Stride Leg Ground Reaction Forces Pre- and Post-Fatigue in Collegiate Baseball Pitchers

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STRIDE LEG GROUND REACTION FORCES PRE- AND POST-FATIGUE IN COLLEGIATE BASEBALL PITCHERS

By

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Bachelor of Science—Athletic Training
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ABSTRACT

Stride Leg Ground Reaction Forces Pre- and Post-Fatigue in Collegiate Baseball Pitchers
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Context: Baseball pitching requires the coordination of the lower and upper extremities to effectively generate and transfer force to the ball. High-velocity pitchers have been found to have significantly greater stride leg force generation than low-velocity pitchers. The influence of stride leg fatigue on pitching has yet to be investigated. Objective: The purpose of this study was to examine the effect of stride leg fatigue on peak vertical ground reaction forces (vGRFs) and hand velocity. Design: Pretest-posttest. Setting: Biomechanics laboratory. Patients or Other Participants: A convenience sample of 11 collegiate baseball pitchers (19.27 ± 0.64 years old; 85.88 ± 12.16 kg; 1.84 ± 0.07 m; eight right-handed, three left-handed) volunteered. To be included, participants needed to be listed as a pitcher on a collegiate baseball roster without reported injuries to the upper or lower extremity that resulted in decreased training volume during the fall baseball season. Interventions: Simultaneous three-dimensional kinematic (200 Hz; Vicon Motion System Ltd., Oxford, UK) and kinetic data (1,000 Hz, Kistler Inc., Amherst, NY, USA) were collected. Participants utilized a self-selected, competition-style warm-up. Retro-reflective markers were placed on bony landmarks of the stride leg, trunk, and throwing arm. Participants threw maximal effort fastballs into a net placed 5.0 meters from the portable pitching mound’s rubber. Participants were positioned so that the stride leg foot landed on the force platform. After 10 rested-state pitches, participants performed a fatigue protocol of stride leg Bulgarian split squats at 60 beats/minute for maximum repetitions. One-minute rest was given between each of the four sets. Following the fatigue protocol, participants threw 10 fatigued-state maximal effort pitches. Main Outcome Measures: Outcome measures included
peak vGRFs of the stride leg and hand velocity at release. The means of valid trials (minimum of seven) were used for analyses. Peak vGRFs were reported as body weight [BW=GRF/(kg·9.81m/s²)]. One-tailed, paired t-tests (α = 0.05) were utilized to test for statistical significance between rested and fatigued conditions and a Pearson product-moment correlation were used to examine the relationship between vGRFs and hand velocity. Statistics were computed in SPSS. **Results:** Participants completed 81.36 ± 21.94 total Bulgarian split squat repetitions and reported an RPE score of 7.82 ± 1.60. Paired t-tests revealed significant decrease (p = 0.005) between peak Fz1 vGRF values in rested-state (1.57 ± 0.49 BW) compared to fatigued-state (1.31 ± 0.62 BW). Hand velocity in the rested-state (23.32 ± 1.60 m/s) was significantly (p=0.004) higher than fatigued-state (22.61 ± 1.55 m/s), but not functionally relevant. Peak vGRF and hand velocity at release were not significantly correlated in either condition (rested-state Fz1: r = 0.162, p = 0.318; Fz2: r =.151, p = 0.329; fatigued-state Fz1: r = 0.228, p = 0.250; Fz2: r = 0.277, p = 0.410). **Conclusions:** Peak vGRFs Fz1 and hand velocity decreased when the stride leg fatigued to a level of statistical significance. Due to the small sample size, the variable does warrant future investigation. Increased understanding of the influence of the stride leg upon pitching endurance and performance could influence rehabilitation and training programs.
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CURRICULUM VITAE
CHAPTER ONE: INTRODUCTION

Overhand pitching is a movement that requires coordination of the lower extremity, trunk, and upper extremity segments in order to effectively transfer force throughout the kinetic chain to project a baseball. 1-6 It has been reported that angular velocities at the shoulder joint during overhand pitching can reach magnitudes near 7000°/s at the point of ball release. 7 When projecting a baseball at high velocities, the movement patterns between the lower extremity and upper extremity need to be coordinated appropriately. 1,3,5,6 Should this coordination of movement break down, the pitcher could be at a higher risk of injury. 1,3,5,6

Historically, injury rates have been relatively low in baseball, with high school baseball players having 75.9/1000 injuries per athlete-exposure. 8 Of all injuries occurring in high school baseball athletes, 63.3% occurred within the upper extremity. 8 High school pitchers specifically experience 47.1% of all upper extremity injuries at the shoulder. 8 In professional baseball players from 2002-2008, 51.4% of injuries were upper extremity related. 9 Pitchers exhibit a higher rate of 67.0% of all injuries occurring at the shoulder, elbow, or wrist joints. 9 Injury prevention programs have been aimed at strengthening and improving the mobility of the upper extremity, but recent evidence indicates that the lower extremity may also influence the upper extremity. 2-4,10,11

While previous research has focused on the role of the upper extremity and adaptations in the overhand pitch, there is limited empirical research regarding the role of the lower extremity. Understanding the potential influence of the lower extremity in the ability to produce torque may be beneficial to increasing and maintaining ball velocity over multiple innings. Oliver and Keeley 12 identified an increased activation of the gluteus medius at stride leg foot contact, by nearly 145% of maximum voluntary isometric contraction; this muscle has its highest activation
during the arm cocking and arm acceleration phases. This evidence supports the presence of a link between the stability of the pelvis and the stability of the upper extremity. Losing pelvic stability could decrease directional force production through the phases of the pitch leading up to ball release.

At the onset of muscular fatigue, pitchers alter multiple kinematic (movement pattern) parameters to their pitching technique, including arm, trunk, and knee positions. Murray et al. found significant decreases in pitching velocity, maximal shoulder external rotation, knee flexion, maximum shoulder distraction force, maximum elbow distraction force, horizontal abduction torque at ball release, and maximum horizontal abduction torque at the end of a five to six inning pitching bout. When fatigued, pitchers had a decrease in ball velocity of nearly 2.24 m/s, decreased maximal glenohumeral external rotation by nine degrees, and the stride leg landed with more knee flexion. The increase of stride leg knee flexion and maximal glenohumeral external rotation upon landing could indicate a loss of coordination in pitching timing patterns that could influence ball velocity.

Escamilla et al. also examined the kinematic changes while pitchers fatigued over several innings and found increased knee flexion during maximal glenohumeral external rotation and ball release and identified an increased hip lean during hand separation, which is also known as the stride of the pitch. These alterations in upper and lower extremity kinematics could indicate a loss of coordination and timing between segments. This may change the efficiency of force transfer from the lower extremity to the upper extremity and not only put the pitcher at a risk of a performance decrease, but also a higher risk for injury.

While the relationship between fatigue and ground reaction forces during pitching has not been investigated, there have been a few studies that have defined a relationship between ball
velocity and ground reaction forces. Higher vertical ground reaction forces (vGRF) of the stride leg have been reported in high-velocity pitchers when compared to low-velocity pitchers. In addition, higher vGRF is produced by collegiate pitchers compared to high school pitchers during maximal glenohumeral external rotation and upon ball release. \(^2,3\)

To our knowledge, the effects of lower extremity fatigue on vGRF during stride leg landing in overhand pitching has not been evaluated. Positive relationships have been found between high velocity pitchers and increased vGRF, however a large component of baseball is the ability to maintain velocity at the onset of fatigue. \(^2,3\) Understanding the influence of fatigue on the vGRF during pitching could aid in a greater understanding of the relationship between the lower extremity and hand velocity. This increased understanding could lead to changes in programs related to performance, rehabilitation, and injury prevention in the baseball athlete.

The purpose of this study is to examine the effect of lower extremity fatigue on stride leg vGRF during overhand pitching. Two discrete points of the vGRF waveform, labeled as Fz1 and Fz2, were identified. Fz1 was defined as the initial peak vGRF following stride foot contact and Fz2 was defined as the subsequent vGRF peak. A secondary purpose of this study is to identify if either peak vGRF, Fz1 or Fz2, are correlated with hand velocity. It was hypothesized that Fz1, Fz2, and hand velocity will decrease during the fatigued state and hand velocity will be positively correlated with both Fz1 and Fz2.
CHAPTER TWO: LITERATURE REVIEW

The following literature review has focused on the role of the lower extremity within each phase of the baseball pitch and its contribution to force production and hand velocity. The actions of the stride and push legs are understood and previous research has been compiled regarding the current theories and patterns of ground reaction forces of both legs with a higher focus upon the stride leg. The next variable of overhand pitching examined is the effect of fatigue upon the pitcher during a game or game simulation. Finally, the justification for the use of a Bulgarian split squat for a baseball specific fatiguing muscular activity will be explained.

Function of the Lower Extremity in Force Production and Injury Risk

The pitching motion can be divided into six different phases that include: windup, stride, arm cocking, arm acceleration, arm deceleration, and follow-through. The windup is initiated with the lower extremity by the pitcher shifting his weight to his push leg. The striding knee is then elevated and flexed as the pitcher enters a single-support phase. A single support phase is defined as a position in which the pitcher only has one foot in contact with the ground, while a double support phase is defined as a time when both of the pitcher’s feet are in contact with the ground. During the stride phase, the pitcher allows his body weight to shift towards home plate and the stride leg moves down and towards the same direction. The stride phase should stretch the pitcher into a lunge like position, but not to the extent that he cannot rotate his hips towards home plate. Once the pitcher’s stride foot makes contact with the mound, entering a double-support position, he is in the arm-cocking phase and can initiate hip rotation. As the hips rotate, this allows for the arm to accelerate as the stride leg begins to extend. After the ball is released the arm has to decelerate by activating the
posterior musculature of the shoulder.6,16,17 Once the shoulder completes deceleration, the follow-through occurs.6,16,17 During this phase, the stride leg has completely extended and the hip is fully flexed as the pitcher ends in a balanced single-support position.6,16,17

Research examining the function of the lower extremity and pitching performance has seen a recent increase in literature regarding the force production of the legs. It has been theorized that the lower limbs not only aid in increased ball velocity, but also creates a stable base for force to be effectively transferred to the upper extremity.2-4,10,18 A stable base has been defined as a pitcher staying balanced with his center of gravity and weight distributed equally between his feet.19 Increased stability could decrease the amount of force lost from the push leg through the phases of a pitch.20

The stride and push legs play different roles in force generation. The stride leg acts to separate the rotation of the pelvis and trunk.21 As the pelvis assumes a more “open” position, or begins to face home plate, the humerus increases in external rotation as the pitcher enters the early-cocking and late-cocking phases of the pitch.19,21 This increase in external rotation creates increased torque about the shoulder and aids in producing a greater ball velocity.9,21 The pelvis cannot rotate towards home plate without significant help from the push leg.21 As the hip joint of the push leg extends, activating the gluteus maximus, and adds power and distance to the striding leg allowing for a more powerful position and aids in the rotation of the hips towards home plate.21,22

A baseball pitch can be described as a stretch-shortening cycle activity. The pitcher has to stretch the muscles through the pelvis and trunk as the hips rotate towards home plate and the shoulders stay facing the first or third base.19,23 As the stretch through the trunk between the
throwing arm and the stride leg increases, there is a subsequently greater force produced from the stored elastic energy and stretch reflexes than a concentric contraction alone.\textsuperscript{24}

In addition to the role of the lower extremity, aside from force generation, pelvic stabilization is important for the upper extremity to rotate upon while the pitcher accelerates the ball.\textsuperscript{12,18} An increased activation of bilateral gluteus medius muscles has a direct relationship with increased activation of the scapular stabilizing muscles, specifically the lower trapezius.\textsuperscript{12} A greater stabilization of the pelvis correlates with a greater stabilization of the upper extremity, which not only means an improvement in force retention from the stride push legs but a decreased risk of injury.\textsuperscript{12}

As the pitch advances to the arm deceleration and follow-through phase, the dominant gluteus maximus contraction shifts from the push leg to the stride leg as it acts to decelerate and stabilize the pelvis.\textsuperscript{22} The maximum force generated by the push leg is highly correlated with wrist linear velocity, which also indicates an increased ball velocity.\textsuperscript{25} As the push leg generates force, the stride leg acts as a braking mechanism by extending the knee to stop the translational motion of the lower extremity and trunk.\textsuperscript{5,25} While the lower extremity is stopping, the upper extremity is still moving towards home plate to deliver the ball.\textsuperscript{25} Between high-velocity and low-velocity pitchers, the high-velocity group has much greater knee extension angular velocity at ball release.\textsuperscript{5}

During the follow-through phase of the throw, the pitcher is again in a single-support position, and could potentially be at a higher risk for injury.\textsuperscript{16} Dillman et al.\textsuperscript{16} believes the follow-through phase of the pitch has a high risk of injury due to the stresses of deceleration forces upon the shoulder and elbow, while Seroyer et al.\textsuperscript{18} claims there is decreased joint loading and much smaller forces. Seroyer et al.\textsuperscript{18} would argue that the deceleration phase is a much
more likely culprit for upper extremity injury due to the large eccentric contractions of the posterior shoulder musculature. This discrepancy could be due to the inability to determine exactly when arm deceleration and follow-through actually occur in relationship to each other.

The aforementioned single-support phases have gained attention regarding injury prevention. Due to the high demand of balance and strength during these positions, there is a larger probability of injury occurring.11 Garrison et al.11 evaluated baseball players with ulnar collateral ligament (UCL) tears of the elbow and balance scores between their stride and push legs in comparison to a control group without UCL tears. It was found that those with UCL tears had significantly lower (p<0.001) Y-Balance Test scores than those without injury in both the stride and push legs.11 This research supports the theory of a lower extremity stable base allows for the upper extremity to safely transfer the force to the ball.

*Ground Reaction Forces and the Overhand Pitch*

As the lower extremity’s role within the baseball pitch becomes more defined from a pitching technique standpoint, identifying the phase of the pitch that generates the most force is important for ball velocity development. Few researchers have investigated the ground reaction forces of pitchers. MacWilliams et al.26 designed a study using a force platform under the push and stride legs to identify the ground reaction force pattern of a pitch. In the anterior-posterior axis, the push limb gradually increases until stride-foot contact, reaching a maximum of -0.35 N/BW.26 After stride foot contact, the push limb leaves the ground and no longer creates a ground reaction force.26

Once the stride foot makes contact with the ground, the anterior-posterior shear force reaches a maximum of 0.72 N/BW just before ball release.26 As for the medial-lateral direction,
the push limb produces minimal forces due to the concentration of the force profile in the
direction of the pitch (anterior-posterior axis). The stride limb exhibits a medial-lateral shear
due to the task of having to stop the rotation of the trunk and upper extremity during
deceleration. The force is medially directed then changes to a lateral direction once the
pitcher’s weight is fully transferred to the stride leg. Finally, in the vertical direction, the push
limb has a peak magnitude early in the pitch cycle with 1.0 N/BW, while the stride leg exhibits a
maximum vertical force right before ball release at 1.5 N/BW. Guido et al. reported
different maximum values with peak ground reaction forces of the stride leg in the anterior-
posterior axis reaching 2.45±0.20 N/BW and vGRF reaching an average of 2.02±0.43 N/BW.

Since the overhand pitching motion is initiated by the lower extremity when the stride leg
hip and knee joints flex towards the trunk during the wind up, the lower extremity and trunk not
only generate the torque that is transmitted to the ball but it also creates the stable base for the
upper extremity to efficiently and safely distribute that force. Previous studies have examined
a relationship between higher ground reaction forces and larger momentum generation of the
lower extremity with higher ball velocity. Kageyama et al. examined the relationship among
kinematic and kinetic variables and fastball velocity between low- and high-ball velocity
collegiate pitchers. Regarding ground reaction forces, Kageyama et al. recorded statistically
significant higher stride leg vGRF values in the higher velocity group when compared to the low
velocity group. The stride leg had a statistically significant peak value of 1.7 N/kg along the
medial/lateral axis in the high velocity group versus a peak value of 1.0 N/kg generated by the
low velocity group. In the vertical axis, the high-velocity group had higher peak values than the
low-velocity group with 19.4 N/kg and 16.6 N/kg, respectively (p<0.01).
Elliot et al. \textsuperscript{1} examined multiple biomechanical variables and concluded that the ability to stabilize the trunk over the stride leg upon ball release is a characteristic of a high velocity overhand pitcher. It was reported that higher resultant ground reaction forces occurred upon stride foot contact in the higher velocity group when compared to a lower velocity group and also mentioned “it would seem reasonable to assume that the genuine power in the pitch followed the planting of the stride foot”. \textsuperscript{1} Based upon these theories, examining the ground reaction forces of the stride leg would prove beneficial in determining high versus low velocity pitchers. \textsuperscript{1,3} Those pitchers who could generate a higher peak ground reaction force would be more likely to have a higher pitch velocity. \textsuperscript{1,3}

Even though the amount of research regarding the role of the lower extremity is minimal, there are some generalizations that have been concluded. A pitcher’s ability to drive his bodyweight from the push leg to the stride leg upon ground contact and having a higher peak vGRF are characteristics of a high velocity pitcher. \textsuperscript{2,3} Due to the nature of the sport, the effect of fatigue causes multiple changes within kinematic and kinetic variables, but changes in ground reaction forces has yet to be examined.

\textit{Fatigue and the Overhand Pitch}

Fatigue has long been a phenomenon that has interested different facets of sports medicine and sports performance. Fatigue has been known to not only alter an athlete’s mechanics but also put the athlete at a higher risk of injury. \textsuperscript{15,28} Strength and conditioning coaches implement training programs aimed at minimizing muscular fatigue to prevent fatigue-related injuries and performance decreases. \textsuperscript{28}
Within baseball, coaches track pitch count, changes in ball velocity, and mechanical markers, like a dropped elbow, to determine if the athlete is fatigued to the point of performance impairment and subsequently remove them from play. More often than not, athletes will make pitching technique alterations in an attempt to maintain velocity. These mechanical changes could put the athlete at a higher risk of upper extremity injury during a fatigued pitching bout, including but not limited to labrum lesions within the shoulder, rotator cuff pathology, and ulnar collateral ligament tears of the elbow.

Throughout baseball sports performance literature there has been a focus on upper extremity fatigue and the kinematic alterations those athletes will implement and the subsequent increased risk of injury to the upper extremity. While the effect of fatigue on the lower extremity and trunk kinematics has been explored within the current literature, the clinical relevance of the lower extremity on upper extremity injury prevention and performance impairment is less explored.

Grantham et al. noted that as the pitcher fatigues their amount of hip lean towards the home plate as their hands separate increases, which caused the pitcher to land with uneven shoulders. Landing with uneven shoulders could lead to increased glenohumeral internal rotation torque and valgus load upon the elbow. This alteration to pitching mechanics could put the pitcher at an increased risk of dropping his elbow during the acceleration phase of the throw. Historically, pitching coaches have used the ‘elbow drop’ as an indicator of fatigue. If the lower extremity fatigues more quickly and causes the upper extremity to compensate in order to keep pitch velocity high that could put the pitcher at an increased risk of shoulder and elbow injuries. Increasing the strength and endurance of the lower extremity may theoretically
minimize the effects of fatigue and allow for the pitcher to increase pitch count, decrease the potential for injury, and improve performance.\textsuperscript{28}

According to Escamilla et al.\textsuperscript{15} during a single pitching performance, “the effect of muscular fatigue on throwing mechanics is believed to cause altered arm and trunk positions during the arm cocking and arm acceleration phases of the baseball pitch”. As the throwing athlete fatigues, the elbow ‘drops’, ball velocity decreases, the peak external rotation decreases, and stride leg knee flexion increases during maximum external rotation and ball release.\textsuperscript{15,28} As fatigue becomes more prevalent the hip flexes more during maximal shoulder external rotation and ball release, there is an increase in hip lean at hand separation, and an increase in stride length.\textsuperscript{2,3} Mullaney et al.\textsuperscript{7} examined upper extremity and lower extremity muscular activity before and after a fatiguing pitching bout of an average of 99 pitches over seven innings by using a handheld dynamometer. They found a significant decrease in strength between rested and fatigued states in multiple muscles of the dominant shoulder, but did not find a significant decrease of strength in the lower extremity.\textsuperscript{7}

There have been multiple studies that examine the effect of fatigue upon pitchers by using a pitch count and having the subject complete the pitching motion for multiple repetitions, but most of these studies have examined the upper extremity.\textsuperscript{7,13,15,28-30} Oliver et al.\textsuperscript{12,14,20} has completed multiple electromyography studies linking the maximal voluntary isometric contraction (MVIC) of the gluteus medius to the upper extremity musculature by having subjects complete certain pitch counts. There has yet to be a study that examines how maximal muscular fatigue of the lower extremity can affect the vGRF of the baseball pitch.\textsuperscript{14,20}
The Bulgarian Split Squat as a Fatiguing Exercise

The Bulgarian split squat was chosen as the fatiguing exercise due to its similar position to the striding, ball acceleration, and ball delivery phases of the baseball pitch. Within a baseball pitch, the stride leg acts to rapidly extend the knee to stop the non-dominant side of the body and transfer the generated forces into the ball. The quadriceps muscle group has to contract and rapidly extend the knee. Along with this rapid extension of the knee, the torso of the pitcher has to stabilize over the stride leg to transfer the power of the forward momentum generated by the push leg in previous phases of the pitch. Stabilizing over a single leg activates the gluteal group, specifically the gluteus maximus and medius.

During a lunge, there is a co-contraction of the hamstrings and quadriceps muscle groups upon knee and hip extension, but once the knee is above 60° of flexion the quadriceps muscle group produces a higher contractile force. The Bulgarian split squat is more controversial regarding the quadriceps to hamstring ratio of muscle contraction. McCurdy et al. identified higher peak quadriceps activation in a two-legged squat at 105.44 mV versus 70.6 mV in a Bulgarian split squat while the Bulgarian split squat had a higher peak hamstring amplitude versus the two-legged squat (103.33 mV and 60.02 mV respectively). McCurdy et al. used 85% of a 3-repetition max Bulgarian split squat for the study, while the proposed study would use the participant’s body weight. Ayotte et al. performed a study with participants performing split squats using body weight as resistance and produced 55-66% MVIC in the quadriceps and only 9-15% MVIC in hamstring activity, which supports the theory that a Bulgarian split squat has a higher activation of the quadriceps versus the hamstrings.

Due to the single-support nature of the stride leg, the gluteus medius and maximus are highly activated during the acceleration, delivery, and deceleration phases of the pitch.
McCurdy et al.\textsuperscript{32} noted a statistically higher gluteus medius peak of 72.17 mV during the split squat than the two-legged squat that registered a peak mean of 57.85 mV ($p<0.033$).\textsuperscript{32} This increase in gluteus medius activation is attributed to the increased demand of having to keep the hips level during a Bulgarian split squat.\textsuperscript{32}

The Bulgarian split squat requires a high muscular demand from the quadriceps, gluteus medius, and gluteus maximus.\textsuperscript{31-33} While there is debate as to the quadriceps to hamstring activation ratio during this activity, previous research indicates there is a large quadriceps activation demand required to complete the movement.\textsuperscript{33} The stabilizing effect of the gluteal muscles is also of high importance to transfer energy to a stable stride leg and the Bulgarian split squat requires a higher gluteal muscular activation to stabilize the single stance position.

Since identifying the importance of the lower extremity in power production and injury prevention, there is an increased need for exploring all the potential changes within the lower extremity upon the onset of muscular fatigue. Understanding changes within vGRF of the stride leg could improve programs aimed to enhance performance and decrease the likelihood of injury. The previous literature has highlighted the importance of the lower extremity within each phase of the pitching motion, summarized the current knowledge regarding the ground reaction force waveform of the stride leg, and identified existing information regarding the effect of fatigue upon pitching. It has become clear there is a need for an increased understanding of the relationship between vGRF and fatigue and the impact upon hand velocity.
CHAPTER THREE: MATERIALS AND METHODS

Purpose

The purpose of this study is to examine the effect of lower extremity fatigue on stride leg vGRF during overhand pitching. A secondary purpose of the study is to identify if vGRF is correlated to hand velocity. It is hypothesized that Fz1, Fz2, and hand velocity will decrease during the fatigued state and hand velocity will positively correlate with both Fz1 and Fz2.

Subjects

Fifteen collegiate baseball pitchers between the ages of 18-30 volunteered to participate in this study. Inclusion criteria included: being apparently healthy adults currently listed as a pitcher on a collegiate baseball roster, no reported injuries to the upper or lower extremity in last six months that resulted in a decrease in training volume, and participation in fall collegiate baseball activities. This information was obtained via self-reporting on a previous medical history questionnaire. Participants were excluded from the study if they were currently injured or were required to miss practices or competition during the fall baseball season due to injury. Eleven of the 15 recruited participants were utilized for data analysis (19.27±0.64 years old; body mass: 85.88±12.16 kg; height: 1.84±0.07 m; 1.55±0.52 years of collegiate pitching). Eight pitchers were right-handed and three were left-handed. Two pitchers, one left- and one right-handed, threw sidearm, not overhand. Prior to data collection, all participants signed Institutional Review Board (IRB #972132) approved informed consent forms, and anthropometric data were collected.
Instrumentation

Kinetic data were obtained via one Kistler (1,000 Hz, Amherst, NY, USA) force platform that was mounted flush with the floor. A Vicon Nexus three-dimensional motion capture system (200 Hz; Vicon Motion System Ltd., Oxford, UK) was used to collect and obtain kinematic data. Retro-reflective markers were placed on the bony landmarks of the stride leg including the base of the second toe, a three-marker heel cluster, medial and lateral malleoli, medial and lateral knee joint center, bilateral anterior superior iliac spines, bilateral iliac crests, bilateral posterior superior iliac spines, and the sacrum. Four-marker cluster sets were placed on the lateral aspect of the middle third of the thigh and leg. Thorax markers were placed on the xyphoid process of the sternum, manubrium of the sternum, bilateral acromioclavicular joints, spinous process of the seventh cervical vertebrae, spinous process of the tenth thoracic vertebrae, and the right inferior angle of the scapula. The dominant (pitching) arm had a four-marker cluster placed on the upper arm, medial epicondyle of the humerus, lateral epicondyle of the humerus, forearm, styloid process of the ulna, styloid process of the radius, and the metacarpal phalangeal joint of the fourth finger. A portable pitching mound (True Pitch Inc., 202-4, Altoona, IA, USA) with a decline of 4° was placed behind the force platform\textsuperscript{2,3}. The mound was adjusted for each pitcher to allow for them to land on the center of the force platform. The participants threw into a strike zone net located 5.0 meters from force platform.

Experimental Design

Prior to arrival, participants were advised to wear tight-fitting shorts, and their team issued baseball turf shoes. Upon arrival to the University of Nevada, Las Vegas’ Sports Injury Research Center (SIRC), the study procedures were explained to the participants, time was
allowed to ask questions regarding the study, and anthropometric data (age, height, and body mass) were measured and recorded.

Participants were allowed to warm up in accordance to their normal pitching performance routine within the SIRC lab space. This included, but was not limited to: running on a treadmill, performing upper extremity banded exercises, stretches for the upper extremity and upper extremity, throwing flat-ground pitches, and pitches on the mound and force platform set-up. Following the warm-up, retro-reflective markers were adhered to anatomical landmarks, and then participants performed the study protocol. Pitchers were instructed to start with both feet on the mound with the push leg adjacent to the rubber. During the pitching motion, pitchers landed onto the force platform with the stride leg. Trials were not use for analysis if they did not land on the force platform. Pitchers were allowed adequate time, approximately 10-20 seconds, between each pitch to simulate a game scenario. Ground reaction force and kinematic data were collected and recorded for the entire pitching motion from wind-up to the ball entering the net. Participants then completed the fatigue protocol. After the fatigue protocol was completed, the participant performed ten more maximal-effort fastball pitches using methodology identical to rested state pitches.

**Fatigue Protocol**

Participants performed four sets of unilateral Bulgarian split squats until muscular failure with one-minute rest intervals between sets. The Bulgarian split squats were conducted in a lunge position with the stride leg, the leg that steps forward in the pitching motion (dominant), in front and the pivot leg, the leg that pushes off the rubber of the mound (dominant or push leg), extended behind the participant with the foot resting on a 50cm high platform. The participants used their own body weight as resistance and were instructed to flex the front knee
(stride leg) to 90° and return to an extended knee position until they were unable to complete another repetition. A metronome set to 60 beats per second was utilized to control the frequency of concentric (‘up’ phase) and eccentric (‘down’ phase) muscle contractions equaling 30 repetitions per minute. The numbers of repetitions achieved for each set were recorded.

Figure 1: Bulgarian split squat exercise ‘up’ position and ‘down’ positions.

Participants rated their perceived exertion using a Borg 0-10 point Rating of Perceived Exertion (RPE) scale with numerical ratings (0.5, very, very light; 1, very light; 2, fairly light; 3, moderate; 4, somewhat hard; 5, hard; 7, very hard; 10, very, very hard). Participants were verbally oriented to the scale with the explanation that a score of 0.5 would indicate very, very little fatigue or tiring, while a score of 10 would indicate the participant could not complete another repetition. A set of repetitions would be completed once the participant indicated they had reached a perceived level of exertion greater than eight. When the participant indicated a rating of eight or nine they were encouraged to perform more repetitions for the next set as they approached a perceived exertion rate of 10. Once a fatigued state was reached, participants
immediately performed ten maximal-effort pitches following the same methodology described above.

**Data Reduction and Analysis**

Ground reaction force (GRF), kinematic, and kinetic data were exported to Visual 3D Biomechanical Software Suite (C-Motion, Inc., Watertown, MA, USA) and were filtered with a low-pass Butterworth digital filter at 6 Hz and 50 Hz, respectively. Once filtered, vGRF data were exported to Microsoft Excel (Microsoft Inc., Redmond, WA, USA) and normalized to body mass (N/BW). Due to limited previous literature presenting vGRF waveform data on the stride leg, each participant’s data was qualitatively analyzed for commonalities in force profiles. Hand velocity was computed as the first derivative of the modeled hand segment.

Of the 15 recruited pitchers, four were eliminated from the data analysis for various reasons. One participant’s vGRF waveform was trimodal and two more participants had rested state bimodal waveforms that no longer exhibited distinct Fz1 and Fz2 values during the fatigued condition. The fourth participant exhibited both trimodal and bimodal waveforms during both conditions.

**Statistical Analysis**

The independent variable includes two levels; rested and the fatigued state. Dependent variables included peak vGRF and ball velocity. Statistical analyses were performed with SPSS software using paired t-tests ($\alpha = 0.05$) to determine statistical significance for each dependent variable. Means and standard deviations of a minimum seven trials were calculated for each participant and were evaluated with paired t-tests to determine statistical significance between the rested and fatigued conditions. Pearson product-moment correlations were used to indicate
which variables had a positive relationship with hand velocity. The correlation was calculated with valid trials for each individual pitch.
CHAPTER FOUR: RESULTS

Eleven of the 15 recruited participants were utilized for the data analysis. Of the four sets of Bulgarian Split Squats, the participants completed 81.36±21.94 total repetitions and reported a mean RPE score of 7.18±1.25 before their final set of pitches. After the fatigued pitching trials, participants reported an RPE score of 7.82±1.60. Peak vGRFs were identified at two separate discrete events, Fz1 and Fz2 for both conditions. Fz1 was defined as the initial peak vGRF following stride foot contact and Fz2 was defined as the subsequent vGRF peak. To allow for comparison of Fz1 and Fz2 during group analysis, the eleven pitchers who maintained a bimodal waveform were used for analysis. Waveforms were evaluated and of the pitchers that were excluded pitcher one had a trimodal waveform in both the rested and fatigued conditions. Pitchers two, three, and four all presented with bimodal waveforms within the rested state, but during the fatigued state the waveform pattern became either linear or trimodal. Due to the chosen method to analyze data that contained the Fz1 and Fz2 events, these four participants were excluded from statistical analysis. Mean and standard deviation values for participants with seven or more viable trials were computed for rested and fatigued states for Fz1, Fz2, and hand velocity (Table 1).

One-tailed paired t-tests revealed a statistically significant decrease (p = 0.005) in peak fatigued Fz1 values compared to the rested condition (1.31±0.62 BW and 1.57±0.49 BW, respectively). There was no significant (p = 0.131) difference between rested peak Fz2 (1.90±0.26 BW) and fatigue peak Fz2 (1.83±0.24 BW). Hand velocity in a fatigued state (22.61±1.55 m/s) was significantly (p=0.014) decreased when compared to the rested state (23.32±1.60 m/s).
Table 1. Peak value vGRF and hand velocity between rested and fatigued conditions and p-values resulting from paired t-tests.

<table>
<thead>
<tr>
<th></th>
<th>Rested</th>
<th>Fatigued</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fz1</td>
<td>1.57±0.49 BW</td>
<td>1.31±0.62 BW</td>
<td>p=0.005*</td>
</tr>
<tr>
<td>Fz2</td>
<td>1.90±0.26 BW</td>
<td>1.83±0.24 BW</td>
<td>p=0.131</td>
</tr>
<tr>
<td>Hand Velocity</td>
<td>23.32±1.60 m/s</td>
<td>22.61±1.55 m/s</td>
<td>p=0.004*</td>
</tr>
</tbody>
</table>

Note: Statistical significant (p < 0.05) is denoted with an asterisk (*)

There was no significant correlation between either peak vGRF events and hand velocity conditions. Rested hand velocity and rested stride leg vGRF had a Pearson-moment correlation of 0.162 to Fz1 and a correlation of 0.151 to Fz2 (Table 2). Fatigued hand velocity and fatigued stride leg vGRF had a Pearson correlation of 0.228 to fatigued Fz1 and 0.277 to fatigued Fz2 (Table 3).

Table 2: Rested state mean peak value vGRF and hand velocity Pearson-moment correlations.

<table>
<thead>
<tr>
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<th>Rested (n=11)</th>
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<tr>
<td></td>
<td>Hand Velocity (m/s)</td>
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</tr>
<tr>
<td></td>
<td>23.32±1.60</td>
<td></td>
<td></td>
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<tr>
<td>vGRF (BW)</td>
<td>Fz1</td>
<td>1.57±0.49</td>
<td>1.90±0.26</td>
</tr>
<tr>
<td>Pearson product-moment Correlation</td>
<td>0.162</td>
<td>0.151</td>
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<tr>
<td>p-value (1-tailed)</td>
<td>0.318</td>
<td>0.329</td>
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Table 3: Fatigued state mean peak value vGRF and hand velocity Pearson-moment correlations.

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<thead>
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<th>Fatigued (n=11)</th>
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<tbody>
<tr>
<td></td>
<td>Hand Velocity (m/s)</td>
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</tr>
<tr>
<td></td>
<td>22.61±1.55</td>
<td></td>
<td></td>
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<tr>
<td>vGRF (BW)</td>
<td>Fz1</td>
<td>1.31±0.62</td>
<td>1.83±0.24</td>
</tr>
<tr>
<td>Pearson product-moment Correlation</td>
<td>0.228</td>
<td>0.277</td>
<td></td>
</tr>
<tr>
<td>p-value (1-tailed)</td>
<td>0.250</td>
<td>0.410</td>
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</table>
CHAPTER FIVE: DISCUSSION

The purpose of the current study was to examine the effect of lower extremity fatigue on stride leg vGRF during overhand pitching. It was hypothesized that Fz1, Fz2, and hand velocity would decrease during the fatigued state. During the fatigued state, Fz1 and hand velocity significantly decreased, but the decrease in hand velocity may not be functionally significant, meaning the change in hand velocity was minimal and is unlikely to impact a pitcher’s performance.

Fz1 was identified as the initial foot contact with the force platform. The vGRF waveform then decreased as the stride knee bent to attenuate forces when making initial foot contact during the stride and early cocking phases of the pitch. As the pitcher advanced to arm acceleration, the vGRF waveform increased and peaked at Fz2. The vGRF waveform then decreased a final time when the ball was delivered and finally released.

There is a limited amount of literature describing the vGRF waveform of the stride leg. MacWilliams et al. is the seminal work reporting a description of the waveform and this study was published in 1998. The authors reported the stride leg vGRF to “gradually built up after foot contact to approximately 1.5 BW, peaking just before ball release”. The current study’s Fz1 values were similar to MacWilliam et al.’s peak vGRF findings, but due to the lack of reported anthropometric and ball velocity data, it would be difficult to compare maximal values between the studies. The current study also supports the claim that maximum vGRF occurs just prior to ball release.

In 2012, Guido et al. designed a study to investigate ground reaction forces and pitching mechanics. Their study, which included force platforms fabricated into a mound, revealed conflicting results with MacWilliams et al. as well. Their vGRF waveform had two
distinct peaks, but they reported that the maximum peak force occurred 45 milliseconds after initial stride foot contact. Guido et al. had a higher peak value for Fz1 than Fz2. The current study also found the vGRF waveform to be bimodal, which agrees with Guido et al.’s reported waveform, but reports Fz2 to be a higher mean value than Fz1, which disagrees with Guido et al.’s findings.

There were some variations between the pitcher’s vGRF waveforms who participated in the current study. Few had an almost linear increase, which would support the findings of MacWilliams et al., while others presented with a trimodal pattern, but predominantly the pitchers had a bimodal vGRF waveform. Possible explanations for the differences in reported vGRF values could be MacWilliams et al. used a force platform that was fabricated into the declined slope of a portable pitching mound, while the force platform for this study was flat and flush with the ground. This alteration in landing surfaces could influence the resulting vGRF. MacWilliams et al. also used all right-handed, true overhand pitchers, while the current study did not control for arm dominance and position. At this time, it is unknown how arm position could influence vGRF. MacWilliams et al. did not report anthropometric or ball velocity data, which could explain why the maximum peak values are in disagreement.

A secondary purpose of the study was to identify if peak vGRF variables are correlated to hand velocity. Within the current body of literature, Kageyama et al. is the most recent study to address ground reaction forces and ball velocity. They were able to identify that pitchers with a higher ball velocity had greater stride leg vGRFs. This study did not use a statistical correlation to determine the relationship between the two variables because they divided their participants into high- and low-velocity groups. While higher stride leg vGRF may be a characteristic of
high-velocity pitchers, this does not answer the question of how these variables interact with one another. Kageyama et al. 3 did not include an illustration or description of the vGRF waveform.

This current study was the first to incorporate fatigue and vGRFs within participants and was not able to identify a relationship between hand velocity and stride leg vGRF. This study also qualitatively revealed information regarding vGRF waveform variability within the pitcher’s waveform when fatigued (Figures 2 & 3). These observations indicate that changes most likely occurred in more variables than peak vGRFs and hand velocity. Further research should evaluate other ground reaction force variables within the stride leg, such as loading rate. Not only is there a need to examine the stride leg more thoroughly, but push leg ground reaction force variables also need to be examined in order to increase the understanding of hand velocity production.
Figure 2: Vertical ground reaction force of a single pitcher who is representative of the biomodal group during the rested condition.

Figure 3: Vertical ground reaction force of a single pitcher who is representative of the biomodal group during the fatigued condition.
There were multiple limitations with the study design. Quantifying and identifying true fatigue is challenging while maintaining a balance between safety and experiment. Subjective measurement tools were utilized to aid the quantification of fatigue by using a modified Borg scale. Due to the design of the biomechanics lab, hand velocity was quantified to evaluate pitching velocity instead of ball velocity. The hand is the fastest moving body segment of the body during the pitching motion, but may not have the same velocity as the ball. Finally, the researcher did not control for variations in pitchers’ handedness and arm slot. Arm slot variations included true overhand, side arm, and submarine style ball deliveries. True overhand and side arm pitchers were present within the participant sample. The influence of arm position upon vGRF is unknown.

Multiple efforts were made to ensure that data collection sessions mimicked pitching in game-time conditions. Pitchers performed warm-ups similar to typical pitching performances. These warm-ups included, but were not limited to: performing stretches, resistance band exercises, and running on a treadmill. Pitchers were allowed to perform has many pitches off the mound until they felt comfortable. Pitchers were given the same amount of time they would experience during a game setting between each data collection pitches.

Practical Applications

As a coach, strength and conditioning professional, or athletic trainer, these results could be valuable for designing rehabilitation and strengthening protocols of the lower extremity in baseball pitchers. If the stride leg becomes fatigued, pitchers may utilize the push leg more, which may cause kinematic changes to the upper extremity and increase stresses upon the shoulder and elbow. Improving the strength of the stride leg to control the eccentric forces
applied to the quadriceps muscle group when landing can decrease the potential for the pitcher to put himself in a mechanical position that could induce injury or diminish performance. Athletic trainers should incorporate eccentric loading exercises to the quadriceps as well when conducting rehabilitation with a pitcher who has an elbow or shoulder injury. Implementing these exercises for starting pitchers, who incur higher pitch counts, could decrease the impact of fatigue related mechanical changes as innings increase.  

Conclusions

This study identified a bimodal vGRF waveform and decreased Fz1 and hand velocity values when the stride leg becomes muscually fatigued. Stride leg vGRF was not found to be meaningfully correlated to hand velocity indicating that either the push leg or other stride leg variables have a much greater influence upon hand velocity. However, our findings are vital because this is the first study to the researcher’s knowledge that has examined the effects of fatigue within a pitcher on outcome variables such as vGRF and hand velocity. This study also adds to the very limited amount of research describing ground reaction force waveforms and values and the subsequent impact upon pitching mechanics and performance. Future research should focus upon other variables of the stride leg, like loading rate, and the push leg to gain a better understanding of the function of the lower extremity in force production and performance and injury consequences that can occur when fatigue becomes prevalent in baseball pitchers.
APPENDIX A: PRE-RESEARCH QUESTIONNAIRE AND DATA COLLECTION FORM

Participant ID: _______________

Date: _______________

Number of years pitching: _______________

Elbow or Shoulder Injury?: _______________
   If so, when?: _______________

Self-reported average velocity: __________

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<td>Sidearm</td>
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Descriptive Data

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Warm Up

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**Rested State Pitches**  
**Good Trial:** Stride foot lands fully on one force platform

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**RPE:** ____________

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**5-Minute Rest**

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**Bulgarian Split Squats**

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<th>Set Number</th>
<th>Number of Repetitions</th>
<th>RPE Score</th>
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Fatigued State Pitches
Good Trial: Stride foot lands fully on one force platform

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</table>

RPE: ____________

Notes

30
APPENDIX B: IRB INFORMED CONSENT FORM (Approval Number 972132-3)

INFORMED CONSENT
Department of Kinesiology and Nutrition Sciences

TITLE OF STUDY: Stride Leg Biomechanics Before and After a Fatiguing Lower Extremity Exercise Protocol in Collegiate Baseball Pitchers

INVESTIGATOR(S): Kara Radzak, PhD, LAT, ATC and Courtney Alley, LAT, ATC

For questions or concerns about the study, you may contact Courtney Alley at alleyc1@unlv.nevada.edu or Dr. Kara Radzak at kara.radzak@unlv.edu.

For questions regarding the rights of research subjects, any complaints or comments regarding the manner in which the study is being conducted, contact the UNLV Office of Research Integrity – Human Subjects at 702-895-2794, toll free at 877-895-2794 or via email at IRB@unlv.edu.

Purpose of the Study
You are invited to participate in a research study in addition to the data we are collected as a service to the team. The purpose of this study is to examine baseball pitching mechanics before and after a fatiguing Bulgarian split squat exercise protocol.

Participants
You are being asked to participate in the study because you fit the following criteria: You are a healthy collegiate baseball pitcher between the ages 18 and 30 coming in today for high-speed, 2-dimensional video (collected as a service to your team) and did not experience any injuries during the past six months or fall baseball season that caused a decrease in training volume.

Procedures
If you volunteer to participate in this study, you will be asked to do the following:

- Allow the research team to take descriptive measurements (i.e. height, body mass) and apply adhesive reflective markers temporarily fixed to joints and other anatomical landmarks. We use infrared motion capture cameras to film your body movements (this is the same technology used to generate animations for films).
- Warm-up however you prefer for a pitching performance
- Throw 10 fastball pitches into the strike zone at your top velocity off a portable pitching mound
Perform a bodyweight Bulgarian split squat exercise until fatigue or failure in four sets of maximal effort repetitions. A Bulgarian split squat is a lunge exercise with the behind foot elevated on a platform.

Throw 10 fastball pitches into the strike zone at your top velocity off a portable pitching mound.

The total duration of the study will be approximately 50-60 minutes.

Bulgarian Split Squat Exercise:

Benefits of Participation
You will receive a high-speed video of your pitching performance that you can use for technical evaluation of your pitching with your coach. In addition, your participation will assist with providing a greater understanding of the importance the lower extremity has regarding pitching velocity and effectiveness in order to improve injury prevention and performance programs.

Risks of Participation
There are risks involved in all research studies, but this study includes only minimal risks. You may become sore and fatigued from the Bulgarian split squat exercise protocol and feel uncomfortable during the data collection. The soreness you experience will be similar to an intense weight training session. If you participate in this study, there is a strong likelihood that you will be sore immediately after the experiment as well as 1-3 days after participating. This soreness may range from be mild or severe.

Cost / Compensation
There will be no financial cost to you to participate in this study. The study will take 50-60 minutes of your time with no direct compensation.

Confidentiality
All information gathered in this study will be kept as confidential as possible. No reference will be made in written or oral materials that could link you to this study. All records will be stored in a locked facility at UNLV for 3 years after completion of the study. After the storage time the information gathered will be deleted and destroyed.
Voluntary Participation
Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study. You may withdraw at any time without prejudice to your relations with UNLV. You are encouraged to ask questions about this study at the beginning or any time during the research study.
**Participant Consent:**
I have read the above information and agree to participate in this study. I have been able to ask questions about the research study. I am at least 18 years of age. A copy of this form has been given to me.

______________________________    __________________________
Signature of Participant                  Date

______________________________
Participant Name (Please Print)

**Audio/Video Taping:**
I agree to be videotaped for the purpose of this research study.

______________________________    __________________________
Signature of Participant                  Date

______________________________
Participant Name (Please Print)
REFERENCES


CURRICULUM VITAE

Courtney J Alley
1738 Autumn Rust Dr.
Las Vegas, NV 89119
phone: (208) 921-3468
Courtney.alley@unlv.edu

EMPLOYMENT

University of Nevada, Las Vegas, Las Vegas, NV
July 1, 2015 - Present

Graduate Intern Athletic Trainer

- Primary sport assignments: Softball, Baseball, and Football
- Learned how to conduct pre-participation physicals and concussion baseline testing for new and returning student-athletes
- Obeyed and enforced policies and procedures of the University of Nevada, Las Vegas and the NCAA
- Scheduled and coordinated medical appointments and follow-ups for student-athletes
- Learned how to implement and develop softball specific injury prevention programs that focused on windmill pitching and overhand throwing
- Created a return to pitching protocol for softball pitchers
- Executed baseball specific injury rehabilitation for pitchers and position players
- Supervised undergraduate athletic training students as a preceptor

Oregon Health and Sciences University, Portland, OR
August 1, 2014 – June 30, 2015

Athletic Trainer

- Developed policies and procedures regarding student-athlete care and emergency action plans
- Collaborated with students, teachers, parents, and school administration to ensure a student's care when injury occurred
- Marketed the utilization of an athletic trainer to the district athletics department
EDUCATION

University of Nevada, Las Vegas, Las Vegas, NV
MS Kinesiology
May, 2017
Thesis: Thesis Topic: Stride Leg Ground Reaction Forces Pre- and Post-Fatigue in Collegiate Baseball Pitchers

Linfield College
BS Athletic Training
June 2001

LICENSES AND CERTIFICATIONS

National Athletic Trainers’ Association Board of Certification
  o Certification Number: 2000017274
Certified Strength and Conditioning Specialist
  o Certification Number: 7247926228
National Provider Identifier
  o 1457758344

PROFESSIONAL MEMBERS

Far West Athletic Training Association (FWATA): 2015- Present
National Athletic Trainers’ Association: 2011-Present
National Strength and Conditioning Association: 2014-Present

PROFESSIONAL INVOLVEMENT

2016 FWATA Felix Rivera Memorial Scholarship

2017 FWATA Student Session Speaker, “The Life After Graduation: Transition from Student to Clinician”

Far West Athletic Training Association Annual Meeting
April 2017, Poster Presentation
“Stride Leg Ground Reaction Forces Pre- and Post-Fatigue in Collegiate Baseball Pitchers”