Rather than arbitrarily identifying a “limp”, practitioners could quickly and reliably quantify an asymmetry and monitor how it changes as rehab progresses. If used in a sports setting, teams could identify when asymmetries develop in subjects as the training period progresses. Physicians can compare gait symmetry across a given time line, allowing for evaluation of rehabilitation or development of pathology. Trunk mounted systems also allow for collection of multiple subjects at the same time, a major limitation of in lab testing.

**Assumptions:**

Subjects are limited to male, college athletes (soccer). It is impossible to assure subjects will be free of both mental and physical fatigue, which can influence gait symmetry. The induction of running asymmetry is limited to bi- and uni-lateral shod conditions and exercise prescriptions of 1600m at varying intensities. Although data was collected under similar weather conditions, factors like temperature and humidity could influence effort of athletes. For the case study, it is limited to one subject recovering from ACL reconstruction and one subject recovering from a foot injury. Lastly, subject’s dietary
intake could not be normalized for this study. Malnourished or dehydrated subjects would not only affect exercise performance via the lack of substrate to produce ATP but could also influence spatial cognition.
Chapter 2

Literature Review
**Human Gait:**

Human locomotion requires the body to synchronize muscle contractions in a manner that is both safe and energy efficient. Over millennia of evolution humans have adapted to maintain a stable base, allowing the upper body to move forward over the lower limbs, precise neuromuscular coordination, and efficient absorption and dissipation of forces [33]. The resulting motion is a cyclical pattern of the left and right lower limbs, defining an individual’s gait. Current practice for evaluating an individual’s gait requires the physician to break each stride into 4 sections; weight acceptance, stance, forward progression, and swing [31,33,34]. Weight acceptance phase (0-10%) includes initial contact (IC) and the loading response (LR) and when the foot comes in contact with the ground and bears the weight of the body. Stance phase (10-50%) includes midstance (MSt) to terminal stance (TSt), the bodies center of mass (COM) is shifting over the foot to prepare for toe-off. The forward progression phase (50-60%) encompasses the terminal stance and pre-swing (pSw) where the body is propelled forward and begins to prepare for the swing phase. The swing phase is broken down into initial (ISw), middle (MSw), and terminal swing (Tsw). During the swing phase the foot is not in contact with the ground and is preparing itself for the next weight acceptance phase. One gait cycle is defined as one full progression of all four of these phases. Generally, this is broken down from heel-strike to heel-strike in a 0-100% as shown in Figure 2 [33].

Normal gait would be a situation where all of these portions of the gait cycle come together in a symmetrical and harmonious manner [35]. Pathological gait entails any deviation from this normal gait pattern. Pathology can arise from deformity like a discrepancy in leg length or issues with joint mobility as seen in ACL reconstruction or joint
replacement procedures [36]. Muscle imbalances, issues with neuromuscular function, and pain can also result in pathological gait [34]. Pathological gait requires the body to compensate across all lower body joints: ankle, knee, and hip [33]. This causes muscles to be utilized that would not typically be needed for a given motion like walking or running.

An example of how pathology leads to increased energy expenditure and further pathology would be individuals who “hike” their hips. Individuals with limited hip flexibility must hike or raise their hip resulting in a circumduction of the lower limb. Not only does this interfere with gait cycle timing, it also requires novel muscle groups to compensate leading to an abnormal load applied to the lower limb [37]. This abnormal load increases the total work that compensatory muscles are performing leading to increased energy expenditure. As well as requiring more work to be performed by novel muscles this circumduction of the hip applies abnormal load to the joints of the lower extremities. Abnormal wearing of the joint capsule may lead to other issues such as arthritis or osteoporosis. Considering that pathology results in an asymmetrical gait it should be no surprise that the monitoring of gait is important in diagnosis and treatment of many pathologies [38].

**Monitoring Gait:**

Traditionally researchers collected gait data by using a combination of force plates and video monitoring systems [39,40]. Force plates are platforms that are able to convert a change in voltage into a force value or ground reaction force (GRF) [41]. When an individual makes contact with the force plate, there is a deflection that creates a change in voltage and through a series of mathematical conversions produces the GRF. This GRF
allows for quantification of dynamic events such as landing or running forces in six degrees of freedom, forces and moments in the X, Y, and Z coordinate [41]. It can also be used to calculate center of mass (COM), an important variable for quantifying balance [41].

Limits to using such technology include the need of a controlled environment and need for multiple platforms [27-30]. Video monitoring is a great tool to calculate joint angles and how they change during varying activities. By using reflective markers and a room equipped with multiple cameras researchers can calculate how a joint is moving, velocity, and then predict forces exerted on said joint by integrating to determine acceleration and utilizing Newton’s second law of motion, force equals mass multiplied by acceleration [41]. This requires a room of a given area set up with up to eight infrared cameras limiting the capacity to capture real-world data. As brought up earlier the force plate needs a group of researchers to calibrate the system by first ensuring the plate is firmly attached to a level surface. Due to the intricacies of calibrating the plates they are often installed once and not moved restricting the out of lab utilization [41].

Another limit to force plates is that full foot contact is required for accurate measurement of GRF [42]. If one were to only strike the plate with his or hers heel a force would be generated but the portion of the foot off of the plate would also exert a force that would not be captured. Since asking a subject to strike the plate would alter gait researchers must install multiple plates to increase the odds of capturing an entire foot strike.

With the main limitation of both tools being that they require a lab setting an alternative is needed to conduct data in the real world. Inertial measuring units (IMU) provide an answer to this problem. An IMU is a combination of accelerometer, gyroscope,
or magnetometer [43]. Accelerometers measure linear accelerations in the X, Y, and Z planes while gyroscopes measure angular velocities along the X, Y, and Z planes. Magnetometers are able to detect magnetic north thus allowing the system to orient itself to a common point. Based on Newton’s second law, F=ma, data collected from accelerometry can be compared to force data like GRF. One study that directly compared force plate data to accelerometry data was a study conducted by Seimetz et al. In this study they wanted to look at how accelerometry and force plate data compared when measuring postural stability [44]. Stabilograms and sway profiles were generated from force plate and sternum-mounted accelerometer respectively. Subject had both visual and proprioceptive systems perturbed in order to see how force plate and accelerometer were able to detect a change in COM. The findings of the study were that the two technologies were not directly comparable but showed similar trends. This was shown by increased COM area on the stabilogram and increase sway profile when the bodies visual and proprioceptive systems were perturbed.

The use of accelerometers has been used in sciences for decades but is only recently being introduced on large scale in team-based sports (12,13). By utilizing accelerometry estimations of forces and how they are distributed across the body as a whole can be obtained [24,25,26]. A study performed by Torrealba et al. [45] identified significant landmarks in gait data collected from accelerometers. The significant findings of this study were two negative accelerations that occurred during the gait cycle. The larger acceleration was associated with heel strike and the lesser peak being associated with toe-off. The authors used the gait cycle and found the toe-off occurred approximately 61% into the gait cycle, which is supported by video monitoring systems like Vicon [45,46].
Zhang et al. [47] looked to identify how accelerometer attachment site affected accelerations. Subjects attached accelerometers above the medial and lateral malleolus and performed a walk where the foot struck a force plate. Accelerometer data from both attachment sites were well correlated with force plate data but lateral attachment was more highly correlated. The hypothesis on these results was that by attaching sensors closer to the point of contact the force exerted on the unit would be higher. This brings light to an important point that the body has built in dampers like the ankle, knee, and hip joint capsule. These dampers include skeletal muscle, ligaments, tendons, and cartilage. As these dampers deteriorate gait will be altered in order to accommodate. If data were to be collected further from the point of contact values may differ but trends should remain.

**Gait Symmetry:**

There are numerous studies examining abnormalities in gait symmetry including detecting an asymmetry in cerebral palsy, stroke, and the elderly to assess risk of falling [19-23, 48-50]. Variable of interest included variation in stride distance, GRF, peak acceleration (PA), and COM. Few studies utilized trunk-mounted units, like GPSports (SPIHPU) units, for collection of acceleration data. Carpes et al. [19] conducted a review looking at leg preference, which included analysis of a variety of symmetry equations. All equations compared variable from the right limb to left limb. From their study and others, the most common methodology to evaluate symmetry is to take the absolute value of right ($X_r$) minus left ($X_l$) divided by one half right ($0.5X_r$) plus left ($0.5X_l$) as shown in Figure 3 [19,39,40]. Carpes et al. [19] found that by using this formula a symmetry percentage ($ASI\%$) can be produced allowing for the identification of symmetry in a subject’s gait [19].
It was important to identify possible sources of error when collecting symmetry data. Based on the proprietor’s information and current literature four sources arose including velocity, running surface, footwear, and attachment site. Crowe et al. [51] looked at how gait variables were influenced by varying walking speeds. Using GRF data researchers found that as velocity increases gait cycle duration, time from right heel strike to next right heel strike, and force in the Y plane, mediolateral, decreased while force in the X, anterior-posterior, and Z, vertical, plane and stride length increased. These findings show the variability in forces as velocity changes making velocity an important factor to consider while testing gait parameters. The X and Z GRF data was highly correlated showing a relationship between the forces at which the foot strikes, weight acceptance phase, the plate to the force generated to propel the body forward, toe-off. These increased forces require the body to increase the rate at which gait cycle occurs to be biomechanically efficient.

Giandolini et al. [52] conducted an experiment where they utilized accelerometers to identify differences between downhill and level ground running. Based on previous studies, they state that downhill running induces higher accelerations at the tibia equating increased forces. Findings of this study were that downhill running promoted rear-foot strike and foot-strike pattern influenced shock intensity. Specifically, they found that forefoot strike produced less force than rear-foot strike. The ankle can be modeled as a first-class lever where the load is applied to the foot, the talocrural joint acts as the fulcrum allowing for forces to be distributed to the muscles of the calf and vice versa. In the forefoot strike the distance between our fulcrum and site of force application is increased whereas in a rear-foot striker this distance is reduced leading to an increased force sent through the
talocrural joint and up the kinetic chain. Although subjects may naturally be rear-foot strikers by ensuring a flat surface we are minimizing the effects of an uneven surface on accelerations.

Our third source of error is that footwear can affect gait symmetry. Hoerzer et al. [53] tested how shod vs unshod influenced GRF data. Their findings were similar to other studies that shod running reduced running asymmetry. They proposed that shoes alter sensory information from the planter and/or the dorsal portion of the foot. However, some subjects did show an increased gait asymmetry giving support for how variable human gait is. This variability can arise from the variation in afferent feedback of the neuromuscular system effecting proprioception [53,54].

Lastly, accelerometer placement will affect the collection of accelerometer data. Two aspects to placement is assuring the unit is securely attached and understanding placement. The first point is intuitive in that if the unit is not securely attached to the body the acceleration can come from the unit moving independently of the attached limb. To reduce these effects, researchers use athletic tape, Velcro, or 2-sided tape to firmly attach units to the body. As mentioned previously the body’s joint and musculoskeletal system disperses force as it travels up the kinetic chain. This idea is supported by a study conducted by Zhang et al. [47] They identified how well accelerometer data, peak acceleration, was correlated to GRF when attaching units to the distal tibia and lateral malleolus. Although both attachment sites we highly correlated to GRF data, lateral malleolus attachment was more highly correlated. This attachment was also supported by studies conducted by Mannini et al. [55] and LeMoyne et al. [56].
Wearable Technology:

Recently several companies have developed wearable units designed to measure variables like velocity, heart rate, acceleration, and running symmetry. The SPIHPU is an 80g trunk-mounted unit that incorporates GPS, accelerometer, and magnetometer housed in a 74mm x 42mm x 16mm waterproof case, Figure 1. The trunk-mounted unit is positioned between the athlete’s scapula, near vertebrae T4 and T5, by a vest provided by manufacture, Figure 4. In addition to the trunk-mounted unit heart rate data is collected via polar heart rate strap. All data from the four instruments is stored on the unit until downloaded to the docking station and interpreted using proprietary software. The GPS unit records at 15Hz and collects position, speed, and distance variables. The accelerometer records impacts, accelerations, and decelerations up to 16g at a recording frequency of 100Hz (Figure 5). The magnetometer is strictly used to track movement profiles and used in conjunction with the accelerometer to establish orientation. Utilizing these four separate technologies allows the proprietors software to generate visualizations of how variables interact with each other. Figure 6 shows how velocity and heart rate of an individual track over the course of an exercise bout.

The increased level of monitoring produces large data sets comprised of over 150 variables allowing for a more quantitative measure of the total training load (TL) endured by the individual [57]. Training load can be defined as both external (the volume and intensity of work being performed) and internal (the physiological and mechanical response to the external load). An athlete’s TL is important to maximizing performance gains as well as reducing the risk of injury. Gabbett et al. [58] model TL by taking the ratio of acute vs. chronic load and maintaining it between a specific range, 0.8-1.3 au. [58]. Using
this scale undertraining and overtraining are represented below 0.8 au or above 1.3 au respectively. Acute and chronic load can be any sliding window of data, 1-6 day average versus 10-18 day average respectively [59]. This way of analyzing TL makes the observer more concerned about the similarity between exercise bouts rather than looking at each exercise bout as an individual stress. The rate at which TL varies is more important than the individual sessions themselves. Modeling TL in such a manner we can compare how we are performing now versus how we were in the past. Analyzing running symmetry in this way will allow for intra-subject comparisons to be made establishing baselines or “normal gait”. Since running symmetry is so varied amongst individuals comparing symmetry to one’s own self provides more powerful insight than comparing to a whole team average or that everyone has perfect symmetry. Assuming a subject has some natural asymmetry in their gait using acute vs. chronic allows for us to see how similar that asymmetry occurs ideally resulting in a ratio of 1[58]. If someone were to chronically over-train or experience a musculoskeletal injury, it would be expected that an unnatural asymmetry would develop compared to one’s own natural gait. This would result in an increased acute vs. chronic ratio and could be used as a marker for injury. In a rehabilitation setting a physician could look for the acute vs. chronic ratio to be less than one due to the reduction of asymmetry over time. This would allow physicians to better understand how the rehabilitation process is progressing and has potential as a return to

**ACL Reconstruction Clinical Cases:**

ACL ruptures are the most common sports associated injury that requires surgery to repair [60]. The ACL protects the proximal tibia from anterior translocation from the distal
femur when the leg is in a flexed position [Butler]. Such injury is associated with a
disruption in gait symmetry due to reduced range of motion (ROM) and reduced strength
specifically in the quadriceps [61,62]. Following surgery physician’s main goals revolve
around promoting long-term joint functionality and avoid re-injury, most susceptible 7-8
months post-surgery.

In order to accomplish this Virginia Tech sports medicine guidelines call for the
recovery period is broken into four stages (early, middle, late, post) each focusing on
restoring pain management, ROM, strength, weight bearing/ joint loading, and
neuromuscular control. The “early” phase begins immediately following surgery and
general extends to six-week post-surgery. During this period the focus is restoring ROM, i.e
gaining full extension, and neuromuscular function. Special focus is placed on muscle
activation and reestablishing normal gait patterns. This includes emphasis on avoiding
poor gait mechanics like stiff-knee gait while promoting normal toe-off to help establish
normal gait speed and cadence.

In order to progress to the “middle” phase patients must show full ROM as well as
accomplish basic gait goals like stepping up/down and symmetrical loading during
unassisted walking. The “middle” phase extends from 6-12 weeks post-surgery. During the
period more dynamic exercises are emphasized. Jogging begins as well as perturbed
balance; single leg stance on foam pad, during this time as regaining endurance becomes a
focus of the rehabilitation prescription. As this prescription progresses, symmetrical
loading is important to ensure normal loading of the repaired joint. Approximately 12
weeks, 3 months, post-surgery, a patient would begin the “late” phase, which only lasts for
four weeks, 16 weeks post-surgery. During this phase jogging duration and intensity is
increased with emphasis on minimizing events like “hard landings” making the patient focus on specific muscle activation without co-contraction, not contracting quadriceps with hamstrings. Increasing multi-joint maneuvers like squats, speed ladder, and plyo-jumps can be added as permitted by patient's pain.

**Summary:**

A review of the literature is clear in establishing gait symmetry as a key variable that can be used to identify musculoskeletal injury and pathology. This metric is typically derived using laboratory techniques and is generally difficult to determine during everyday activities performed outside of a research or clinical setting. Recently trunk-mounted accelerometers incorporated as part of a GPS based monitoring device have showed promise. However, few data exist to validate these devices against bi-lateral foot or ankle mounted accelerometers and during conditions where symmetrical and asymmetrical gait exists. Thus, there is a need to validate trunk-mounted against bi-lateral devices and during period of known altered gait.
Figure 1. The GPSports SPI HPU unit.
Figure 2. Synchronization of left and right lower extremities during gait cycle. Top: Walking gait, Bottom: Running gait. Image obtained from: http://clinicalgate.com/assessment-of-gait/
\[ \text{ASI}_\% = \left[ \frac{|X_r - X_l|}{\frac{1}{2}(X_r + X_l)} \right] \cdot 100 \]

Figure 3. Symmetry index equation. \( X_r \) and \( X_l \) represent peak vertical forces during right and left foot strike, respectively (Z-axis)[19]
Figure 4. SPIHPU with vest front (top) and back (bottom) showing unit in pocket
Figure 5. Raw SPIHPU acceleration data. Shown are Z-axis (yellow), X-axis (red) and Y-axis (green). The resultant is shown in blue. The Figure was obtained from GPSports Team AMS software package.
Figure 6. Heart rate and velocity visualization. The red line represents heart rate and the blue line represents running velocity. The Figure was obtained from GPSports TeamAMS software package.
Chapter 3

Methods
Subjects:

The study used healthy collegiate soccer players with no current lower body injury. Current lower body injury will be defined as an injury that has occurred within the past 30 days. An additional subject recovering from anterior cruciate ligament (ACL) reconstruction surgery will also be monitored. Subject's information can be seen in Table 1. All procedures were approved by the Virginia Tech Institutional Review Board (IRB and 16-387 and 16-619). All procedures were fully explained to all subjects and informed consent was obtained prior to data collection.

Accelerometry:

Subjects were asked to where trunk mounted accelerometers (SPI HPU, GPSsport) (all studies) as well as bi-ankle-mounted accelerometers (MSR145S, MSR Electronics GmbH) (Validation Study). SPI HPU units were mounted in accordance to manufacture recommendation being secured near vertebrae T-4 and T-5 with proprietary vest. Characteristics of the two accelerometers are shown in Table 2. Ankle mounted units were secured at the lateral malleolus with PowerFlex tape using the lateral malleolus and fibula as landmarks as supported by literature [47]. PowerFlex was chosen as the best means to secure accelerometers to the ankle due to its material designs which would minimally perturbs subjects natural gait. Once units are mounted warm-up activities were performed to familiarize subjects with equipment and protocols.

Trunk mounted accelerometers are 100 Hz, 16g tri-axial accelerometer equipped with a 50 Hz magnetometer to determine axial orientation. The associated software produces a symmetry index using a proprietary algorithm (GPSports, TeamAMS). This
algorithm identifies and compares peak acceleration values of each foot strike and computes symmetry using the equation in Figure 3.

Accelerometer data from the two lower leg-mounted accelerometers were sampled 50 Hz using manufacturer provided software. They were then analyzed using MATLAB. A rolling average was first used to low-pass filter the data which allowed for identification of peak acceleration (PA) along the vertical or Z-axis for each foot strike. Next we will need to compare each unit’s (left vs right) data by applying the peak acceleration along the Z axis from right and left stance phase (identified as Xr and Xl respectively, in the symmetry equation used in Figure 3.

**Validation Trial:**

In order to induce gait asymmetry, subjects were tested under three test conditions in the order of bi-lateral shod (wearing two shoes), uni-lateral shod (wearing left shoe), and unshod (no shoes) conditions. Subjects were asked to wear soccer cleats of their choice. During each trial, they performed 15-50m runs at approximately 70% intensity, self-reported, with a minute recovery between efforts (5 for each condition). All trials were administered on the same day utilizing a flat artificial turf field (FieldTurf) to minimize effects from varying surfaces.

Symmetry scores from each trial within a condition were averaged. Trunk- and lower leg-mounted symmetry scores were compared using a 2-way repeated measures ANOVA (condition X device) using JMP. Running velocities were compared using a 1-way ANOVA (condition). Significance was established at the p<.05 level. Effect sizes were
calculated using $\eta^2 (\eta^2 = \frac{SS_{\text{effect}}}{SS_{\text{total}}})$ with 0.01 considered small, 0.06 considered medium and 0.14 considered large.

**Application Trial:**

Three, 1600m efforts trials of varying intensities were conducted on separate days. These included a 1600m run performed in approximately 16 km/hr (6 minute mile), 16 x 100m sprints performed at near maximal velocity, self-reported, and a 1600m jog at approximately 8 km/hr (12 minutes per mile). Trials were conducted on separate days, to better isolate the fatiguing exercise and were carried out as part of routine, off-season training. All efforts were performed on a 400m outdoor running track with all subjects completing each activity at the same time. For this trial, subjects were fitted with the trunk-mounted units alone. Running symmetry scores were determined for the first and last 100m of each 1600m trial and for first and last of the 100m sprints bout using the SPIHPU and proprietary software.

Differences in running symmetry and velocity were determined by 2-way repeated measures ANOVA (trial X time) using JMP. Significance was established at the $p<.05$ level. Effect sizes were calculated using $\eta^2$ as described above.

**Case Studies:**

Two case studies are presented as further validation of the SPIHPU units ability to identify running symmetry and asymmetry. In the first case study, a single male subject who was recovering from ACL reconstruction surgery was examined. Data collection began 60 days post-surgery and continued for 6 weeks. For this individual, recovery was
monitored semi-weekly. Running symmetry was determined during varying lengths of straight-line constant velocity running. As the subject was cleared for greater training participation, running speed (intensity) was allowed to increase.

A second subject suffered a blow to the lower leg during off-season training. He continued to train for the remainder of the session. Following the session, he was diagnosed with an ankle sprain and entered into a rehabilitation program. Running symmetry was assessed immediately before and after the injury. It was also assessed for 10 days following injury (rehabilitation program) after which the subject was cleared for full participation in training activities.

For both subjects, accelerometer data were recorded during the designated rehabilitation protocol established by Virginia Tech Sports Medicine staff. Running speeds and exercise intensities were adjusted by the staff as tolerated by each subject. Running symmetry values were determined prior to (acute injury study) and during the rehabilitation periods as described for the Validation and Application studies.
Table 1. Subject characteristics for each study.

<table>
<thead>
<tr>
<th>Variable</th>
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<th>Application Trial (n=16)</th>
<th>Case Studies (n=2)</th>
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Table 2. Accelerometer specifications.

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<tr>
<td>Data collection (Hz)</td>
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Chapter 4

Results
**Validation Trial:**

Raw accelerations for unilateral-shod running are shown in Figures 7 and 8. Shown are Z-axis (vertical) accelerations detected with the SPIHPU units (trunk-mounted) for successive foot strikes as well as the bilateral ankle mounted devices. As can be seen, peak accelerations are noticeably different between right and left foot strike.

The mean symmetry (Figure 9) and mean running velocity (Figure 10) were compared between each trial for each subject (ANOVA tables are shown in the Appendix). Symmetry scores were significantly greater for the unilateral shod condition (1S) compared to the other two conditions for both trunk and ankle mounted accelerometers. The effect size for condition was considered large. There were no differences in symmetry between the bilateral (2S) and un-shod (0S) conditions. There was a small difference between data collected from trunk- and ankle-mounted devices however, no device by condition interaction was found. This indicates a running asymmetry when subjects experienced an artificially induced alteration in gait.

Running velocity for the 2S condition was significantly lower than the 0S condition. Velocities during the 1S and 0S condition were not different. This amounted to a 4.7% reduction in running velocity compared to the other conditions (medium to large effect size).

These results suggest that trunk-mounted accelerometry can detect artificially-induced running asymmetry. In addition, the magnitude of asymmetry detected by the trunk-mounted units was similar to that detected by lower leg mounted accelerometers.

**Application Trial:**
The mean running symmetry scores (Figure 11) and running velocities (Figure 12) showed the type of exercise performed affected running symmetry. The intensity of activity did not significantly affect symmetry. However, there was a higher asymmetry during the final 100m if the 1600m trial. The 1600m trial was the only activity to show a significantly increased symmetry score. The effect sizes for activity (trial), interval (first and last 100m) and their interaction were all considered medium.

The 16 x 100m showed a significant decrease in velocity between first and last trial. As anticipated, running velocities were highest during the 16x100m efforts and lowest during the 1600m jog. Effect sizes for activity was considered large and considered small for the interval and the interaction.

These results suggest that running symmetry, as determined using trunk-mounted accelerometry, is not greatly affected by running speed but is altered by fatiguing activity.

Case Studies:

For the first case study, a single subject suffered a tear to his right anterior cruciate ligament (ACL) and underwent reconstruction surgery. Five weeks following surgery, he began a program of slow jogging along with traditional strengthening and range of motion exercises. His exercise intensity was gradually increased over the next three months. Figure 13 shows significant asymmetry following ACL reconstruction. In this case, symmetry scores are positive reflecting an injury to the right leg. An initial increased running asymmetry appears to arise as the rehabilitation program begins. This likely reflects the gradual increase in running velocity during the rehabilitation program. After
two months of rehabilitation, running asymmetry was still evident both visually and from SPIHPU data.

For the second case study, an individual suffered an ankle injury to his left leg resulting from being kicked on during a training session. After sustaining the injury, the subject continued to train for several minutes after which the session ended (Figure 14). He was later diagnosed with an ankle sprain and his training was limited for several days. As he became symptom free, his activities were increased and resumed full training within two weeks. Figure 14 shows acute changes in running symmetry from the period before the injury and after. Prior to the injury, there are large variations in running symmetry. This likely reflects the nature of the activity being performed. Soccer training requires players to execute a number of directional changes at both low and high running velocities. The increased impact force during a change of direction movement would likely affect the symmetry calculation. Following the injury, this subject shows a marked increase in symmetry reflecting an asymmetrical gait pattern. Also note the large change in symmetry occurring immediate after the injury compared to the validation and application trials.

In Figure 15 the player’s symmetry scores over the days before and following the injury. This shows a large negative asymmetry scores in the days following the injury. These are followed by decreasing asymmetry through the recovery and rehabilitation period.

Both case studies indicate that running symmetry determined by trunk-mounted accelerometry is altered immediately after an injury and remains so during rehabilitation.
Figure 7. Raw accelerometry data obtained from the HPI SPU unit. R and L denote right and left foot strikes, respectively.
Figure 8. Raw accelerometry data from the bi-lateral accelerometers. R and L denote right and left foot strikes, respectively.
Figure 9. Running symmetry values during bi-lateral shod (2s), uni-lateral shod (1s) and unshod (0s) running trials. * p<.05 vs 0s and 2s conditions.
Figure 10. Running velocity during bi-lateral shod (2s), uni-lateral shod (1s) and unshod (0s) running trials. *p<.05 versus 0s and 2s.
Figure 11. Running symmetry values during the three 1600m trials. *p<.05 versus the first 100m of the trail.
Figure 12. Running velocity values during the three 1600m trials. * p<.05 versus 100s and jog, † p<.05 versus 100s and 1600m. ‡ p<.05 versus 100s first 100m and last 100m
Figure 13. Mean running symmetry scores during an ACL reconstruction rehabilitation program.
Figure 14. Running imbalance scored during a training session in a single player before and after sustaining a foot injury. The session consisted of a warm-up, fitness training and match play. Approximately 140 after the start of the session, the player sustained a foot injury. Training ended approximately 15 minutes later.
Figure 15. Running imbalance scores before and after suffering an ankle injury. The injury occurred on day 0. The subject was restricted from full training between days 1 and 9. After day 9, the subject resumed full participation.
Chapter 5

Discussion
The results of this study show that the SPI HPU accelerometer can be used to detect asymmetrical gait patterns. Four pieces of evidence support this conclusion: 1) An artificially induced gait abnormality induced a running asymmetry 2) Changes in running symmetry were qualitatively and quantitatively similar (visual and SPIHPU data), 3) Running symmetry is affected by exercise to fatigue and 4) two case studies of injured subjects revealed alterations in running symmetry. Based on these results, it is evident that the SPI HPU units can detect both normal and abnormal gait patterns.

**Validation Trial:**

This trial demonstrated a novel approach to inducing a running asymmetry in normally healthy subjects. By having subjects remove their right shoe, a leg length discrepancy was created. This discrepancy led to an increased positive (favoring the right leg), running symmetry produced by the GPSports proprietary software and ankle units. The data showed a statistically significant difference when comparing symmetry scores of the bilateral-, unilateral- and un-shod conditions. When calculating the symmetry score a trend developed in which the proprietary symmetry algorithm began detecting a running symmetry during the early part of steady state, constant velocity, running and continued until the subjects speed fell below the threshold of 8 km/h. It was hypothesized that this delay in detection of running symmetry was due to the 10 step minimum needed for the proprietary algorithm to calculate a symmetry score. Unfortunately, without knowing their exact algorithm it is hard to make definitive conclusions as to the source of this abnormal distribution of foot-strikes taken into consideration to develop the symmetry score. By validating the score against ankle accelerometers we showed similar trends in data where
the ankle units reported increased scores. This was expected as data was being collected closer to the point of contact.

An interesting finding of this study experiment was the statistically significance between unshod and shod velocities where the unshod condition showed an increased velocity. The first thought was that this may have been a result of fatigue but all subjects went through the experimental protocol progressing from shod to uni-shod to unshod where fatigue would most affect the unshod trials. Due to the rest and order of exercises we do not feel as though fatigue had any effect on our experiment rather it may be the biomechanics response of the foot. Kelly et al. conducted an experiment that compared foot biomechanics during shod and unshod running. The main findings were that when velocity was controlled, 14 km/h, shod running led to an increased stride duration and ground contact time while decreasing peak loading rate and peak propulsive force when compared to unshod conditions. This begins to make more sense if the longitudinal arch (LA) of the foot is modeled as a spring. During the loading phase the LA is compressed converting kinetic energy to potential energy stored in the tendons and ligaments. As the gait cycle enters terminal stance the LA extends this potential energy is returned to the ground and propulsion occurs.

**Application Trial:**

To our knowledge this study was the first to look at how fatiguing activities contribute to running symmetry. During the 16 x 100s and 1600m trials subjects were exerting maximal effort due to the intervals of each trial. Considering the 16 x 100s and 1600m were statistically significant for velocity and symmetry respectively we were able
to influence directly and indirectly alter running symmetry. During the 1600m bout, velocity was consistent between first and last 100m portion while symmetry score doubled, 2.106%. The 16 x 100s showed a significant reduction in velocity, \( \sim 2.56 \text{ km/h} \), and an increase in symmetry score, 0.731%, which had a relatively low p value of 0.062. Although the change in symmetry scores were not statistically significant the low p-value supports further studies where velocity could be better controlled. The development of increased running asymmetry and change in velocities is thought to be the result of musculature becoming fatigued and larger muscle groups being recruited as the smaller muscle groups fatigue. These smaller muscle groups would be muscles associated with fine motor control contributing to running technique. A loss of technique can lead to alterations in running mechanics ultimately resulting in a difference between how the body was being loaded from the beginning of each trial to the end.

During the jog there was a small reduction in running symmetry, 0.156%, may give support for a warm-up activity. The jog was performed at a self-selected speed below 40% of maximal effort. If a warm-up is to prepare the body through active stretching and muscle warming, this may also reduce a subjects running symmetry score off the subject. A limit to this experiment was that subject performed each trial on separate days due to the intensity of the 100s and 1600m.

Although some physiological or psychological differences may have been present in subjects between days the trials were conducted in the same week minimizing these effects. Future studies could utilize RPE scores to better understand these potential sources of error. Studying how different athletes would respond to the same experiment could also change the findings. A sprinter may maintain more consistent velocities while a track
athlete specializing in the 1600m may not show as severe of an asymmetry development due to the specificity of training scheme. Findings of this nature can give coaches data which can be used to identify points of races where athletes can focus on being more efficient.

**Case Studies:**

We were able to detect significant running symmetry scores directly following the subjects left foot being struck by another player. This could be used to detect musculoskeletal injury as shown in Figure 14, which warrants further research potentially in athletes immediately following a concussive grade impact. We also showed how symmetry scores reduced throughout the rehabilitation period and were near normal as the player was cleared to return to play. This speaks highly of Virginia Tech sports medicine team but also shows a use in understaffed clinics. Several subjects can be monitored simultaneously and be compared across successive days.

When looking at the subject recovering from ACL reconstruction data initially looks irregular. When data is compared to the rehabilitation prescription the scores begin to make more sense. Early phases of rehab focus on regaining strength and gaining ROM, considering the subjects do not begin to perform unassisted walking until the middle phase, 6 weeks, into the prescription. This period is recorded as symmetry scores favoring the right side of moderate magnitude. As the subject enters late phase, more challenging intensities are encouraged leading to higher symmetry scores. We were able to continue monitoring the subject past the initial physical therapy prescription. This is important considering patients are most susceptible to re-injury up to eight months.
post-surgery [60]. Since most insurance companies will not approve patients to attend sessions past a certain date or allotments of sessions this gives promise to wearables. If these patients could do activities wearing an accelerometer that uploaded data to a database and interpreted for them, then they could continue receiving feedback as to how they’re rehabilitation is progressing.

During the ACL data collection there were two 10-day periods, 53-62 and 65-75, where our system was down. This would have been key data for interpretations to be made and utilize acute vs. chronic ratios. Further research should be done on subjects recovering from injuries to identify potential risk factors to re-injury such as excessive asymmetry.

**Conclusions:**

Considering the few studies utilizing trunk-mounted accelerometers our purpose was first to validate trunk-units against ankle-units then show how running symmetry varies with fatigue and lastly show some real world utilization of such variables. Similar trends between symmetry scores generated from trunk-mounted and ankle-mounted accelerometers supported the use of the SPIHPU unit for collecting acceleration data. Detecting a change in running symmetry during varying fatigable activities highlights a potentially new metric to measure an athlete’s health. Potential uses in settings like physical therapy clinics are numerous in providing feedback on how recovery is progressing. Trunk-mounted units allow for collection of data across a large group of athletes providing information to personnel on a day to day basis.

Future studies could identify how running symmetry varies between times of acceleration, steady state, and deceleration running. These periods of movement may give
information helpful to groups like sprinters who are looking to maximize efficiency.

Another area of potential use is the use of trunk-mounted accelerometers for balance test such as the Y-test. There is a need for more quantitative ways to assess subjects after concussive blows in contact sports. Teams already utilizing such products shows a potential in evaluating their capacity to measure postural sway allowing for quick and effective evaluation of players.
References


Appendix
### Analysis of variance tables for the Validation Study

#### Variable – Running Symmetry

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<th>Source</th>
<th>df</th>
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<th>F</th>
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#### Variable – Running Velocity

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### Analysis of variance tables for the Application Study

**Variable – Running Symmetry**

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**Variable – Running Velocity**

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Informed Consent Documents

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: Quantifying the Physical Demands and Injury Risk of Training and Competing in College Athletics

Investigators: Jay H. Williams  jhwms@vt.edu, 1-8208

Name  E-mail / Phone number

You are being asked to be in a research study. It is entirely your choice. In order to decide whether or not you want to be a part of this study, it is important that you read and understand this form. It is also important that you ask any questions that you may have and that you understand all the information in this form. This process is called “informed consent.”

I. Purpose of this Research Project

This research is being conducted by faculty and graduate students of the Department of Human Nutrition, Foods and Exercise at Virginia Tech. The purpose of this study is to determine the relationship between physical demands of participating in varsity collegiate athletics and the risk of injury. Our goal is to establish guidelines for developing training programs that will improve competitive performance while minimizing the risk of injury. This study will provide the groundwork for those goals. You are being asked to participate because you are a member of a Virginia Tech intercollegiate varsity sports team. You have also been cleared for participation in intercollegiate athletics by medical personnel. We plan to enroll 200 student-athletes over the course of three years. It is also important for you to know that the results from this study may be used for research publications. However, your anonymity and confidentiality is insured.

II. Procedures

This study will require your participation for pre-season, in-season and off-season training. During all practices and competitions, you will be asked to wear a small device that records your movements and heart rates through global positioning, acceleration and heart rate monitoring (GPSports units). The data from this device will then be downloaded and analyzed by the investigators. Prior to practice and competition, you will be asked to provide subjective ratings of your readiness for the day’s session, including the level of muscle soreness and the level of physical recovery. After each session, you will be asked to rate your level of perceived exertion for the session.

The Virginia Tech Athletic Department Sports Medicine staff will also provide the researchers with information regarding any injuries that you might suffer during practice or competitions. This information will be limited to the type of injury, body location of the injury, and cause of injury (if known). The Sports Medicine staff will also notify the researcher you are required to limit or miss practice of competition due to the injury.

During the course of the study, you will not be asked to perform or participate in any physical activities outside of normal practice and competition. If you are diagnosed with an injury or illness that requires you to sit out or miss a session, you will not be asked to participate until you are medical cleared. Thus, your participation will be limited as allowed and required by the coaching and medical staff. In addition, the injury information collected will be limited to that which is routinely exchanged between the
coaching and Sports Medicine staffs.

Should you agree to participate, you will be expected to:

- Participate in all practices and competitive events as allowed by the Sports Medicine staff and required by the coaching staff.
- Wear the GFSports units during practice and competition.
- Provide perceptual evaluations of practice and competitions.
- Notify the Sports Medicine staff of all injuries.

III. Risks

You may experience discomfort and fatigue during practices and competition due to physical exertion. In some cases, extreme physical exertion can result in injury and health problems including death. As such, Virginia Tech Sports Medicine staff will be present at all practice session and competitive events. However, it is important to emphasize you will not be asked to perform any physical activities other than those normally required of a varsity student-athlete and directed by the coaching staff. Thus, the added risks of participating in this study are minimal.

IV. Benefits

The benefits of this research is an understanding of the physical demands of participating in intercollegiate athletics and their association to performance and injury risk. Our goal is to use this information to help the coaching and medical staffs of each sport better train their athletes in a manner that maximizes performance but minimizes injury risk.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research project may be published by my name or identity will not be revealed. Information obtained during the course of the study will remain confidential, to the extent allowed by the law. Your name will not appear on any of the results. No individual responses will be reported. Only group findings will be reported to publications. Confidentiality will be maintained by assigning each participant an identification number and recording all data by those identification numbers. The only record with the participant’s name and identification number will be kept on a password secured hard drive stored in a locked office. At no time will the researchers break confidentiality or release identifiable results of the study to anyone other than individuals working on the project without your written consent.

The Virginia Tech (VT) Institutional Review Board (IRB) may view the study’s data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

You will receive no compensation for participating in this study.

VII. Freedom to Withdraw

It is important for you to know that you are free to withdraw from this study at any time without penalty. You are free not to answer any questions that you choose or respond to what is being asked of you without penalty.

Virginia Tech Institutional Review Board Project No. 16-387
Approved April 26, 2016 to April 25, 2017
Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject.

Should you withdraw or otherwise discontinue participation, you will be compensated for the portion of the project completed in accordance with the Compensation section of this document.

VIII. Questions or Concerns

Should you have any questions about this study, you may contact one of the research investigators whose contact information is included at the beginning of this document.

Should you have any questions or concerns about the study's conduct or your rights as a research subject, or need to report a research-related injury or event, you may contact the VT IRB Chair, Dr. David M. Moore at moored@vt.edu or (540) 231-4991.

IX. Subject's Consent

I have read the Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

_________________________________________ Date__________
Subject signature

_________________________________________
Subject printed name
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Quantification of Running Symmetry Using Trunk-Mounted Accelerometry

Investigators:

<table>
<thead>
<tr>
<th>Name</th>
<th>E-mail/Phone number</th>
</tr>
</thead>
<tbody>
<tr>
<td>David J. Saba</td>
<td><a href="mailto:dsaba@vt.edu">dsaba@vt.edu</a>, 412-330-0471</td>
</tr>
<tr>
<td>Jay H. Williams</td>
<td><a href="mailto:jhwms@vt.edu">jhwms@vt.edu</a>, 540-231-8298</td>
</tr>
</tbody>
</table>

You are being asked to be in a research study. It is entirely your choice. In order to decide whether or not you want to be a part of this study, it is important that you read and understand this form. It is also important that you ask any questions that you may have and that you understand all the information in this form. This process is called “informed consent.”

I. Purpose of this Research Project

This research is being conducted by faculty and graduate students of the Department of Human Nutrition, Foods and Exercise at Virginia Tech. The purpose of this study is to determine the relationship between physical demands of participating in varsity collegiate athletics and the risk of injury. Our goal is to establish the use of a trunk-mounted accelerometer to determine gait abnormalities, namely running symmetry. This could prove to be a powerful tool in measuring the extent of running asymmetries or “limps” that are associated with injury rehabilitation. We will artificially induce a limp by asking you to run wearing neither, one or both of your shoes. We will then determine of the accelerometer data can detect the difference in your gait.

You are being asked to participate because you are a member of a Virginia Tech intercollegiate varsity sports team. You have also been cleared for participation in intercollegiate athletics by medical personnel. It is also important for you to know that the results from this study may be used for research publications. However, your anonymity and confidentiality is insured.

II. Procedures

This study will require your participation in running activities during which you will be asked to wear small devices that record your movements. One device will be worn on the back between your shoulder blades (GPSports) and two will be attached to the outside of each ankle (MSR145S) and two will be placed under both feet, inside of your sock (Ped-o-Ped). You will be asked to perform a total of nine 100m runs at approximately 70% of your maximal effort. You will be asked to perform these runs under three conditions: wearing both shoes, a single shoe and no shoes. All three trials will be conducted on the same day. All activities will be performed on an artificial turf field to minimize the risk of slipping. Your time commitment to this project is estimated at 30 minutes.

During the course of the study, you will not be asked to perform or participate in any physical activities outside of moderate intensity running. If you are diagnosed with or sustain an injury during the activity, you will be asked to stop and cease participation in the study. The Sports Medicine staff at Virginia Tech will be available to diagnose and treat any injuries.

Should you agree to participate, you will be expected to: 1) Participate in nine, moderate intensity 100m runs wearing neither, one or both shoes, 2) wear the accelerometers during the activity.

Virginia Tech Institutional Review Board Project No. 16-619
Approved August 10, 2015 to August 9, 2017

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III. Risks

You may experience discomfort and fatigue during the trials due to physical exertion. In some cases, extreme physical exertion can result in injury and health problems including death. In addition, induction of a running asymmetry may cause minor musculoskeletal discomfort including delayed onset muscle soreness and sock running on artificial turf can result in slipping. As such, Virginia Tech Sports Medicine staff will be available to diagnose and treat any medical conditions within the scope of their training. However, it is important to emphasize that you will not be asked to perform any physical efforts well below the intensity and duration of a typical soccer training session. However, the amount of asymmetrical running will be limited to less than 300m and sock running is a commonplace during a training cool-down. Thus, the added risks of participating in this study are minimal.

Any expenses accrued for seeking or receiving medical or mental health treatment will be the responsibility of the subject and not that of the research project, research team, or Virginia Tech.

It should be noted that there is the potential for equipment damage (e.g., stained or torn socks) to occur when performing the activities described here. After testing, socks will be inspected by the investigators for damage. Should you suffer sock damage, they will be replaced by the investigators.

All trials will be conducted on an artificial turf field. Thus there is minimal risk of injury due to slipping while wearing socks.

IV. Benefits

The benefits of this research is an understanding running gait asymmetries and how they can be used to diagnose injuries and monitor rehabilitation. As trunk-mounted wearable technology is increasing in use and popularity, the use of such devices can greatly aid in the rehabilitation process.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research project may be published but your name or identity will not be revealed. Information obtained during the course of the study will remain confidential, to the extent allowed by the law. Your name will not appear on any of the results. No individual responses will be reported. Only group findings will be reported to publications. Confidentiality will be maintained by assigning each participant an identification number and recording all data by those identification numbers. The only record with the participant’s name and identification number will be kept on a password secured hard drive stored in a locked office. At no time will the researchers break confidentiality or release identifiable results of the study to anyone other than individuals working on the project without your written consent.

The Virginia Tech (VT) Institutional Review Board (IRB) may view the study’s data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

You will receive no compensation for participating in this study.

VII. Freedom to Withdraw

It is important for you to know that you are free to withdraw from this study at any time without penalty. You are free not to answer any questions that you choose or respond to what is being asked of you without penalty.
Please note that there may be circumstances under which the investigator may determine that a subject should not continue as a subject.

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**VIII. Questions or Concerns**

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**IX. Subject’s Consent**

I have read the Consent Form and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent:

________________________   Date_______

Subject signature

________________________

Subject printed name
VITA
David Joseph Saba

David was born in Newport News Va. on May 11 1993 to Dave and Lisa and older brother to Ashley. After moving to Pittsburgh Pa. David attended Seton LaSalle high school in Mt. Lebanon Pa. where he enjoyed participating in crew and swimming. Following high school David attended Virginia Polytechnic Institute and State University where he majored in Human Nutrition, Foods, and Exercise. After identifying an interest in exercise physiology David decided to continue with a post-bachelor program focusing on sports analytics and human biomechanics. David’s master research looked at identifying the capacity of a popular trunk-mounted monitoring system as well as how running intensity influenced gait symmetry. After completing his masters David will attend the Southwest College of Naturopathic Medicine where he hopes to focus on pain management and sports medicine.