

An Exploration of Soccer Cleat Traction Characteristics Suited to the Mechanical Profile
of the Female Athlete

by

Emily Claire Karolidis

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Dissertation Committee:

Michael E. Hahn, Ph.D, Chair

Andrew R. Karduna, Ph.D., Core Member

Jordan C. Troester, Ph.D, Core Member

Susan L. Sokolowski, Ph.D., Institutional Representative

University of Oregon

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DISSERTATION ABSTRACT

Emily Claire Karolidis

Doctor of Philosophy in Human Physiology

Title: An Exploration of Soccer Cleat Traction Characteristics Suited to the Mechanical Profile of the Female Athlete

Market-available soccer footwear is historically designed according to male athlete mechanics. With known sex differences in movement patterns, joint moments, and joint loading, it should not be assumed that the female body is able to withstand the same amount of rotational and translational traction as do males. Soccer cleats could play a key role in moderating female athletes' exposure to torsional injury mechanisms over the course of game play, such as those mechanisms related to ACL injury. The purpose of this dissertation was to understand the effect of soccer cleat traction parameters on the cutting and landing mechanics of female soccer athletes. Based upon results gathered in this dissertation, novel prototypes of data-driven female traction plates were co-developed and mechanically validated in partnership with Puma SE.

This dissertation includes four projects: the first three were foundational in understanding the effects of traction parameters on female mechanics, while the final project involved the design and validation of prototypes informed by these findings. Project 1 assessed the effect of shortened stud lengths on knee stabilizer muscle activity and mechanics of seven female soccer players during abrupt stopping and cutting tasks in a turf motion capture lab. Results indicate a stud length reduction to 50-75% of the original stud length trends towards an improvement in frontal and sagittal plane knee kinetics and kinematics, and knee stabilizer muscle activity favoring the hamstring group.

Project 2 involved 10 male and 10 female soccer athletes performing unanticipated cutting tasks before and after systemic fatigue in cleats of both elliptical and bladed stud shapes. Knee kinetics, kinematics and utilized traction ratio were evaluated. Significant three-way interaction effects were found on the rate of utilized traction during initial contact, and main effects of sex and fatigue were found on knee valgus angle and knee flexion angle at initial contact, respectively. Project 3 assessed plantar pressure data collected during cuts performed during the systemic fatigue protocol of Project 2. Significant main and interaction effects of sex, cleat and fatigue were found on peak pressure across the anterior heel, medial forefoot, and lateral toes. Systemic fatigue progression was found to increase mediolateral center of pressure excursion and posterolateral peak pressure most notably among female participants in the bladed cleat. Based on results identified in Projects 1-3, Project 4 designed and mechanically validated cleat prototype iterations that would encourage lower risk knee mechanics for the female athlete. In this small sample validation, the cutting mechanics of 6 female athletes were compared before and after fatigue across two prototypes and one market available soccer cleat. Preliminary data identify lower risk knee mechanics to be encouraged in the prototypes when compared to the market available product. Joint power trends suggest the moderate prototype design, featuring a 12-25% reduction in stud length and elliptical-style studs, to reduce eccentric knee activity most effectively during cutting stance. The results of this dissertation illustrate how relatively minor modifications to traction parameters can have critical impact on the mechanics of female athletes. This series of studies demonstrates the importance of designing and validating footwear for the female athlete.

This dissertation includes co-authored material submitted for publication, as well as unpublished co-authored material.

CURRICULUM VITAE

NAME OF AUTHOR: Emily Claire Karolidis

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED

University of Oregon, Eugene & Portland, OR, USA
McGill University, Montreal, QC, Canada

DEGREES AWARDED

Doctor of Philosophy, Human Physiology, 2024, University of Oregon
Master of Science, Interdisciplinary Studies: Individualized Program, 2022,
University of Oregon
Bachelor of Science [Hons], Kinesiology, 2018, McGill University

AREAS OF SPECIAL INTEREST

Footwear biomechanics
Female athlete mechanics
Sports product design

PROFESSIONAL EXPERIENCE

External Footwear Biomechanics Researcher, University of Oregon x Puma, 2024
Graduate Employee, University of Oregon, 2020-2024
Graduate Teaching Assistant, University of Oregon, 2020-2022
Project Manager, University of Oregon x C-Therm Technologies, 2019-2021
Research Assistant, ParriagGroup, 2017-2020
Undergraduate Research Assistant, Occupational Biomechanics and Ergonomics
Laboratory, McGill University, 2017-2018

GRANTS, AWARDS, AND HONORS

Puma SE, Fixed Price Research Agreement for Female Soccer Cleat
Development, \$75 000, 2024

Best Doctoral Podium Presentation, Northwest Biomechanics Symposium, 2024

Ursula (Sue) Moshburger Scholarship, Department of Human Physiology,
University of Oregon, 2024

Nike Footwear Research Award Finalist, Footwear Biomechanics Symposium,
2023

Ursula (Sue) Moshburger Scholarship, Department of Human Physiology,
University of Oregon, 2023

New Balance Global Footwear Research Award Recipient, 2020

First Year Fellow Award, University of Oregon, Department of Human
Physiology, 2020

Spark Grant for Research and Innovation, Department of Product Design,
University of Oregon, \$500, 2020

Arthur and Lorna Henry Prize, Department of Kinesiology and Physical
Education, McGill University, 2017

Faculty of Education Scholarship, Faculty of Education, McGill University, 2017

Dean's Honour List, Faculty of Education, McGill University, 2017

J. W. McConnell McGill Entrance Scholarship, McGill University, 2014

PUBLICATIONS

Karolidis, E., & Hahn, M. E. (2023). Changes in knee mechanics with systemic fatigue and soccer cleat stud shape appear to differ by sex. *Footwear Science*, 15(sup1). <https://doi.org/10.1080/19424280.2023.2204556> [Full Article in Review]

Sokolowski, S.L., Karolidis, E., & Hakimian, A. (2023). Sports apparel warm and cool touch effusivity spectrums based on human perception. *Proceedings of the Applied Human Factors and Ergonomics Conference 2023*

Sokolowski, S. L., Karolidis, E., Hakimian, A., Ackermann, S., (2022). Measuring cool touch of key sports performance apparel t-shirt materials using a Modified Transient Plane Source (MTPS) sensor to inform future technology development. *Proceedings of The Minerals, Metals & Materials Society 2022 Annual Meeting & Exhibition*, p. 1327-1337. https://doi.org/10.1007/978-3-030-92381-5_126

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From this milestone, to the next, and all others that may come to be.

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CHAPTER I

INTRODUCTION

Background and Significance

A sport met with complex mechanical demands, soccer involves rapid coupling of acceleration, deceleration, and directional changes. To perform these high-intensity movements, substantial power must be both generated and absorbed by lower limb musculature [16]. Soccer performance footwear is designed to improve the athlete's ability to generate shearing, propulsive forces [99]. Patterns of nodular-like protrusions, known as studs, are integrated into the outsole of the soccer shoe to produce traction against a penetrable playing surface [99]. Traction is a property defined by the interaction of surface and shoe, calculated as the ratio of the force of movement resistance to the normal force about the shoe-surface interface [89]. While similar to friction in principle, the viscoelastic properties of the footwear outsole and its' non-uniform surface construction differentiate friction from traction in the context of footwear [77,89].

Soccer cleat traction offers both translational and rotational resistance [96]. Though beneficial to maneuverability, excess traction affects torsional loading at both the knee and the ankle [43,105]. Cleats with high rotational resistance at the forefoot have been associated with a higher risk of non-contact injury [96]. This injury risk is most notable at the knee [96]. When traction is in excess, there can be disconnect between whole-body momentum and planted foot stability. Support structures of the knee, such as the anterior cruciate ligament (ACL), are subjected to high torsional and shearing loads

[43]. Though critical for sport performance, high traction footwear can elevate the risk of non-contact torsional injury risk.

Anterior Cruciate Ligament: Structural Susceptibility to Injury

The anterior cruciate ligament (ACL) is a stabilizing ligament within the knee joint structure, connecting the anterior aspect of the tibial intercondylar notch to the posteromedial aspect of the lateral femoral condyle [36,84]. One of two cruciate ligaments in the knee, these structures are the primary regulators of knee anteroposterior mobility and provide additional support against varus and valgus rotational stress [36]. The ACL itself is responsible for preventing excessive forward translation of the tibia relative to the femur [36]. An injury will occur when excess tensile force is applied onto the ACL, loading the tissue to a point of ligamentous strain, tear, or rupture [108]. It has been estimated that 70% of reported ACL trauma in soccer originate from non-contact events [92]. Non-contact ACL injury occurs when force at the knee surpasses the load that can be withstood by the ACL [108]. Most commonly, this is found in dynamic tasks that involve a rapid change in running velocity, or upon multiplanar knee joint loading while bearing body weight [107]. In the sport of soccer, non-contact ACL injury is most often observed during one-step-stops, deceleration, cutting tasks and unanticipated directional changes [63,92].

The risk factors of ACL injury have been thoroughly investigated in both cadaveric and human subject models. To best quantify the in vivo ACL strain response under controlled external loading, researchers Fleming et al., surgically implanted strain transducers on anterior middle ACL tissue [37]. Utilizing a knee-loading fixture, anterior-

posterior shear force, internal-external torque, and valgus-varus moments could be applied at the knee, in combination with compressive external loading, simulating weight-bearing [37]. Fixed at 20° of knee flexion, ACL strain is significantly increased when anterior shear force is applied at the proximal tibia, and with an increase in internal rotational moment both with and without weight-bearing [37]. Supporting research in cadaveric models looked to combined loading of the ACL at both extended and flexed knee positions [64]. This research found anterior shear force to generate significant ACL loading, and knee valgus and internal rotation moments to also generate significant ACL loading when in combination with an applied anterior shear force [64]. Furthermore, it was identified that with a decrease in knee flexion, loading of the ACL due to anterior shear force, internal and valgus knee moments is magnified [64]. Identifying the mechanisms that load the ACL offer important information related to risk factors of injury. A reduction in knee flexion angle, an imbalance favoring quadriceps to hamstrings muscle contraction, an increase in internal knee extensor moment, and elevated anterior shear force at the proximal tibia are widely regarded risk factors of ACL injury [8,107,108]. A combination of valgus and internal rotational moments are also recognized risk factors, particularly when paired with anterior shear force [107].

The Female Anterior Cruciate Ligament

ACL injuries are highly prevalent in the sport of soccer, due to the complexity of lower body mechanics required for game play. ACL injury rates among female soccer players are particularly high, where female athletes are at a 2 to 3-time greater risk of ACL tear than their male counterparts [103]. A review of the occurrence of ACL injuries

in male and female high school athletics found that the highest rate of ACL injury per 100000 units of athlete exposure was in female soccer, at 12.2 [49]. Furthermore, it was estimated that over 53% of female athletic-related ACL injuries occurred while playing soccer, making female athletes two-times more likely to sustain an ACL injury in soccer than any other female sport [49]. Similar rates of ACL injury incidence are observed among college-aged varsity athletics [3]. A 13-year epidemiological evaluation of The National Collegiate Athletic Association Injury Surveillance System reported the average female ACL injury rate to be 0.33 per 1000 units of athlete exposure, the highest rate of ACL injury incidence across all collegiate sport, whether male or female [2].

There is a noticeable sex disparity in the incidence of ACL injury, as widely established by decades of epidemiological research. Behind said discrepancy, researchers have found underlying differences in female knee joint laxity, anatomical alignment, and neuromuscular control strategies - each proving to be significant factors in the mechanism and occurrence of female ACL injury [22,25,98]. Ligamentous laxity, or joint hypermobility, has been associated with an increased risk of non-contact knee ligament injury [76]. Ligaments are critical to joint structural integrity; laxity of these support structures decrease the passive joint restraint which in turn decrease the stability of the joint [76]. Elevated circulating levels of estradiol and progesterone have been correlated to elevated joint hypermobility, suggesting sex hormones to be a mediator of increased female joint laxity [19,90]. Discussions of anatomical differences are commonly centered around the increased Q-angle of the female athlete. The Q angle, or quadriceps angle, is the angle formed by the intersection of a line connecting the anterior superior iliac spine to the center of the patella, and the patella to the tibial tuberosity [1]. The Q-angle is used

to approximate the line of action of the quadriceps muscle, where an increase in Q-angle is thought to increase the lateral force component on the patella and the tibial tuberosity [46]. The effect of Q-angle on ACL injury risk, however, is disputed in literature. Researchers instead look to femoral anteversion and dynamic knee valgus orientation as more accepted anatomical indicators of ACL risk [51,107]. When looking to athlete mechanics, the performance of high agility tasks, such as cutting, running, and landing find significant gender-based differences in lower body kinetic and kinematic profiles [21,22,25,53,62]. Unique to the female athlete, dynamic control patterns of the knee joint demonstrate quadriceps dominance, where developmental imbalances tend towards greater knee extensor strength, recruitment, and coordination [75]. Tasks of abrupt deceleration find females with lesser external knee flexion moments, lower hamstring muscle activation, greater quadriceps activation and greater valgus positioning on land [21,22,25,53,62].

There are observable parallels between female mechanical deficits and ACL injury risk factors. Female movement patterns and muscle recruitment strategies suggest a predisposition of female athletes to greater mediolateral, anterior translational and torsional forces on the tibia [62]. The tendency towards high-risk mechanics is not only problematic for acute, high load ligament failure. Repetitive, higher-than-average loading at the ACL could cause accumulated microdamage, suggesting athletes with unfavorable mechanics could hold a predisposition to serious injury [18,61]. With an unmatched strength ratio about the knee joint stabilizers, and tendencies towards high-risk landing strategies [62], the female knee is subjected to greater ACL loading and may hold greater overall injury susceptibility.

Soccer Footwear: Male-Centric Design

Despite apparent anatomical and mechanical differences between sex, differences that are often magnified in dynamic, high-intensity sport, female athletes must often wear male sports product, such as footwear. This is particularly problematic in the sport of soccer, where soccer footwear is historically designed for and validated according to male mechanics. In a sport with recognized risk involving high traction footwear, and female players holding the highest incidence rate of ACL injury of any sport, the needs of female athletes seem to be overlooked. With proven differences in movement patterns, joint moments, and joint loading during sport-specific activity, it should not be assumed that the female body is able to withstand the same amount of rotational and translational traction as do males. By this thought, soccer cleats could hold a key role in moderating female athletes' exposure to injury.

Soccer cleat traction is altered through modifications to the studs, whether that be stud shape, stud configuration on the cleat plate, stud length and stud materiality. The optimization of soccer cleat stud characteristics is a delicate balance between surface penetration, stress distribution and translational and rotational torque [7]. The number and configuration of studs requires careful consideration- while a greater number of studs may improve the distribution of stress along the outsole, it may in turn increase axial resistance [7]. Research into the effect of stud shape or geometry is debated in literature, though predominantly performed on male, elite, soccer athletes. Initially thought to increase the risk of torsional injury, bladed geometries demonstrate comparable lower extremity loading to conical geometries [15,39]. However, sex-specific kinematic differences are observed between high (bladed) and low (turf) traction cleat variations

[13]. A soccer footwear study headed by Butler [13] suggested sex to be a significant moderator on the interaction between cleated footwear and lower extremity mechanics, where higher traction footwear reduces female peak knee flexion. This is preliminary evidence that female mechanical susceptibilities to ACL injury may be exacerbated by current high traction footwear, however it is one of few known studies to investigate its' effect on female athletes. Therefore, there is a need to better understand how traction may affect female athlete mechanics and torsional injury risk.

General and Specific Aims

Female-specific biomechanics is notably under-investigated, despite its' importance in understanding female injury mechanics. Despite the high prevalence of ACL injuries in female soccer, there is a lack of applicable research solutions working towards the protection of female athletes and prevention of career-ending injury. Bridging the gap between technical biomechanics research used to assess ACL injury risk metrics, with product design's capacity for direct intervention through informed sport product conception- this project seeks to re-evaluate the existing standards for soccer cleat design, inclusive of the needs of female athletes. This dissertation presents as the first investigation into cleated footwear designed for and validated according to female athlete lower limb mechanics. The first three aims explored in this dissertation will offer suggestion of how individual traction characteristics can be best suited to the mechanics of the female athlete, inclusive of stud length and stud shape. Upon completion of these aims, the design direction of optimized traction plates specific to the mechanics of the female athlete was prototyped. Traction parameters were co-designed with the Puma

Innovation team (Puma SE, Herzogenaurach, Germany), who then developed tooling based on the decided specifications, modifying stud lengths, stud shapes and stud configuration. Proof-of-concept samples were then mechanically evaluated based on resultant female athlete mechanics. The outcomes of this dissertation will bring forward the importance of sex-specific research and design standards. It is the intent of this body of work to inform future iterations of soccer cleats made for and validated by the female consumer.

Specific Aim 1. Research into soccer cleat stud length is limited to performance and perceptual metrics. However, there is substantial literature on the relationship between surface compliance and cleated footwear on lower extremity injury. Research has shown that there is an inverse relationship between turf surface integrity and muscle, tendon, and ligament trauma- where increased surface hardness is related to lower shoe-ground contact times [4, 70]. With increased stud depression, there is potential for increased frictional force between the surface and the cleat, as well as increased force required to release the foot from the ground [4]. Due to differences in body mass, body size, and mechanical susceptibilities between male and female athletes, traction could be made unsuitable through excess stud length. This aim investigates the influence of soccer cleat stud length on female athlete knee stabilizer muscle activity and mechanics. It is hypothesized that a reduction of stud length to 50-75% of original length will present with more favourable muscle activity and mechanics- reducing knee loading during sport-specific tasks.

Specific Aim 2. High traction footwear may exacerbate female susceptibility to torsional injury mechanisms, such as those of ACL injury, if rotational resistance exceeds ligament loading capacity [13]. Stud shape is a moderator of rotational resistance at the shoe-surface interface; mechanical footwear testing finds bladed stud patterns to generate significantly higher rotational torque when compared against elliptical stud patterns [13,94]. While notable differences can be observed with mechanical traction testing, the resultant effects of differing stud geometries on lower extremity mechanics are contended in literature [15,31,39,67]. While thought to increase the risk of torsional injury, bladed geometries have demonstrated comparable lower extremity loading to elliptical geometries [15,39]. However, literature debating the potential adverse effects of bladed stud patterns are predominantly performed on elite, male soccer athletes, without consideration of fatigue. Sex-specific kinematic differences are, in fact, observed between high (bladed) and low (turf) rotational traction cleat variations [13].

The implementation of fatiguing protocols is a recent push in ACL injury research to best identify mechanical weaknesses that result from fatigue- such as patterns of joint destabilization, increased joint laxity, and unfavorable adaptations to energy absorption strategies [5,41,68,69]. Inducing systemic fatigue will offer a more thorough understanding of lower extremity loading as affected by soccer cleats with fatigue progression, such as that experienced during game play. With mechanical weaknesses identified particularly in fatigued, female athletes, [41,52,57,69,109] more information is needed to understand the effects of varying stud shapes on female joint mechanics. This aim will determine whether there are differences in lower extremity mechanics between two commonly observed soccer cleat stud shapes, and how those differences may be

affected by sex, and fatigue. It is hypothesized that bladed soccer cleats will present with greater knee loading in the female athletes, particularly in the cutting tasks. It is expected that these differences will increase in a fatigued state in the female athletes. It is predicted that there will be no significant differences in lower extremity mechanics observed between cleats and fatigued states in the male athletes.

Specific Aim 3. A reduction in footwear contact surface area, such as that found with a soccer cleat plate compared to a trainer outsole, demonstrates notable increases in both the mean and peak pressure resolved across regional plantar surfaces [88]. Plantar loading is therefore highly dependent on footwear properties. With increased regional pressure distribution in cleated footwear, the location and type of soccer cleat studs has potential to alter forefoot loading patterns, thereby modifying movement patterns and joint moments [23,60,73,86,103]. Said differences in plantar pressure have been moderated by sex, with females demonstrating more sensitivity to differences in stud configuration and shape compared to males [86]. However, existing research findings are limited to acute agility tasks performed at sub-maximal speed, limiting external validity. To best inform sex-specific modifications to soccer cleat stud configuration, data collected must resemble that of fatiguing, maximal speed, sport-specific activity. The following aim is an investigation into the influence of bladed and elliptical geometries on male and female plantar pressure distribution patterns (peak pressure, regional pressure time integrals, center of pressure trajectory) in a fatiguing running and cutting protocol. Based on previous sub-maximal findings by Queen et al., it is hypothesized that female athletes will have greater loading on the lateral column of elliptical cleats, in particular [86]. Such

results would suggest improving the lateral arrangement of studs on a female-informed cleat design.

Specific Aim 4. Lower-extremity performance profiles with a changing stud length and stud shape will have been investigated in previous aims. Plantar pressure distribution trends have also been compared between male and female athletes, before and after achieving systemic fatigue in the previous aim. By the start of this final aim, suggested stud parameters according to knee loading and plantar pressure behaviours can be suggested for the female athlete- such as the margin by which stud length should be reduced, the preferred stud shape, and proposed stud configuration best suited to the performance parameters of the female athlete. This culminating aim looks to test traction characteristic combinations with proof-of-concept samples, manufactured by industry partner PUMA SE (Herzogenaurach, Germany). This fourth aim assesses female mechanics with customized traction plates, designed around preferred stud parameters, as defined in aims 1-3. Resultant athlete mechanics will be evaluated across the proof-of-concept samples and compared against market available footwear controls. This exploration will guide concept validation for a future female cleat.

Organization of Dissertation

This dissertation is written in a manuscript-style format, where chapters III through VI have been or will soon be submitted for publication to peer-reviewed journals. The following section explains how these chapters fit together into a coherent body of work. A bridge statement explaining the flow of studies is included at the conclusion of chapters III-V.

This current chapter (Chapter I) reviews background information regarding the functional anatomy of the ACL, female athlete susceptibility to ACL injury, and the role that soccer cleat footwear may play in female non-contact ACL injury. This chapter asserts the importance and necessity for this research. Chapter II will present the methodology used in each study. Chapter III addresses Specific Aim 1, identifying the effect of soccer cleat stud length reductions on female athlete knee mechanics and knee stabilizer muscle activity during sport-specific tasks. Chapter IV will address Specific Aim 2, detailing the effect of soccer cleat stud shape (bladed versus elliptical) on male and female knee mechanics and utilized traction during unanticipated cutting before and after fatigue. Chapter V utilizes data from the same larger study of Chapter IV, seeking to address the effect of stud shape on the plantar pressure loading behaviours of male and female athletes throughout a fatiguing running and cutting protocol. This research addresses Specific Aim 3. Utilizing data from the three previous aims, female cleat designs were co-designed and developed in partnership with Puma SE in Specific Aim 4. Chapter VI mechanically evaluates the proposed cleat iterations against a market available model, validating the viability of these design interventions. To conclude, Chapter VII summarizes the notable results of this body of work, providing implications

from these series of studies, while reflecting on limitations at play. Future directions are proposed in continuation of this line of study.

This dissertation includes co-authored work, some of which is under review in peer-reviewed journals. Chapter IV is in review in the journal *Footwear Science*. Chapter III, V and VI are in preparation for submission to appropriate journals. For all work in this dissertation, Emily C. Karolidis was the primary investigator, responsible for study design, data collection, analysis, interpretation, and dissemination. Alex N. Denton was primarily responsible for data analysis in Chapter V and assisted in data collection and result interpretation for Chapter V and VII; Alex is co-authored on both in preparation manuscripts. Michael E. Hahn, the co-author on all works, advised on all aspects of this collective dissertation.

CHAPTER II
GENERAL METHODOLOGY

Participants

Chapter III

To address Specific Aim 1 (Chapter III), seven female soccer players were recruited. Participants must have competitively participated in soccer until the end of high school and must still regularly play soccer to at least a recreational level. The participants selected were between the ages of 18 and 25, did not have any history of knee injury, were healthy and active, and wore a shoe size of women's 7.5 (+/- half a size) to comfortably fit into the cleated conditions. Participant demographics are provided in Table 2.1.

Table 2.1. Participant demographics (mean \pm SD) for Aim 1.

	Age (y)	Height (cm)	Weight (kg)
Subjects (n = 7)	21 \pm 1.3	166.8 \pm 3.2	58.4 \pm 4.3

Chapter IV & V

To address Specific Aim 2 (Chapter IV) and 3 (Chapter V), twenty soccer players were recruited, ten of which were female. Participating athletes were between the ages of 18 and 26, with a history of competitive soccer, ranging from current NCAA Division III athletes to university club team or competitive local league members. Participants had no lower extremity injury in the past year, no history of ACL injury, and wore a shoe size of

women’s 8-9 (\pm half a size) or men’s 10-11 (\pm half a size) to comfortably fit into the provided cleats. Participant demographics are provided in Table 2.2.

Table 2.2. Participant demographics (mean \pm SD) for Aim 2 & 3.

	Age (y)	Height (cm)	Weight (kg)
Female (n = 10)	19.9 \pm 1.7	165.3 \pm 4.6	60.4 \pm 6.3
Male (n = 10)	22.0 \pm 2.2	175.6 \pm 5.5	73.7 \pm 7.4
Total (n = 20)	21.0 \pm 2.3	170.5 \pm 7.3	67.0 \pm 9.7

Chapter VI

Lastly, to address Specific Aim 5 (Chapter VI), six female college-aged soccer athletes were recruited. Participating athletes were between the ages of 18 and 26, with a history of competitive soccer, ranging from NWAACC community college team, current university club team or competitive local league members. Participants had no lower extremity injury in the past year, no history of ACL injury, and wore a shoe size of women’s 8 (\pm half a size) to comfortably fit into the provided cleats.

Table 2.3. Participant demographic (mean \pm SD) for Aim 4.

	Age (y)	Height (cm)	Weight (kg)
Subjects (n = 6)	19.8 \pm 1.3	168.0 \pm 6.3	60.6 \pm 4.9

Written informed consent was obtained from subjects prior to data collection; study protocols were approved by the University of Oregon Institutional Review Board for Chapter III (01172020.024), Chapter IV & V (STUDY00000640), and Chapter VI (STUDY00001474).

Study Design and Experimental Protocol

Chapter III

In a randomized order, participants were assigned four pairs of soccer cleats (Nike Mercurial Superfly 7 Elite FG) of varying stud length: original length, 75% length, 50% length and 25% length. Participants performed sport-specific tasks in each cleat condition to quantify mechanical differences moderated by stud length adaptations. In a turf biomechanics facility, participants performed sprint-stop and unanticipated cutting tasks at 80% of their self-selected maximum speed. Retroreflective markers on the lower limbs and pelvis were recorded using motion capture (Vicon Motion Systems, Oxford, UK), time synchronized to surface embedded force platforms (Advanced Medical Technologies Inc., Watertown, MA, USA). Simultaneously, surface electromyography (Noraxon Inc., Scottsdale, AZ, USA) recorded Biceps Femoris and Vastus Lateralis muscle activity during the sport-specific tasks. Participants performed three sprint-stops and six unanticipated cuts per shoe condition.

Chapter IV, V

Participants visited the turf biomechanics facility, described previously, for two separate collections. Athlete mechanics were compared between cleated conditions of differing stud geometries, a cleat with a bladed stud shape (adidas Predator Edge .2) and a cleat with an elliptical stud shape (adidas Copa Sense .3), randomly assigned to each collection date. Participants performed unanticipated cutting tasks, described previously, both before and after a fatiguing running and cutting protocol. Participants were taken to a nearby turf fieldhouse to perform the five-stage fatigue protocol, where plantar

pressure insoles (Novel, Munich, Germany) detailed pressure distribution over the course of the fatigue protocol. Cutting steps from the first stage of the fatigue protocol were chosen to represent the pre-fatigue state and cutting steps from the third stage were chosen to represent the post-fatigue state. Participants performed six unanticipated cutting tasks both before and after completing the fatigue protocol.

Chapter VI

Participants visited the facility for three separate collections. Participants were randomly assigned one of three cleats for each visit, two of which were manufactured prototypes based on data collected in Aims 1-3, and the one market-available product in which prototypes were based upon (Women's Future Ultimate FG/AG, Puma SE, Herzogenaurach, Germany). Cleat iterations are described in greater detail in Chapter VI. Participants performed the protocol described in Chapter III & V, except plantar pressure data was not recorded during the fatigue protocol.

Data Collection

Chapter III

Participants were outfit with a bilateral marker set consisting of 20 retro-reflective markers defining seven segments (foot, shank, thigh, pelvis), in accordance with the Plug-In-Gait marker set. Three-dimensional marker data were collected at 100 Hz using a 16-camera motion capture system (Vicon Motion Systems, Oxford, UK), while time-synchronized ground reaction force data were collected at 1000 Hz using four surface embedded force platforms (Advanced Medical Technologies Inc., Watertown, MA,

USA). Surface electromyography (Noraxon Inc., Scottsdale, AZ, USA) recorded muscle activity representative of the knee flexor (Biceps Femoris) and extensor (Vastus Lateralis) muscle groups of the right limb at 1500 Hz. The four footwear conditions were assigned in a randomized order for each participant.

Chapter IV

Participants were outfit with a bilateral marker set consisting of 36 retro-reflective markers defining seven segments (foot, shank, thigh, pelvis), in accordance with the Qualisys CAST lower body marker set. Three-dimensional marker data were collected at 100 Hz using a 16-camera motion capture system (Vicon Motion Systems, Oxford, UK), while time-synchronized ground reaction force data were collected at 1000 Hz using four surface embedded force platforms (Advanced Medical Technologies Inc., Watertown, MA, USA). Participants performed two data collections, where a different, randomized created pair (adidas Predator Edge .2, adidas Copa Sense .3) was assigned each visit.

Chapter V

In place of the provided insole, in-shoe plantar pressure insoles (Novel, Munich, Germany) were installed inside the cleat. Plantar pressure data was recorded at 100 Hz for the 1607-, 799-, and 401-meter stages of the fatigue protocol.

Chapter VI

Data collection procedures were identical to Chapter IV. Participants performed three data collections, where a different, randomized cleated pair (market available cleat, ‘moderate’ prototype, ‘novel’ prototype) was assigned each visit.

Data and Statistical Analysis

Chapter III

Motion capture and force plate data were processed in Nexus 2.12 (Vicon Motion Systems, Oxford UK). Data were smoothed using a Woltring filter and autocorrelated to detect force plate events. Standard inverse dynamics and joint kinematics were calculated using the Plug-in-Gait model [102] (Nexus, Vicon Motion Systems, Oxford, UK). Peak knee flexion, internal knee extensor moment at peak flexion, peak external knee abductor moment, and peak anterior tibiofemoral shear force were assessed for each stopping and cutting task trial. A mean across each activity was calculated for each footwear condition, and then averaged across subjects.

Using a custom Python script (The Python Software Foundation, Fredericksburg, VA, USA), sEMG signals were bandpass filtered (3-500 Hz, 4th order Butterworth), full wave rectified and linear enveloped (6 Hz). Signals were normalized to subject maximum dynamic contraction magnitude in the cutting task of the control (100% stud length) condition. Integrated EMG (iEMG) analysis was performed from initial contact until peak flexion, standardized to a period of 0.5s. The ratio between Vastus Lateralis (VL) and Biceps Femoris (BF) iEMG was calculated for each task trial, and a mean across each activity was calculated per footwear condition and subject. Analysis of iEMG ratios (time

constant = 0.5s) were presented as the ratio of normalized VL to BF, where $1 < 1$ represents greater relative BF activity, and $1 > 1$ represents lower relative BF activity.

Statistical analyses were performed using SPSS, the Statistical Package for the Social Sciences, version 22 (IBM, Armonk, NY, USA). Repeated measures analysis of variance (RM-ANOVA) statistical tests ($\alpha = 0.05$) compared the effect of soccer cleat stud length on each knee kinetic and kinematic variable for both stopping and cutting tasks. From the ratio of standardized VL:BF iEMG, RM-ANOVA ($\alpha = 0.05$) detected differences in the BF comparator across footwear conditions in both tasks. To assess whether normalized BF or VL activity were independently affected by stud length, separate RM-ANOVA tests ($\alpha = 0.05$) were performed for each task. If statistical significance was found, Bonferroni post-hoc paired t-tests were performed.

Chapter IV

Processing was completed using Visual 3D (HAS-Motion, Kingston, Ontario, Canada). Raw marker coordinate and force plate data were filtered using a 4th order lowpass Butterworth filter at 6 and 15 Hz, respectively. The thigh coordinate system was defined at the virtual hip joint center, the shank coordinate system origin was defined as the midpoint of the medial and lateral femoral epicondyle markers, and the ankle joint coordinate system origin was defined as the midpoint between the medial and lateral malleoli markers. To define all axes, x defined the mediolateral axis, y defined the anteroposterior axis and z defined the longitudinal axis. For joint angle calculations, a Cardan sequence of x - y - z defined flexion/extension, eversion/inversion, and internal/external rotation.

Knee flexion angles, knee valgus angle, knee extensor moment, and anterior shear force were all calculated for the shank segment with respect to the thigh. The knee flexion angle at initial contact, along with the other variables at peak knee flexion angle, were extracted for each respective cut and averaged to calculate subject and condition-specific means.

Utilized traction ratio was calculated as the horizontal ground reaction force divided by the vertical ground reaction force from initial contact to toe off, defined by a 50 N vertical ground reaction force threshold. In MATLAB (Mathworks, Inc., Natick, MA), utilized traction ratio across stance was normalized to 101 data points, and average waveforms were calculated across the six cuts for each condition. Condition-specific mean waveforms were then computed across the six participants.

Statistical analyses were performed using R-Studio (RStudio Inc., Boston, MA, United States). A three-way mixed effects analysis of variance (ANOVA) ($\alpha = 0.05$) was used to test the effects of cleat condition (within-subject), fatigue state (within-subject) and sex (between-subject) on the knee kinetic and kinematic variables, and the discrete utilized traction ratio metrics. In the case of a significant main effect, Bonferroni post-hoc tests assessed significant differences between conditions.

To analyze differences in utilized traction ratio waveforms across stance phase, statistical parametric mapping (SPM) was used. An open-sourced SPM package [82,83] developed in MATLAB (MathWorks, Natick, MA) was utilized to determine significant differences in sex, cleat condition and fatigue across the normalized time series data. The t-statistic between conditions was compared on a continuous level, and the null hypothesis was rejected if the critical test statistic values exceeded the critical threshold ($\alpha = 0.05$).

Chapter V

Cutting steps during the initial 400 meters of the 1607-m stage were chosen to represent the on-field pre-fatigue condition and cutting steps during the final 190 meters of the 401-m stage were chosen to represent the on-field post-fatigue condition. Cutting steps contained both left and right cuts when possible.

Using a custom MATLAB script developed by Alex N. Denton, data were filtered using a dual-pass fourth-order Butterworth filter at 25 Hz. Stance phase was defined using a vertical ground reaction force threshold of 50 N. Once cleaned, pressure data were normalized to body weight and subdivided into eleven regions, reflective of cleat stud placement. The heel was subdivided into four masks: Heel Upper Medial (HUM), Heel Upper Lateral (HUL), Heel Lower Medial (HLM) and HLL (Heel Lower Lateral). The forefoot was subdivided into seven masks: Forefoot Upper Medial (FUM), Forefoot Upper Lateral (FUL), Forefoot Center Medial (FCM), Forefoot Central (FC), Forefoot Center Lateral (FCL), Forefoot Lower Medial (FLM) and Forefoot Lower Lateral (FLL). As ACL injury is most likely to occur during initial contact [54], peak plantar pressure was analyzed within the first 0.05 seconds of stance. The mean COP position at initial contact and 0.05s after initial contact, as well as the COP excursion during stance and the first 0.05s of stance, were analyzed along the mediolateral (COP_x) and anteroposterior (COP_y) axes. Temporal waveforms of COP_x and COP_y excursions across full cutting stance were normalized to 101 data points to establish participant and condition-specific means.

As described in Chapter VI, statistics were performed in R-Studio (RStudio Inc., Boston, MA, United States). Identical statistical methods described in Chapter IV for both discrete and continuous variables were used in Chapter V.

Chapter VI

Similar data and statistical analysis methods were used for the discrete and continuous variables in Chapter VI as was previously described for Chapter IV. Discrete variables include peak knee flexion angle, knee flexion angle at initial contact, peak knee valgus angle, peak knee extensor moment and peak anterior shear force. Ankle, knee, and hip power were calculated across cutting stance (defined using a vertical ground reaction force threshold of 50 N). Peak discrete negative ankle, knee and hip power were also statistically analyzed.

As described in Chapter VI, statistics were performed in R-Studio (RStudio Inc., Boston, MA, United States). Discrete variables were statistically analyzed using a 2-way ANOVA with repeated measures (cleat condition, fatigue) at $\alpha = 0.05$. To statistically analyze continuous joint power data, SPM was used, as described in Chapter VI.

CHAPTER III

THE EFFECT OF SOCCER CLEAT STUD LENGTH ON FEMALE KNEE MUSCLE ACTIVITY AND MECHANICS

This chapter is currently in preparation for publication to the Journal of Applied Biomechanics. Emily C. Karolidis designed the study and collected and analyzed the data. Susan L. Sokolowski provided mentorship and general oversight. Michael E. Hahn provided mentorship, aided in study design, general oversight, and editing and finalizing the final manuscript.

Introduction

The anterior cruciate ligament (ACL) is a stabilizing tissue within the knee joint structure. Susceptible to overload, ACL rupture is prevalent in sport involving dynamic, multiplanar joint loading. Athlete mechanical landing strategy offers insight on ACL loading behaviour, with problematic loading occurring in cases of restricted knee flexion and elevated quadriceps muscle force, worsened when combined with valgus rotational moments [107,108].

By nature of its' physical speed and tactical directional changes, the sport of soccer has a high prevalence of ACL injury, predominantly non-contact in nature. The rates of ACL injury among female soccer players are particularly high, with female athletes at a 2 to 3-time greater risk of ACL tear than males [103]. This has been associated with underlying differences in female knee joint laxity, anatomical alignment, and neuromuscular control strategies, translating into higher-risk kinetics and kinematics

during landing and cutting [22,25,98]. Females demonstrate quadriceps dominance, where imbalances tend towards greater knee extensor strength, recruitment, and coordination [75]. Tasks of abrupt deceleration find females with lesser external knee flexion moments, lower hamstring muscle activation, greater quadriceps activation and greater valgus positioning on land [21,22,25,53,62]. There are observable parallels between female mechanical deficits and ACL injury risk factors. Female movement patterns and muscle recruitment strategies suggest a predisposition to greater mediolateral, anterior translational and torsional forces on the tibia [62]. With a propensity towards high-risk landing strategies the female knee is subjected to greater loading at the ACL which may contribute to greater overall injury susceptibility [62].

Despite both anatomical and mechanical differences between male and female athletes, sports product is often founded upon male athlete data. Soccer footwear has historically been designed according to male mechanics yet is advertised as unisex product [91]. In a sport with recognized risk involving high traction footwear, cleats should be moderated to adapt the amount of rotational and translational resistance offered to the more injury susceptible female body. Authors Butler et al., suggest sex to be a significant moderator on the interaction between cleated footwear and lower extremity mechanics, finding higher traction footwear to reduce peak knee flexion angle in female athletes [13]. This is initial evidence suggesting soccer cleats could hold a key role in moderating female athletes' exposure to injury. Greater consideration must be placed on the resultant joint loading sustained from high traction footwear in female athletes.

Soccer cleat traction is altered through modifications to the studs. Modifications to studs include be stud shape, stud configuration on the cleat plate, stud length and

adjustments to materiality. Soccer cleat stud length can modify the depth and duration of sport surface penetration. However, research into soccer cleat stud length is limited to performance and perceptual metrics. Literature on the relationship between surface compliance and cleated footwear can offer insight on traction considerations. Research shows an inverse relationship between turf surface integrity and muscle, tendon, and ligament trauma, where increased surface hardness is related to lower shoe-ground contact times [4,70]. With increased stud depression, there is potential for increased frictional force between the surface and the cleat, as well as increased force required to release the foot from the ground [70]. Due to sex differences in body mass, size, and mechanics, traction could be made unsuitable through excess stud length.

This study is an investigation into soccer cleat stud length best suited to the mechanics of the female athlete. Athlete lower extremity kinetics, kinematics and muscle activities will be compared between cleated conditions of various stud lengths during the performance of an unanticipated cutting task. The variables that are explored in this study are the movement patterns predisposing females to ACL injury, including peak knee flexion angle, peak internal knee extensor moment, peak external knee valgus moment, peak anterior tibiofemoral shear force, and knee stabilizer (biceps femoris, vastus lateralis) muscle activity patterns. The goal of this study is to find the cleated condition that least exacerbates female pre-existing susceptibilities to ACL injury. It is hypothesized that there is an ideal zone of stud length (50-75% original length) that produces most favorable knee mechanics during stopping and cutting tasks. It is predicted that a reduction of stud length to 50-75% of original stud length would optimize the traction offered at foot-ground contact for the size and mechanics of the female athlete,

seeing greater normalized hamstring activity against quadriceps activity, an increase in knee flexion both at initial contact and at peak, a reduction in internal extensor and external valgus moments, and a reduction in anterior shear force.

Methods

Footwear Conditions

Four pairs of Nike Mercurial Superfly 7 Elite FG soccer cleats (women's size 7.5) were acquired for this research project. Prior to modification, each individual stud geometry was measured using a caliper, offering a three-dimensional assessment of stud size and shape (Figure 3.1) to control for material plasticity and elastic deformation on ground contact.

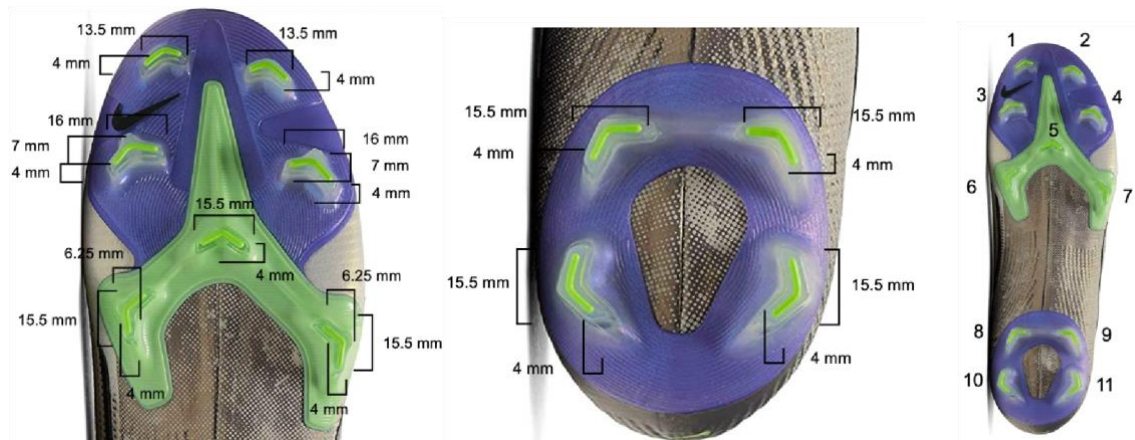


Figure 3.1. Stud shape parameters & stud labeling assignment of control condition. Contact surface area was controlled in each cleat variation by matching stud shape area to measurements of control condition.

Three pairs were modified from their original condition, where the stud lengths of these selected pairs were reduced to a fraction of the control (unmodified) stud length. Soccer cleat pairs were adapted to 25% of existing stud length, 50% of existing stud

length and 75% of existing stud length, with the final condition remaining as 100% of existing stud length (control, no modifications) (Table 3.1). A Dremel with a sanding band was used to abrade the studs to their specified length and shape. Contact surface area of the studs were measured to match that of the control condition, ensuring stud length reduction did not alter the surface area of ground penetration. The girth of the neck of the stud was similarly maintained.

Table 3.1. Stud length of each numerically assigned cleat, referenced in Figure 3.1, for each cleated condition. For certain studs, stud length differed between medial and lateral sides, as affected by outsole shape contoured around the last. Lateral and medial border lengths are indicated by (l) and (m), respectively.

Stud	100%	75%	50%	25%
1	7.00 mm	5.25 mm	3.5 mm	1.75 mm
2	7.00 mm	5.25 mm	3.5 mm	1.25 mm
3	11.50 mm	8.60 mm	5.75 mm	2.90 mm
4	11.50 mm	8.60 mm	5.75 mm	2.90 mm
5	7.00 mm	5.25 mm	4.5 mm	1.25 mm
6	14 mm (l) 12 mm (m)	10.5 mm (l) 9 mm (m)	7 mm (l) 6 mm (m)	3.5 mm (l) 3 mm (m)
7	14 mm (l) 12 mm (m)	10.5 mm (l) 9 mm (m)	7 mm (l) 6 mm (m)	3.5 mm (l) 3 mm (m)
8	15 mm (l) 14 mm (m)	11.25 mm (l) 10.5 mm (m)	7.5 mm (l) 7 mm (m)	3.75 mm (l) 3.5 mm (m)
9	15 mm (l) 14 mm (m)	11.25 mm (l) 10.5 mm (m)	7.5 mm (l) 7 mm (m)	3.75 mm (l) 3.5 mm (m)
10	19 mm (l) 15 mm (m)	14.25 mm (l) 11.25 mm (m)	9.5 mm (l) 7.5 mm (m)	4.75 mm (l) 3.75 mm (m)
11	19 mm (l) 15 mm (m)	14.25 mm (l) 11.25 mm (m)	9.5 mm (l) 7.5 mm (m)	4.75 mm (l) 3.75 mm (m)

Participants

A total of 7 female college-level soccer players participated in this research study (age: 21.1 ± 1.3 years, mass: 58.4 ± 4.3 kg, height: 166.8 ± 3.2 cm), representative of the elite female soccer athlete target demographic. The subjects selected did not have any history of knee injury, were healthy and active, and wore a shoe size of women's 7.5 (+/- half a size) to comfortably fit into the cleated conditions. Athletes performed this data collection in accordance with University of Oregon Institutional Review Board approval, and all subjects provided informed consent (ID 01172020.024).

Protocol

Data collection was performed at the Marcus Mariota Sport Performance Center, located at the University of Oregon (Eugene, OR, USA). This biomechanics facility is equipped with artificial turf, simulating a typical ground-cleat interaction for female collegiate soccer. Installed in the laboratory is 1.25" UBU Sports FT38 artificial turf with slit-film monofilament thatch fibre construction. Beneath the turf surface attaches a 5/8" Armcell Nitrile rubber pad, and a ProPlay-Sport 23D 23 mm closed cell polyethylene shock pad, installed to increase surface compliance. To increase the area of approach, an additional strip of turf, simulating a runway was aligned with the collection space. A 16-camera motion capture system (Vicon Motion Systems, Oxford, UK, sampled at 100 Hz) collected the trajectories of retroreflective markers affixed to the athlete. Time-synchronized ground reaction force data were collected using four AMTI surface embedded force platforms, positioned in a 2x2 square of force platforms (Advanced Medical Technologies Inc. Watertown, MA, USA, sampled at 1500 Hz). Noraxon surface

electromyography (sEMG) was integrated with the Vicon system for real-time recording of muscle activity response (Noraxon Inc., Scottsdale, AZ, USA, sampled at 1500 Hz).

Participant anthropometric measurements were assessed using a tape measure and goniometer; recorded dimensions included subject height (mm), weight (kg), right and left leg length (from the greater trochanter to the medial malleolus, mm), right and left knee width (knee flexion/extension axis, mm) and right and left ankle width (medial to lateral malleolus, mm). Recorded anthropometric measurements were used to help generate subject-specific plug-in-gait models, in combination with marker data. Twenty retroreflective markers were positioned on the subject in accordance with the lower body functional Plug-In-Gait model guidelines [102] located bilaterally on the anterior superior iliac spine, posterior superior iliac spine, lateral thigh (along axis defined by greater trochanter and flexion extension axis of knee), anterior thigh (aligned with lateral thigh marker, located at anterior most portion of the thigh), lateral knee (defined by the flexion-extension axis), lateral shank (along axis defined by knee flexion-extension axis and lateral malleolus), anterior shank (aligned with lateral shank marker, located at anterior most portion of the shank), lateral ankle (lateral malleolus), toe (second metatarsophalangeal joint), and heel (calcaneus). In addition, sEMG were positioned on participant right limb Vastus Lateralis (VL) and Biceps Femoris (BF) in accordance with established standards [26]. Muscle groups were chosen to depict the representative activity levels of the quadriceps muscle group (knee extensors) and hamstring muscle group (knee flexors).

A static trial was recorded for each footwear condition and programmed to calculate condition-specific models of musculoskeletal geometry. The subjects were

tasked with performing two sport-specific activities, a sprint-stop task and an unanticipated cutting task, repeated for each cleated condition. Subjects were first instructed to perform the sprint-stop task. Subjects ran at 80% of their maximum speed for 10 meters down the turf runway, and then abruptly stopped on the force platform deck (Figure 3.2). Athletes were then instructed to run the unanticipated cutting task. Subjects ran at an instructed 80% of their maximum effort for 10 meters down the turf runway into a 120-degree cut, followed by a 5-meter deceleration (Figure 3.2). Cut direction was randomized by the researcher, ensuring the cut performance was unanticipated, called out to the athlete two meters in advance of the force platform deck. For each cut to be considered admissible, the foot opposite the directional cut must have been planted on one of the four force plates. Subjects were tasked with completing three trials of the sprint-stop activity, and six trials of the cut activity (three cuts in each direction) for each footwear condition.

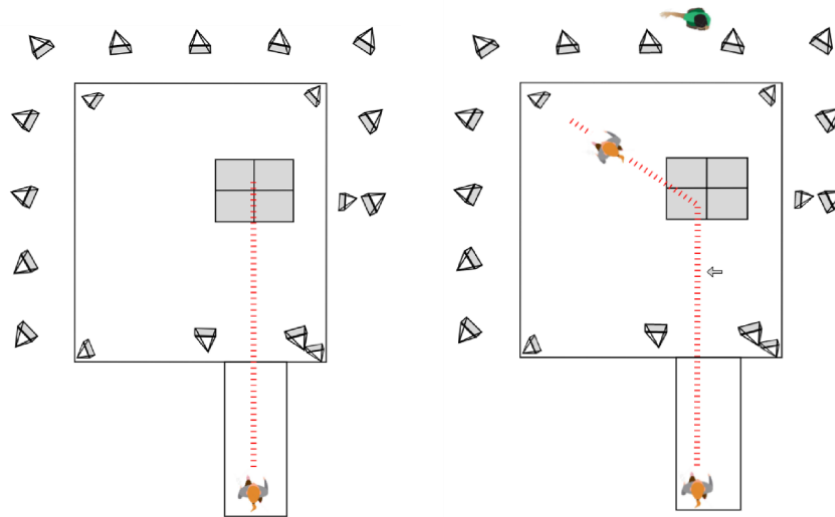


Figure 3.2. Depiction of the start-stop task (left), athletes stopped with each foot on a separate force platform. Depiction of cut task (right), arrow demarcates the point at which the researcher instructed the cut direction, both visually and verbally.

Data Analysis

Marker data trajectories were filled and smoothed using a Woltring filter, and autocorrelated to detected force plate events [102]. Standard inverse dynamics and joint kinematics were calculated using the Plug-in-Gait model [102] (Nexus, Vicon Motion Systems, Oxford, UK). Peak knee flexion, internal knee extensor moment at peak flexion, external knee abductor moment, and anterior tibiofemoral shear force were assessed for each stopping and cutting task trial. A mean across each activity was calculated for each footwear condition, and then averaged across subjects.

Since sEMG were only placed on subject right limb, signals from sEMG were analyzed exclusively from trials of left directional cuts (right foot contact). Signals of sEMG were bandpass filtered (3-500 Hz, 4th order Butterworth), full wave rectified and linear enveloped (6 Hz) utilizing a custom Python script (The Python Software Foundation, Fredericksburg, VA, USA). Signals were normalized to subject maximum dynamic contraction magnitude in the cutting task of the control (100% stud length) condition. Subjects' contractions during dynamic activity were found to well exceed the amplitude of muscle-group specific maximum voluntary isometric contractions, therefore data were normalized to activity patterns observed during the cutting task of the control footwear condition. Integrated EMG (iEMG) analysis was performed from initial contact until peak flexion, standardized to a period of 0.5 s. The ratio between VL and BF iEMG was calculated for each task trial, and a mean across each activity was calculated per footwear condition. Footwear condition data was then averaged across subjects. Analysis of iEMG ratios (time constant = 0.5s) were presented as the ratio of normalized VL to

BF, where $1:<1$ represents greater relative BF activity, and $1:>1$ represents lower relative BF activity. Processing procedures for sEMG data are shown in Figure 3.3.

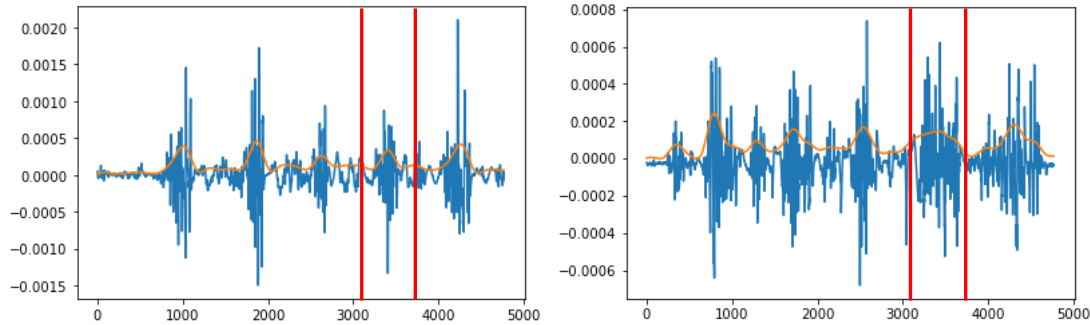


Figure 3.3. Process of sEMG waveform filtering for Vastus Lateralis (Left) and Biceps Femoris (Right). Filtered data is depicted by orange waveform. Red lines show standardized period of 0.5s (750 frames) that denote initial contact to peak knee flexion. Selected data were then normalized and a summated integral of VL and BF was calculated.

Statistical Analysis

Statistical analyses were performed using SPSS, the Statistical Package for the Social Sciences, version 22 (IBM, Armonk, NY, USA). Subject trial data were averaged across cleared condition for each variable. Averages across participants were then analyzed statistically. Repeated measures ANOVA statistical tests were conducted ($\alpha = 0.05$) to compare the effect of soccer cleat stud length on each knee kinetic and kinematic variable. If statistical significance was found, post-hoc paired t-tests were conducted with an adjusted alpha value.

With sEMG data, two separate analyses were performed. From the ratio of standardized VL:BF iEMG, the BF comparator value for each footwear condition was entered into a repeated measured ANOVA ($\alpha = 0.05$) to detect differences in cleat stud length on relative VL: BF muscle activity during stopping and cutting tasks. To assess

whether normalized BF or VL activity were independently affected by stud length condition, separate repeated measures ANOVAs ($\alpha = 0.05$) were performed for each task. Post-hoc paired t-tests were performed at an adjusted alpha value if statistical significance was found.

Results

Kinetics & Kinematics

Sagittal and frontal plane mechanical variables were assessed between cleated conditions. No statistically significant effect of cleat condition on peak knee flexion, peak internal knee extensor moment, peak external knee valgus moment, or peak anterior shear force were found ($p > 0.092$ for stopping tasks, $p > 0.093$ for cutting tasks). Table 3.2 and 3.3 present descriptive statistics, with green colour fill denoting preferred mechanical landing strategy from the perspective of ACL injury risk. According to risk factors of non-contact ACL injury, peak knee flexion should increase, while internal knee extensor moment, external knee valgus moment, and anterior tibiofemoral shear force all decrease [13]. Across the stopping task data, it can be observed that there is similar peak knee flexion in the stopping task across the 25%, 50% and 75% conditions, but the 100% condition does show a lower average peak knee flexion. This trend approaches significance ($p = 0.092$). The 75% condition demonstrates lowest average peak internal extensor moment, peak external valgus moment and peak anterior shear force in the stopping task. However, this is not statistically significant.

Table 3.2. Average \pm standard deviation of peak knee flexion, internal extensor moment, external valgus moment and anterior shear force between cleared conditions during the stopping task. Favorable mechanics see an increase in knee flexion, and a decrease in the selected kinetic variables, denoted in green.

<i>Stopping Task</i>				
	Peak Knee Flexion (°)	Peak Internal Extensor Moment (Nm/kg)	Peak External Valgus Moment (Nm/kg)	Peak Anterior Shear Force (N/kg)
25%	68.32 \pm 7.68	3.34 \pm 2.01	0.95 \pm 0.62	5.42 \pm 3.25
50%	69.53 \pm 8.17	3.39 \pm 1.97	0.97 \pm 0.61	5.77 \pm 3.64
75%	68.21 \pm 8.99	2.28 \pm 2.00	0.79 \pm 0.62	4.81 \pm 4.25
100%	64.95 \pm 7.00	3.03 \pm 1.98	0.87 \pm 0.55	5.47 \pm 2.91

In the cutting task, lowest risk metrics are most often observed in the either the 50% or 75% condition across both tasks, however, these differences are not statistically significant. Similar to the cutting task, there is a trend toward statistical significance in peak knee flexion angle ($p = 0.093$).

Table 3.3. Average and standard deviation of peak knee flexion, internal extensor moment, external valgus moment and anterior shear force between cleared conditions during the cutting task. Favorable mechanics see an increase in knee flexion, and a decrease in the selected kinetic variables, denoted in green.

<i>Cutting Task (Right and Left Cut Average)</i>				
	Peak Knee Flexion (°)	Peak Internal Extensor Moment (Nm/kg)	Peak External Valgus Moment (Nm/kg)	Peak Anterior Shear Force (N/kg)
25%	50.34 \pm 2.41	4.44 \pm 1.07	1.53 \pm 0.47	13.12 \pm 1.15
50%	48.56 \pm 4.82	4.34 \pm 0.98	1.24 \pm 0.34	12.30 \pm 1.78
75%	51.40 \pm 3.65	4.25 \pm 0.87	1.48 \pm 0.55	13.16 \pm 0.93
100%	48.93 \pm 4.60	4.35 \pm 1.05	1.44 \pm 0.54	13.12 \pm 0.83

iEMG

Analysis of iEMG represents stabilizing muscle involvement during dynamic tasks (Table 3.4). Repeated-measures ANOVAs compared the effect of cleated condition on iEMG ratio in both the stopping and directional cut tasks. For the stopping task, Mauchly's test indicated a violation of the sphericity assumption, $\chi^2(5) = 15.1$, $p = 0.012$, therefore the Huynh-Feld corrected results were reported. There was no statistically significant difference of iEMG ratio in the stopping task ($p = 0.145$). No significant effect of cleated condition on iEMG ratio could be reported for the cutting task, as well ($p = 0.595$). Trends identify greater normalized activity of the BF over the VL across all cleated conditions and activities. Greatest normalized BF contribution trended with the 75% cleat condition for the stopping task, and the 50% condition for the directional cut. The 25% cleat condition observed the lowest iEMG ratio across both the stopping and directional cut task.

Table 3.4. Analysis of iEMG to time constant of 0.5s. Data presented as the ratio of normalized VL to BF, where a ratio $1 < 1$ represents greater relative BF activity, while $1 > 1$ represents lower relative BF activity.

	Stopping Task	Directional Cut
25%	1 : 1.05	1 : 1.09
50%	1 : 1.37	1 : 1.55
75%	1 : 1.86	1 : 1.41
100%	1 : 1.40	1 : 1.36

Individual muscular contributions to the iEMG ratio for each condition are displayed in Figure 3.4 for the stopping task, and Figure 3.5 for the cutting task. RM-

ANOVAs compared the effect of cleat condition on iEMG summation of the VL and BF for both the stopping and cutting task; no statistically significant effect of cleat condition was found on mean muscle activity in the stopping ($p > 0.158$) or directional cut task ($p > 0.648$).

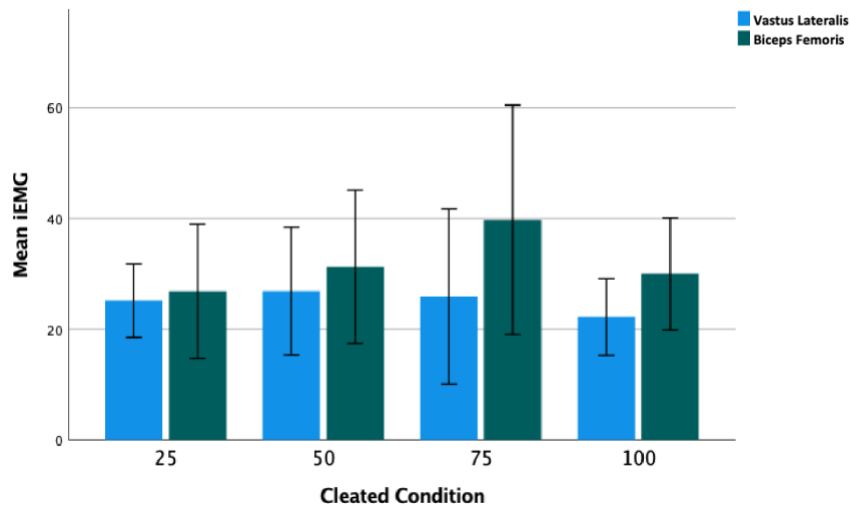


Figure 3.4. Bar mean of Vastus Lateralis and Biceps Femoris iEMG summation for stop task

Trends in descriptive statistics found greatest BF activity is in the 75% cleat condition for both the stopping and directional cut tasks. This was not met with proportional increases in VL activity. The 75% condition did, however, observe the greatest amount of variability across conditions. The smallest summation of BF iEMG is observed with the 25% condition in both tasks. This condition found similarly low iEMG summations of VL activity, indicative of a proportional decrease of knee stabilizer muscle involvement.

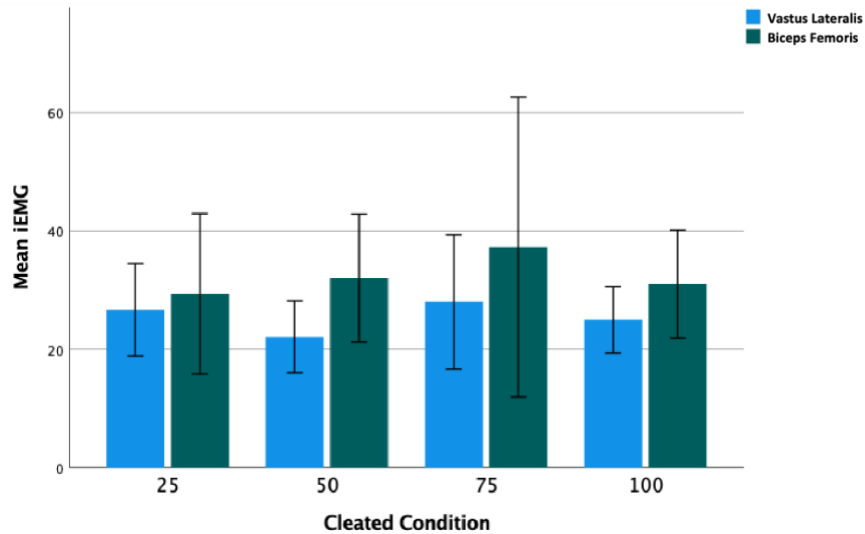


Figure 3.5. Bar mean of Vastus Lateralis and Biceps Femoris iEMG summation for directional cut task

Discussion

Knee variables were compared between four cleated conditions and across two dynamic sport-specific tasks. No statistically significant differences were observed in peak knee flexion angle, peak knee internal extensor moment, peak knee external abduction moment or peak anterior tibiofemoral shear force across cleated conditions in either the stopping or the cutting task. Similarly, there was no statistically significant effect of soccer cleat stud length on iEMG ratio of BF to VL, iEMG summation of BF activity or iEMG summation of VL activity in either task. Trends in descriptive statistics can, however, be observed. Trends in the data find peak knee flexion, peak internal knee extensor moment, peak external knee abduction moment, peak anterior tibiofemoral shear force and iEMG ratios to favor either the 50% or 75% stud length condition in both tasks. High subject-to-subject variability and low sample sizes may contribute to the lack of

reported significance. Inter-subject differences could be noted across each variable, hypothesized to be moderated by the subject's chosen 80% maximum approach speed.

Modifications to Traction

This is the first study to have evaluated the specific influence of a changing stud length on knee mechanics in either female or male athletes. Traction characteristics, however, are variables often explored in the context of lower extremity injury. Comparable scale of frontal and sagittal plane peak flexion angles, peak moments, and peak shear force values can be found in literature evaluating athlete-surface interaction in cleated footwear [13,42,50,89,96]. Authors Stefanyshyn, Lee, and Park [96] looked to the influence of soccer cleat traction on male athlete ankle and knee joint resultant moments. Cleat conditions were chosen to reflect the variability of firm ground cleat design—differing in stud number, shape, materiality, length, and positioning. No statistically significant differences in joint moments were found in either a 180-degree turn, or 45-degree angle cut between traction offered by shorter elliptical studs or longer bladed studs. Similarly, Kaila [50] looked to the effect of modern studded and bladed soccer cleats on knee loading during sidestep cutting in male professional soccer players. Results closely followed those of Stefanyshyn et al., [96] finding no significant differences in peak mean or mean knee flexion, knee valgus moment, or knee anterior shear force during sidestep cut with changing cleat condition. While the abovementioned literature did not evaluate stud length, specifically, it could offer speculation that differences in traction-induced loading may not be perceptible in acute laboratory-based dynamic tasks. In addition, female athletes were not included in the sample pool. While this offers a

glimpse at limited knee mechanical adaptations with a change in traction, it cannot be generalized to the body size, mass, or mechanical susceptibilities of the female athlete.

To assess the sex by cleated footwear interaction, researchers analyzed sagittal and frontal plane dual-land jumping mechanics between cleated footwear of turf and bladed varieties in male and female athletes [13]. Significant interactive effects of peak dorsiflexion and peak knee joint flexion angles were found, with female athletes experiencing significantly less peak knee flexion with increasing traction. The reduction in joint range of motion suggests a stiffer lower extremity, increasing soft tissue loading and strain. Previous works by this group provide further evidence of sex-based discrepancies [86]. Bladed, firm ground and hard ground type cleats were worn by male and female athletes while performing cross-cut activities. Loading patterns captured by insole pressure sensors demonstrated sex differences across cleated variations, where significant differences in plantar pressure between bladed, firm ground and hard ground cleats could only be discerned in female athletes. The sensitivity threshold for female athlete tolerance to cleated footwear adaptations appears to be lower. With an increase in traction observed at the foot, there is a complementary increase in forefoot loading rate; in parallel, increased traction finds a stiffer joint response- both factors of which are responsible for increased loading and strain resolved at the soft tissue. This is of particular concern for female athletes with existing susceptibility to ligamentous injury, as widely referenced in this review.

Cleat-Surface Interaction

Interaction with playing surface is a key factor when considering soccer cleat suitability. Considering insufficient traction can be problematic for slippage, and excess

traction can increase potential for injury, wearing the appropriate cleat to suit the demands of the playing surface is of high importance [72]. In this investigation, female athletes were tasked with completing dynamic tasks in a turfed facility wearing adapted variations of a firm ground soccer cleat. The Nike Mercurial soccer cleat was chosen as it is the most often worn pair of soccer cleats by female varsity soccer athletes at the University of Oregon. Anecdotally, the Mercurial is often seen in high school through international-level competitive play, in part, due to the slender last used to construct this cleat. While this firm ground cleat was not designed for use on turf, it is not uncommon for female athletes to play across a variety of surfaces in their same, preferred, firm ground cleat. A 2015 estimate found 70% of the US Women's National Team games in 2014 had been played on turf fields, compared to 0% of the US Men's National Team [66]. NCAA women's soccer athletes similarly play on a variety of grass and turf fields, but often wear high traction, firm ground cleats regardless of the surface. An eight-month, 2000 subject, prospective cohort study of female soccer rate of injury found twice as many severe injuries to have occurred on artificial turf than on natural grass [97]. Observed trends in this data found there to be more ligament injuries and overall knee injuries on artificial turf compared to natural grass in female athletes [97]. While footwear choice was not controlled for nor disclosed, it can be interpreted that the increased shoe-surface friction associated with the increased stiffness of synthetic playing surfaces could have led to this result. Controlling for traction offered by firm ground studs may help to moderate high shoe-surface friction in synthetic playing environments.

Knee Stabilizer Muscle Activity

No statistically significant differences in iEMG ratios nor individual muscle activity were detected. However, trends can be observed between iEMG ratios and individual knee stabilizer muscle activity patterns. In the stopping task, an increase in iEMG ratio favored the 75% condition. This footwear condition presented with the greatest summated BF iEMG, while having moderate activation levels of antagonistic VL iEMG when compared to the other footwear conditions. In the cutting task, there was an observed increase in the iEMG ratio favoring the 50% condition. The greatest summated BF iEMG was not found in the 50% condition, but again, the 75% condition. Unlike the stopping task, reduced activation of normalized VL led to this observation. This was a surprising finding, as it was not the consistent increase in BF nor consistent decrease in VL that led to these preferred activation ratios. Task-specific muscular requirements are likely the reason behind this. Little research has looked to the muscle activity of knee stabilizer muscles in the context of soccer cleat traction. Authors Gehring et al. [42] reported an increase in male quadriceps activity from bladed to conical stud shape during a change of direction task. No differences in hamstring activity were observed between conditions. Authors suggested increased quadriceps activity of the shorter, conical stud may increase internal load on the knee. Whether this was the effect of stud shape, stud length, or stud positioning, however, is unclear. This somewhat aligns with the findings shown in this research, where a decrease in stud length to 25% sees descriptive trends that increase VL contribution, which can potentially be attributed to decreased traction and therefore decreased stability and quadriceps overcompensation on contact. Surface EMG is not well-researched in the field of cleated sport and this interpretation is speculative.

This study has several limitations worth noting. Most notably, the sample size, as enrollment proved challenging with the singular shoe size and exclusions warranted with previous ACL injury. As such, patterns in the data are limited to observed trends and not statistically significant differences. Additionally, the Vicon Plug-In-Gait model was used for data collection and processing. The functional Plug-In Gait model used in this experiment was designed to assess walking and running gait, best formulated to meet the needs of a clinical gait assessment. This collection involved highly dynamic activity, as well as a task that involved a rapid change of direction. While the Plug-In-Gait model and software were used to simplify the demands of processing, it was not designed for this type of dynamic activity. sEMG was unable to be synced to the Vicon interface, as the Noraxon-Nexus Plug-In is still under development. As a result, sEMG collection was asynchronous, and required the temporal identification of waveform events by the researchers. Data lags varied between trials, ranging from 0 frames to 120 frames. The inconsistency in the lag required certain trials to be excluded from the collection.

Conclusion

The effect of soccer cleat stud length on knee mechanics, and knee stabilizer muscle activity was evaluated in female soccer athletes. While no statistically significant results were found between stud conditions across two sport-specific tasks, trends in peak knee flexion angle, peak internal knee extensor moment, peak external knee abduction moment, peak anterior tibiofemoral shear force, and normalized ratios of vastus lateralis to biceps femoris demonstrated favorable outcomes in the 50% and 75% stud length conditions. While this research does not provide definite conclusions on the relationship

between stud length and female knee mechanics, it does offer suggestive evidence that a reduction of stud length holds potential in reducing knee loading during performance of dynamic tasks if sample sizes were to increase. Future works should look to the effect of a reduced stud length across bladed, elliptical, and mixed stud types in female athletes pre- and post-fatigue.

Bridge

To identify traction properties best suited to the mechanics of the female athlete, changes to each cleat plate parameter must be independently analyzed. Previous works identified trends that a reduction of stud length may improve knee flexor muscle activity contributions and influence lower risk knee kinetic and kinematic movement strategies. The goal of this next chapter is to determine the effect of stud shape on the knee mechanics of both male and female soccer athletes. To identify potential cleat-mediated effects over the course of game play, mechanics before and after a systemic fatigue protocol are assessed. Data in this chapter further support the need to research and develop cleated footwear based upon female mechanical data. Chapter V uses data from this same larger study to analyze the effect of stud shape on plantar loading behaviours throughout a fatigue protocol. Data from these chapters help in identifying a mechanically preferred stud shape for the female athlete.

CHAPTER IV

CHANGES IN KNEE MECHANICS WITH SYSTEMIC FATIGUE AND SOCCER CLEAT STUD SHAPE APPEAR TO DIFFER BY SEX

This chapter is submitted for review to Footwear Science. Emily C. Karolidis designed the study and collected and analyzed the data. Michael E. Hahn provided mentorship and aided in study design, general oversight, and editing and finalizing the final manuscript.

Introduction

Soccer performance footwear is designed to maximize grip, improving the ability of the athlete to generate shear, or propulsive forces on ground contact [99]. The traction achieved by soccer cleats manifests as both translational and rotational resistance between shoe and surface [96]. When in excess, this resistance can alter multi-planar joint loading at both the ankle and knee [96,105]. Excessive rotational traction at the forefoot has been associated with a higher risk of lower extremity non-contact injury, with particular risk identified at the knee joint [96]. With a surplus of traction at the ground-cleat interface, there is disconnect between whole-body momentum and planted foot stability, where support structures of the knee, such as the anterior cruciate ligament (ACL), are placed under high shear strain [43]. While high traction footwear presents a mechanical advantage for propulsive and braking speeds, it is these same movements of rapid deceleration and directional acceleration that are associated with the highest risk of sport-specific noncontact ACL ruptures [53].

Injuries of the ACL are highly prevalent in the sport of soccer. Incidence rates among female soccer players are particularly high, with female athletes at a 2- to 3-time greater risk of ACL tear than their male counterparts [103]. This notable sex-based discrepancy has been associated with underlying differences in female knee joint laxity, anatomical alignment, and neuromuscular control strategies, translating into unique sex-based kinetic and kinematic performance profiles [22,25]. Female movement patterns and muscle recruitment strategies suggest a predisposition of female athletes to greater mediolateral, anterior translational and torsional forces on the tibia [62]. Such mechanical weaknesses have been suggested to worsen with systemic fatigue progression, such as that sustained during game play, with observed patterns of further joint destabilization, increased joint laxity and unfavourable energy absorption strategies among female athletes [5,41,69].

Despite apparent anatomical and mechanical sex-based differences, female athletes must often wear male sports products, such as footwear. This is particularly problematic in the sport of soccer, where footwear is predominantly designed for and validated according to male mechanics [91]. With known differences in movement patterns, joint moments, and joint loading during sport-specific activity, it should not be assumed that the female body is able to withstand the same amount of rotational and translational traction as do males. By this thought, soccer cleats could play a key role in moderating female athletes' ACL injury incidence. Greater consideration must be given to the resultant joint loading sustained from high traction footwear in female athletes.

The stud shape of soccer cleats is a moderator of rotational resistance at the shoe-surface interface; mechanical footwear testing finds bladed stud patterns to generate

significantly higher rotational torque when compared against elliptical stud patterns [13,94]. Despite notable differences in their mechanically evaluated traction coefficients, the resultant effects of differing stud geometries on lower extremity mechanics are contended in literature [15,31,39,67]. While thought to increase the risk of torsional injury, bladed geometries have demonstrated comparable lower extremity loading patterns to elliptical geometries; though predominantly evaluated in male athletes [15,39]. An improved understanding of traction utilization, rather than mechanically available traction, may better explain lower extremity mechanics as they relate to stud shape modifications. Utilized traction ratio, or the ratio of horizontal to vertical ground reaction force components, is a useful way of characterizing these athlete-shoe-surface interactions [24,59].

This study looks to determine whether there are sex differences in traction utilization and lower extremity mechanics between two commonly observed soccer cleat stud shapes, before and after systemic fatigue progression. It is hypothesized that bladed soccer cleats will induce greater knee loading in the female participants when compared to elliptical cleats, due to an increase in the mechanically available traction coefficient. It is thought that female mechanics will deteriorate in a fatigued state, regardless of stud shape worn. By contrast, it is hypothesized that there will be no significant differences in lower extremity mechanics nor traction kinetics observed between stud shape or fatigue states in the male participants.

Methods

Participants

Twenty college-aged soccer athletes participated in this study, ten females (age: 19.9 ± 1.7 years, mass: 60.4 ± 6.3 kg, height: 165.3 ± 4.6 cm), and ten males (age: 22.0 ± 2.2 years, mass: 73.7 ± 7.4 kg, height: 175.6 ± 5.5 cm). Participating athletes were between the ages of 18 and 26, with a history of competitive soccer, ranging from current NCAA Division III athletes to university club team or competitive local league members. Participants had no lower extremity injury in the past year, no history of ACL injury, and wore a shoe size of women's 8-9 (\pm half a size) or men's 10-11 (\pm half a size) to comfortably fit into the provided cleats. Informed written consent was provided by each participant in accordance with the University of Oregon's Ethics Committee requirements.

Protocol

Each participant performed two data collections, assigned a different, randomized cleat condition per visit. Chosen cleats were the adidas Copa Sense .3, with traction characterized by an elliptical stud shape, and the adidas Predator Edge .2, with traction characterized by a bladed stud shape (adidas, Herzogenaurach, Germany). Data collection procedures were identical between laboratory visits aside from the cleat condition worn for testing. Cutting task mechanics were compared between male and female participants across cleated conditions, before and after completion of a systemic fatigue protocol.

Data collection was performed at the Marcus Mariota Sport Performance Center located at the University of Oregon (Eugene, OR, USA). This biomechanics facility is

equipped with artificial turf, simulating a typical ground-cleat interaction for female collegiate soccer. Installed in the laboratory is 1.25" UBU Sports FT38 artificial turf with slit-film monofilament thatch fibre construction. Beneath the turf surface attaches a 5/8" Armcell Nitrile rubber pad, and a ProPlay-Sport 23D 23 mm closed cell polyethylene shock pad, installed to increase surface compliance. To increase the area of approach, an additional strip of turf was aligned with the installed turf, offering a ten-meter runway into the data collection space. A 19-camera motion capture system (Vicon Motion Systems, Oxford, UK, sampled at 100 Hz) was time-synchronized with ground reaction force data, collected using four AMTI surface embedded force platforms, positioned in a 2x2 square (Advanced Medical Technologies Inc. Watertown, MA, USA, sampled at 1000 Hz). Retroreflective markers were placed on the pelvis and lower extremities of the participants in accordance with the Qualisys CAST lower body marker set [14]. Skin glue was used to attach thigh and shank markers in clusters, ensuring marker fixation throughout the entire data collection; marker fixation is critical, as time spent re-applying markers upon completion of the fatigue protocol may be enough to initiate recovery. A static neutral trial of the complete marker set was first recorded, then the set was reduced to 28 markers for dynamic trials.

Participants were tasked with performing unanticipated cutting tasks prior to, and immediately following a systemic fatigue protocol. Participants were instructed to run at 80% of their self-selected maximum speed into a 120-degree directional cut (Figure 4.1). Cut direction was randomized by the researcher, signaled to the participant two meters in advance of the force platform deck. For each cut to be considered admissible, the foot opposite the direction of cut must have been planted on one of the four force platforms.

Six unanticipated cuts were recorded (three in each direction) to represent mechanics observed in a pre-fatigued state.

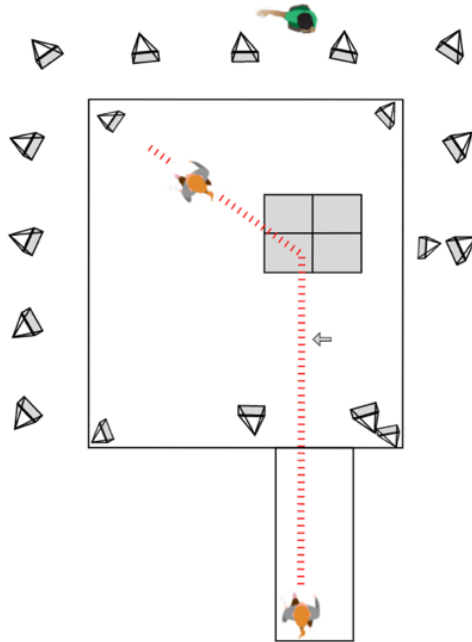


Figure 4.1. Depiction of the cutting task left direction. Arrow demarcates the point at which the researcher visually instructed the cut direction.

Following pre-fatigued cutting task completion, participants were taken to a nearby indoor regulation-sized American football field (The Moshofsky Center, University of Oregon, Eugene, OR) and instructed on the multi-stage fatiguing protocol. This facility is equipped with a third-generation hybrid synthetic surface (FieldTurf Vertex Core) with a three-layer sand/rubber infill. To best mimic fatiguing activities observed in a soccer game, this study implemented an Adapted Gauntlet Test, where each stage consists of a series of intermittent cuts across the length and width of a football field. Suited to the constraints of the field, this study modified the Gauntlet Test to instead perform 1607-, 799-, 401-, 208-, and 100-meter stages, each separated by 1

minute rest, as seen in Figure 4.2. This is an adapted version of the original Gauntlet Test, which is a validated assessment of cardiorespiratory fitness used to predict aerobic performance of collegiate soccer players [12]. This fatigue protocol is designed to be performed at a maximal effort to induce systemic fatigue. Differences in mechanics pre- and post-fatigue, such as those states observed at the beginning and end of a soccer match, can then be assessed.

Following completion of the fatigue protocol, participants were immediately returned to the biomechanics facility. To prevent recovery, this facility transition was performed hastily, with the time taken between the final stage of the fatigue protocol and the start of motion capture recording to be under ten minutes. At this time, six unanticipated cuts were recorded (three in each direction) to represent mechanics observed in a fatigued state.

Identical procedures were followed on the second laboratory visit. The second visit was scheduled within a range of 4-40 days after the first visit.

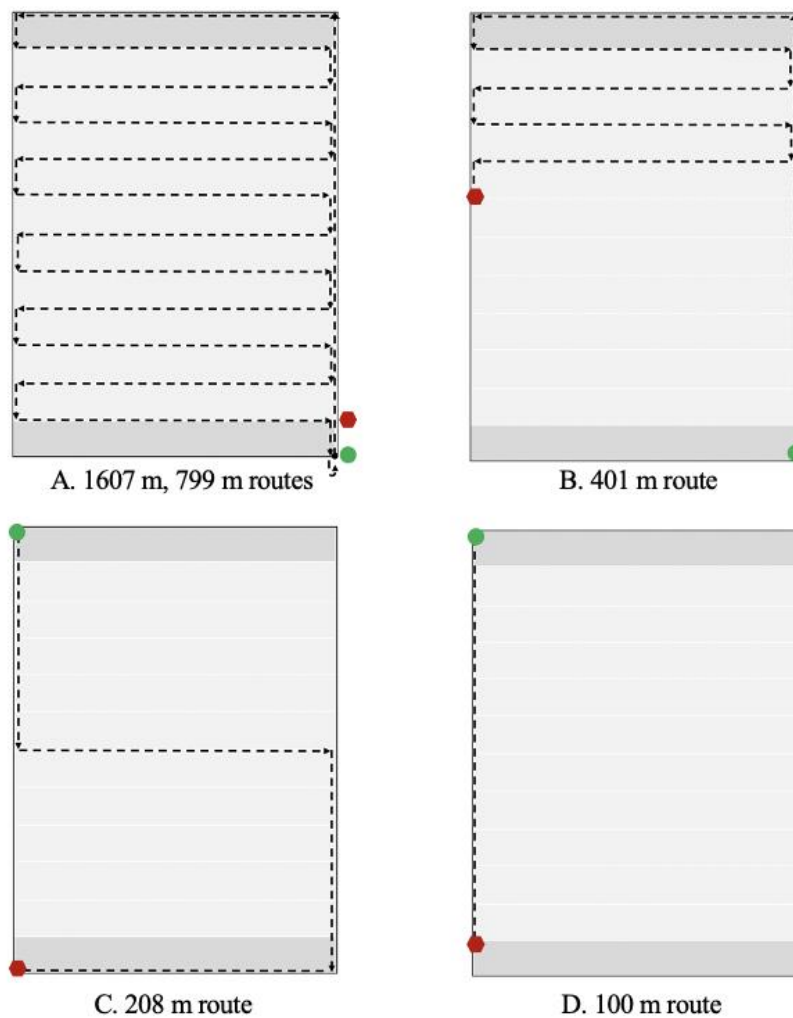


Figure 4.2. A. In the 1607 meter running stage, participants performed two laps of the outlined route, starting on the green circle, and terminating on the red stop sign. A singular lap of this outlined run is the 799-meter running stage. B. The 401-meter running stage is just under half a lap. C. The 208-meter running stage consists of three major cuts spanning the size of the field. D. The 100-meter running stage is a straight sprint down the field.

Variables

Knee Kinetics & Kinematics

Synchronized marker coordinate and force plate data were imported into Visual 3D v5 (C-Motion Inc., Germantown, MD) for post-processing. Low pass, 4th order Butterworth filters were applied to the marker coordinate and force plate data, at 6 Hz and

15 Hz, respectively. Standard inverse dynamics and joint kinematics were calculated using Visual3D.

To assess athlete approach speed, velocity of the left ASIS y-axis marker position was calculated from the start of the approach run to the point of lateral deviation, indicating the start of the cutting phase trial. This marker was chosen as a proxy of athlete centre of mass, where velocity was calculated to detail intrasubject reliability across conditions.

Knee flexion angle at initial contact (KFA), peak knee valgus angle during initial stance (KVA), peak internal knee extensor moment (KEM), and peak anterior tibiofemoral shear force (ASF) were analyzed to reflect movement patterns indicative of ACL loading. Metric means across cutting trials pre- and post-fatigue were calculated for each subject per footwear condition.

Utilized Traction

Filtered ground reaction force data were exported to MATLAB (MathWorks, Natick, MA). Using a vertical ground reaction force threshold of 50 N to establish ground contact during cutting stance, the utilized traction ratio (UTR) was calculated by dividing the horizontal by the vertical component of force. This time-dependent calculation is based upon methods developed by De Clercq et al., [24]. Temporal waveforms of UTR were calculated for each trial and interpolated to establish subject and condition-specific means. Rate of traction utilization from 0-15% stance, and average utilized traction from 15-85% stance was calculated across sex, cleat condition and fatigue state. In previous work, researchers have chosen to exclude the initial 0-10% and final 90-100% of cutting

stance due to extensive variability. However, as ACL injury is most likely to occur within the first 0.05 seconds of initial contact [54,74], it is necessary to understand traction utilization during initial stance.

Statistical Analysis

Statistical analyses were performed using R-Studio (RStudio Inc., Boston, MA, United States). Mixed model univariate analyses of variance (ANOVA) statistical tests ($\alpha = 0.05$) were conducted to compare the effect of sex, fatigue state, and cleat type on the discrete kinetic and kinematic variables. If statistical significance was found, post-hoc pairwise t-tests were performed with a Bonferroni correction. One dimensional, three-way with two repeated measures (cleat & fatigue) Statistical Parametric Mapping (SPM) ($\alpha = 0.05$) was used to independently assess differences in the time series waveforms of UTR [82,83].

Results

Approach Velocity

Mixed model ANOVA tests examined the main and interactions effects of sex, cleat condition, and fatigue state on approach velocity. Descriptive statistics are summarized in Table 4.1. A significant main effect of sex ($p < 0.05$) was found, showing male participants to have a 0.23 to 0.52 second faster approach velocity than female participants by matched condition. A significant main effect of fatigue ($p < 0.001$) was also observed, with fatigue reducing condition-matched approach velocity by 0.15 to 0.39 seconds. A significant sex-fatigue interaction was discovered ($p < 0.05$), pairwise post-

hoc analyses found significant differences ($p < 0.001$) between male and female approach velocities before fatigue. Data trends suggest systemic fatigue to have a more detrimental effect on approach velocity in males than females. A significant sex-cleat interaction ($p < 0.05$) was also observed, pairwise post-hoc analyses found significant differences ($p < 0.001$) between male and female bladed conditions.

Table 4.1. Approach velocity (m/s; mean \pm standard deviation) of the unanticipated cutting tasks, calculated from the start of the approach run to the moment of lateral deviation.

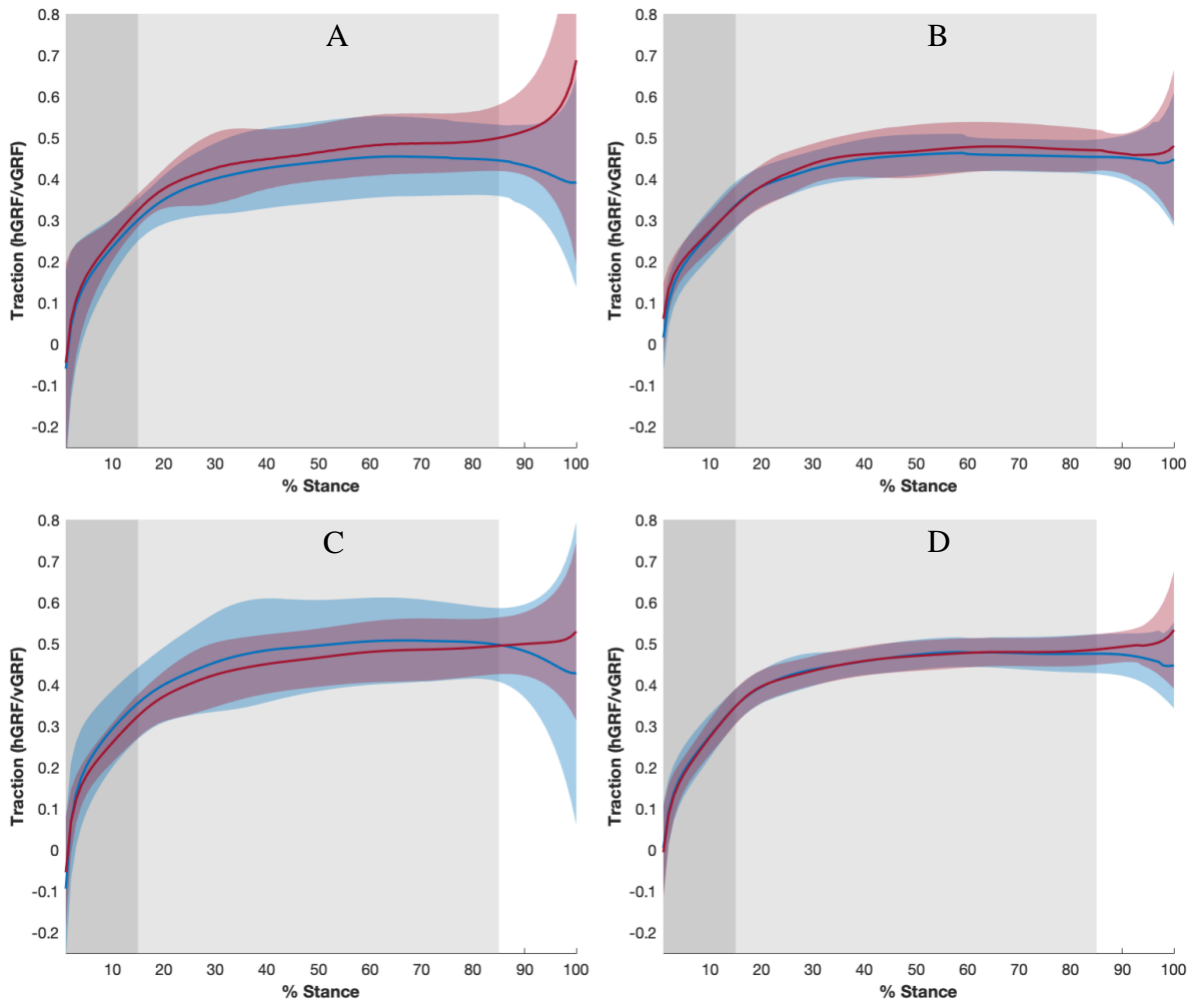
	Male		Female	
	Pre-Fatigue	Post-Fatigue	Pre-Fatigue	Post-Fatigue
Bladed	4.95 \pm 0.29	4.71 \pm 0.38	4.43 \pm 0.42	4.28 \pm 0.38
Elliptical	4.95 \pm 0.38	4.56 \pm 0.40	4.53 \pm 0.38	4.33 \pm 0.42

MAIN EFFECT: Sex ($p < 0.05$), Fatigue ($p < 0.001$)

INTERACTION EFFECT: Sex-Cleat ($p < 0.05$), Sex-Fatigue ($p < 0.05$)

Utilized Traction Ratio

Time series data of utilized traction ratio are summarized in Figure 4.3. Statistical parametric mapping identified a main effect of fatigue ($p < 0.01$) on UTR from 84.3 to 100% of cutting stance. A sex-fatigue interaction ($p < 0.05$) was also found during the push-off phase, from 92.9 to 98.3% of cutting stance. No detectable differences were found during initial cutting stance.



MAIN EFFECT: Fatigue from 84.3-100% stance ($p < 0.05$)
INTERACTION EFFECT: Sex:Fatigue from 92.9-98.3% stance ($p < 0.05$)

Figure 4.3. Mean (solid line) and standard deviation (shaded) of utilized traction ratio (hGRF/vGRF) between pre-fatigue (blue) and post-fatigue (red) states across sex and footwear condition. A) Male bladed cleat B) Female bladed cleat C) Male elliptical cleat D) Female elliptical cleat. Dark grey area reflects region used to calculate rate of traction utilized during initial contact phase (0-15% stance), light grey area reflects interval used to calculate the average utilized traction during loading & midstance phases (16-85% stance).

Discrete variables extracted from UTR time series data were independently run through mixed model ANOVA tests, summarized in Table 4.2. A significant three-way interaction ($p < 0.05$) between sex, fatigue state and cleat condition was determined for the rate of traction utilized from 0-15% stance. A main effect of cleat ($p < 0.05$) was also

observed, with elliptical cleats having a higher rate of traction utilized during the initial contact phase than bladed cleats. Approaching significance, fatigue state ($p = 0.05$) demonstrated trends towards a reduction in the rate of UTR with fatigue. Average UTR during the loading-midstance phase was significantly affected by cleat condition ($p < 0.05$), with elliptical cleats achieving higher average traction than bladed cleats.

Table 4.2. Discrete variable means \pm standard deviation from UTR time series waveforms.

			Rate of Utilized Traction (0-15% Stance)	Average Utilized Traction (15- 85% Stance)
Male	Bladed	Pre-Fatigue	0.033 \pm 0.02	0.43 \pm 0.09
		Post-Fatigue	0.033 \pm 0.02	0.46 \pm 0.07
	Elliptical	Pre-Fatigue	0.043 \pm 0.02	0.48 \pm 0.10
		Post-Fatigue	0.035 \pm 0.02	0.45 \pm 0.07
Female	Bladed	Pre-Fatigue	0.028 \pm 0.01	0.44 \pm 0.04
		Post-Fatigue	0.024 \pm 0.01	0.45 \pm 0.05
	Elliptical	Pre-Fatigue	0.030 \pm 0.01	0.46 \pm 0.03
		Post-Fatigue	0.031 \pm 0.01	0.46 \pm 0.03

MAIN EFFECT: Cleat on rate of UTR ($p < 0.05$), Cleat on average ($p < 0.05$)

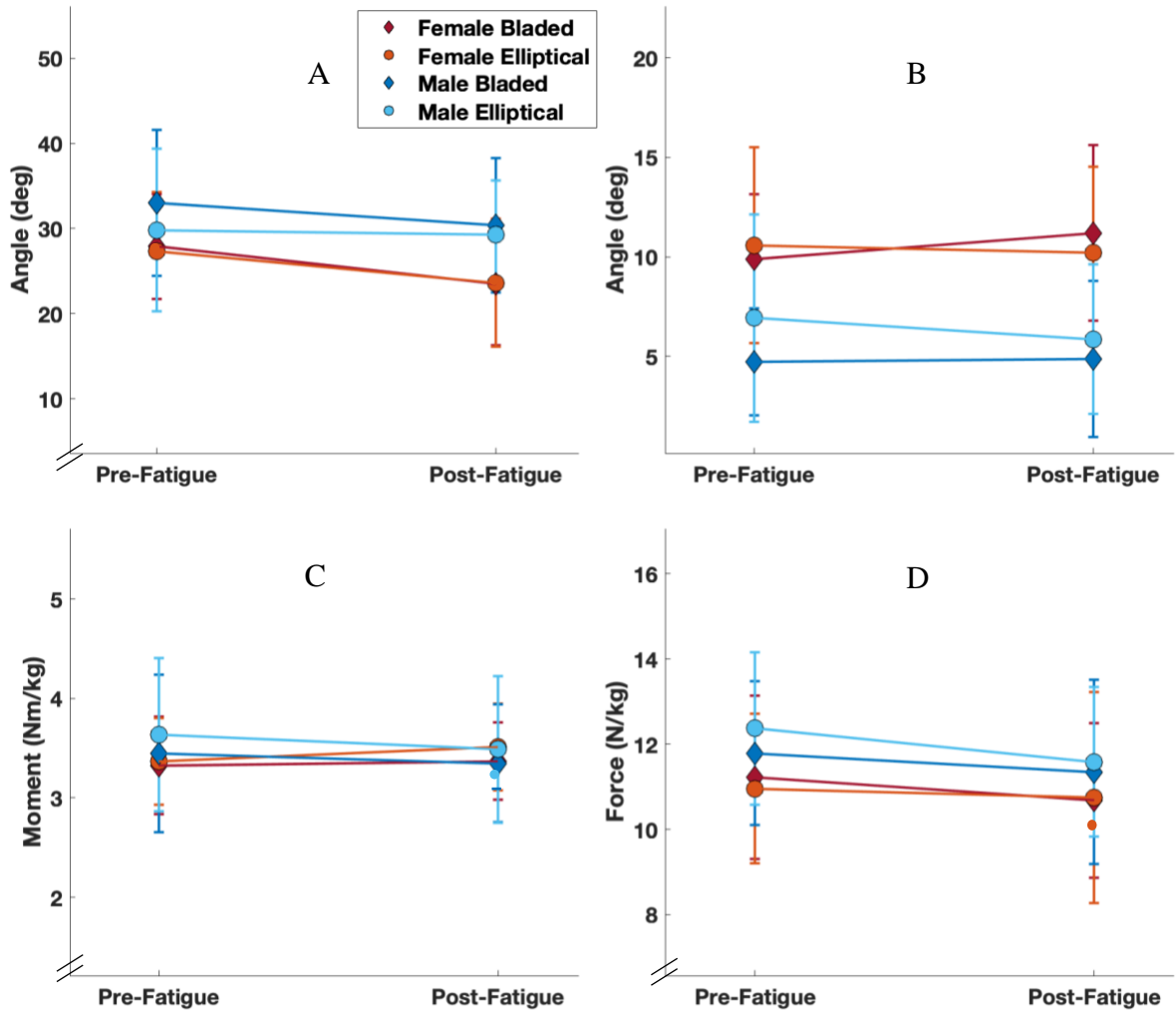
INTERACTION EFFECT: Sex-Fatigue-Cleat ($p < 0.05$) on rate of UTR

Knee Kinetics & Kinematics

Multiple mixed model ANOVA tests were used to examine the main and interaction effects of sex, cleat condition, and fatigue state on the aforementioned knee metrics.

Figure 4.4 presents select knee mechanics variables across fatigue states and cleat conditions for the female and male participants, respectively. Preferred mechanical landing strategy is marked by an increase in KFA at initial contact, and reductions in KVA, KEM, and ASF [13]. Percent change between matched condition comparisons are

summarized in Table 4.3, colorized on a scale of protective to detrimental mechanical risk. No statistical tests were run on the percent change condition matched comparisons.

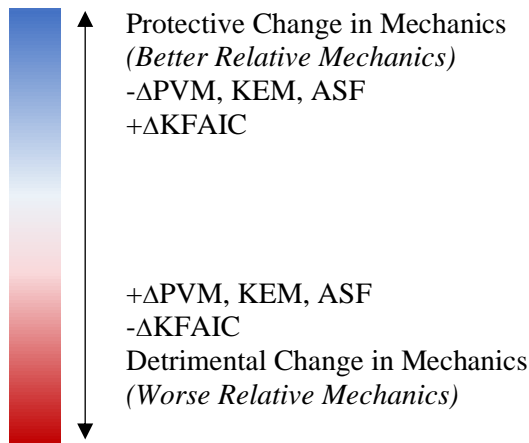


MAIN EFFECT: Fatigue on KFA ($p < 0.01$) (A), Sex on KVA ($p < 0.05$) (B)

Figure 4.4. Interaction plots of knee mechanical parameters averaged across sex, clefted condition, and fatigue state. A) Knee flexion angle at initial contact B) Knee valgus angle at peak knee flexion C) Knee extensor moment D) Anterior shear force.

Table 4.3. Percent change in knee metrics across condition matched comparisons.

Condition Comparisons		Knee Metrics (% Δ)			
		Knee Flexion Angle at IC (deg)	Peak Knee Valgus Angle (deg)	Knee Extensor Moment (Nm/kg)	Anterior Shear Force (N/kg)
Sex	Male Pre-F Ell vs. Female Pre-F Ell	-8.42	52.94	-7.12	-9.70
	Male Post-F Ell vs. Female Post-F Ell	-19.27	74.28	0.65	-6.18
	Male Pre-F BI vs. Female Pre-F BI	-15.44	110.33	-3.47	-2.86
	Male Post-F BI vs. Female Post-F BI	-23.02	130.4	0.82	-4.93
Fatigue	Male Pre-F Ell vs. Male Post-F Ell	-1.82	-15.4	-3.97	-5.81
	Male Pre-F BI vs. Male Post-F BI	-7.89	3.25	-3.02	-2.77
	Female Pre-F Ell vs. Female Post-F Ell	-13.44	-3.6	4.06	-2.14
	Female Pre-F BI vs. Female Post-F BI	-16.15	13.11	1.29	-4.85
Cleat	Male Pre-F Ell vs. Male Pre-F BI	10.64	-32	-4.97	-4.79
	Male Post-F Ell vs. Male Post-F BI	3.8	-17.01	-4.03	-1.71
	Female Pre-F Ell vs. Female Pre-F BI	2.16	-6.49	-1.24	2.43
	Female Post-F Ell vs. Female Post-F BI	-1.03	9.72	-3.87	-0.40



There were no significant three-way interactions for the knee kinetic or kinematic variables. A two-way interaction between sex and fatigue state approached significance for KEM ($p = 0.0548$), suggesting a trend of fatigue to detrimentally increase KEM in females, while protectively decrease KEM in males. A main effect was observed for fatigue state on KFA ($p < 0.01$), with fatigue decreasing KFA for both sexes and cleat

conditions. There was also a main effect of sex on KVA ($p < 0.01$), with females exhibiting greater KVA across both fatigue states and cleat conditions. While not statistically significant, trends in KVA further suggest potential differences in the interaction between fatigue state and cleated condition. Both male and female participants tended to increase KVA post-fatigue in bladed style cleats and reduce KVA post-fatigue while wearing elliptical style cleats.

Discussion

Innovation in footwear design looks to challenge the limits of cleated footwear capabilities- offering improved traction at the foot-ground interface to elevate athlete performance. Adaptations in the past several decades have seen sharper-edged bladed studs, studs of increasing length, and manufactured composites that are stiffer in nature [96]. Consideration should be made for athlete internal structures that must withstand the additional loading associated with high traction designs, particularly those of female participants who are smaller in stature, and at higher risk of knee ligament injury. The purpose of this study was to better identify how soccer cleat stud shape, a known moderator of ground-cleat rotational resistance, may influence sex-specific landing mechanics and traction utilization, before and after systemic fatigue. Experienced soccer participants performed unanticipated cutting tasks before and after a fatigue protocol in soccer cleats of differing stud type; bladed and elliptical. This research seeks to increase understanding how soccer cleat stud parameters may affect female cutting mechanics over the course of game play, and how this footwear-system interaction may influence the overall ACL injury risk profile.

While a benchmark assessment of contact resistance, available traction measured using a mechanical apparatus does not inform on athlete-surface interactions. Calculations of utilized traction, or the force ratio on ground contact, may be a more accurate portrayal of how cleated modifications may affect resultant loading of the lower extremity [59]. While timeseries data show no significant interactions or main effects in UTR during initial contact through midstance, important differences in discrete UTR metrics were discovered. From 0-15% of initial cutting stance, there is a significant three-way interaction on the rate of UTR ($p < 0.05$). This phase of cutting stance corresponds with when ACL injury is most likely to occur [54,74]. Differences in the rate of UTR development evidence differences in the absorption and redirection of impact forces during unanticipated cutting activity. Results therefore suggest fatigue and cleat condition to uniquely moderate the male and female landing response. Cleat condition also significantly affected this discrete variable ($p < 0.05$), revealing that elliptical cleats generate greater horizontal impulse than bladed cleats during initial stance. The less rotationally resistant elliptical stud shape may allow for a higher instance of stud rotation and therefore horizontal traction during a cut. Previous research has shown higher traction bladed models to result in less stud rotation than rounded cleats at ground contact [31]. The authors suggest that this likely results in greater rotational loading on the joints of the lower limb [31]. Progressing into midstance, average UTR is also significantly affected by cleat condition, with greater relative horizontal force contributions observed in the elliptical over the bladed condition. Despite mechanically available traction favouring bladed stud types, the resulting traction utilized by the athlete may be influenced by landing mechanics.

Across the four knee mechanical variables assessed, no significant interaction effects were reported. The interaction between sex and fatigue on KEM approached significance ($p = 0.0548$), suggesting a trend of fatigue reducing KEM of males, while increasing KEM of females. Main effects were observed, finding sex to significantly affect KVA ($p < 0.01$), and fatigue to significantly affect KFA ($p < 0.01$). Main effects and trends in the data indicate the influence of sex on mechanical landing strategy. Female participants were found to have cleat- and fatigue-matched valgus angles ranging from 4 to 11 degrees, or an estimated 50-130% higher range than male participants. A well-understood kinematic risk factor of ACL injury, a knee valgus of 5 degrees has been estimated to load the ACL 6 times more than when the knee is aligned in the frontal plane [62]. Female participants in this study exhibited more than two times this threshold of knee valgus. This tendency towards increased frontal plane knee motion in female participants is well-established in literature, reasoned to be associated with differences in anatomical alignment and motor control strategies [62,95]. Significant differences have been observed in medial-lateral co-contraction of knee joint stabilizer muscles in females, but not in males [81]. This unmatched lateral dominance is less effective at providing resistance to valgus positioning.

It was also observed that female participants have less knee flexion at initial contact across both fatigue states and cleated conditions. While sex is not a significant main effect on KFA, fatigue state is. In addition to effects observed in KFA, trends across KVA and KEM both suggest that fatigue negatively influences the cutting mechanics of female participants. In comparison, the fatigue response of male participants instead appears to offer joint protective strategies. This difference in fatigue response amplifies

existing differences in sex-based mechanical cutting strategy, further elevating the risk of female injury, comparatively. This negative female athlete fatigue response can be corroborated with previous research [20,52,69], suggesting the fatigue-induced alteration of motor control strategies is in part responsible for the compromise of joint stability in female ACL injury [17].

The effect of soccer cleat stud shape on lower extremity mechanics remains a point of debate in literature. Despite evidence of elevated rotational friction coefficients in bladed stud types, this increase in rotational traction has not been reported to alter lower extremity mechanics in a systematic review by Cardoso Filho et al. [15]. However, this systematic review of literature is strongly biased towards male data. Of the few studies to include female subjects, results did suggest there to be greater interference in female landing mechanics with bladed stud types than alternative stud types, when compared to males [13,86]. While no significant effects of cleat condition were reported in the present study, the elliptical cleat appears protective against the fatigue-induced knee valgus increases observed with the bladed cleat in both male and female participants. The difference in utilized traction between elliptical and bladed cleat types may be at root of this observation. The significant interactions observed with the rate of UTR development may moderate landing mechanics enough to alter frontal plane behaviour. Moderating traction according to mechanics observed during a fatigue state may be of critical importance to ACL injury prevention.

This study has two limitations worth noting. An important consideration is that the soccer cleats used in this study were not identical in construction, which is a limitation when looking to compare subject mechanics as moderated by traction properties. Without

having the option to manufacture customized cleats, it was necessary to acquire different cleat models to compare stud shapes. With consultation from contacts at adidas, it was determined that these two model cleats had similar innovation to internal structures and material properties to be able to make this stud shape comparison. Additionally, while it would have been optimal to have assessed athlete mechanics on an outdoor, firm ground grass pitch, this research was limited by the accessibility of motion capture and force plate equipment outside of the lab. However, the common practice of high-level female soccer players reverting to firm ground cleats in turf stadiums reduces the impact of this limitation.

Conclusion

The effects of sex, stud shape and fatigue state were evaluated by examining knee mechanics indicative of ACL loading and utilized traction ratio during cutting tasks. No interaction effects were noted to be statistically significant on knee mechanics, though main effects of sex and fatigue were observed on KVA and KFA, respectively. A significant three-way interaction on the rate of traction utilized at initial contact was found, demonstrating the influence of fatigue and cleat condition on sex-specific ground interaction. While this research does not provide definitive conclusions on the optimal stud shape according to female knee mechanics, trends suggest that an elliptical cleat shape holds potential in reducing fatigue-induced knee valgus during the performance of cutting tasks. This study demonstrates the importance of designing and validating product for the female athlete, most importantly, according to mechanics observed during the most susceptible fatigued state.

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Bridge

The goal of this chapter was to understand the effects of soccer cleat stud shape and fatigue on the knee mechanics of male and female soccer athlete during unanticipated cutting. This study demonstrated the importance of considering fatigue state when assessing female knee mechanics, as mechanical susceptibilities become more apparent. Elliptical stud shape was shown to potentially mediate fatigue-induced knee valgus angle among female athletes. Data in this chapter offer important consideration for preferred stud shape design choices for female athlete soccer cleats. This next chapter uses data recorded in the broader study design encompassed by Chapter IV and V. Chapter V seeks to understand the effect of soccer cleat stud shape on the plantar loading behaviours of male and female athletes across a fatigue-induced running task. This chapter will provide further evidence of regional pressure adaptations to stud shape modifications.

CHAPTER V

THE EFFECTS OF CLEAT TYPE AND FATIGUE STATE ON PLANTAR LOADING PATTERNS IN SOCCER ATHLETES

This chapter is in preparation for submission to The British Journal of Sports Medicine. Emily C. Karolidis designed the study and collected the data. Alex N. Denton analyzed the data. Michael E. Hahn provided mentorship and aided in study design, general oversight, and editing and finalizing the final manuscript.

Introduction

Unlike performance footwear for running or court sports, soccer footwear offers minimal underfoot cushioning [7]. Soccer cleat tooling is designed to maximize traction rather than shock absorption at ground contact due to the compliance offered by natural and synthetic grass surfaces used in game play. With limited shielding offered by internal structures within the average soccer cleat, the plantar surface of the foot must regularly withstand substantial loads [78]. The outsole of the soccer cleat is designed to depress into the grass surface when a normal load is applied [105]. Studs gripping into the surface will increase ground reaction forces at ground contact [56,88], creating zones of localized pressure on the sole of the foot. With a reduction in footwear-ground surface area, such as that found in soccer cleat studs compared to a trainer outsole, greater mean and peak pressures are resolved across the plantar surface [88]. Therefore, cleat plate properties, such as the arrangement, number, and geometry of each studded contact point influence how pressure is distributed across the plantar aspect of the foot ultimately impacting

lower limb joint moments and forces [60,73]. Stud geometry is a cleat plate modification that directly adapts the amount of traction available at ground contact. Bladed geometries produce higher translational and rotational resistance than elliptical stud patterns on both natural and artificial grass surfaces [58,94]. Understanding loading patterns and regional pressure across cleated stud geometries could highlight potential overuse injury susceptibilities or kinetic chain pathomechanics.

Evidence suggests that consequential interactions at the cleat-surface interface are associated with exposure to non-contact torsional injury [96,105]. Nearly two-thirds of non-contact injuries in soccer have been estimated to result from excess traction at ground contact [33]; anterior cruciate ligament (ACL) ruptures comprise a sizeable portion of these non-contact injuries [40,47]. Movements of rapid deceleration and unanticipated changes of direction are associated with the highest risk of non-contact ACL ruptures [29,53], predictably aligning with instances of highest utilized traction [94]. In cases of ligament rupture, ACL injury is estimated to occur within 50 milliseconds of ground contact [54]. Therefore, effective absorption and redirection of external forces during initial cutting stance are crucial in the prevention of injurious ACL loading. Video analysis of injury mechanisms in professional and collegiate sport have identified rearfoot contact patterns prior to ACL injury more frequently than forefoot contact patterns [8,9,27]. Center of pressure (COP) during initial stance has been linked with injurious knee loading; a more posteriorly directed COP position coincides with increased combined valgus and internal rotation moments [79], knee extensor moments [101] and knee joint negative work [30]. Bladed cleats have been reported to generate greater lateral pressure than elliptical style cleats during both running and slalom

activities, suggesting higher traction footwear may result in unnatural loading of the foot, predisposing injury [6].

At an elevated risk of ACL injury, female soccer athletes are estimated to have a three-time higher rate of ACL tear than their male counterparts [3,85]. Female loading mechanics predispose greater mediolateral and anterior translational forces on the tibia [62]. Additionally, females have lower knee flexion angles, higher knee valgus at initial contact, and increased ankle eversion angles during cutting tasks [38,62]. Despite females having known mechanical susceptibilities to ACL injury [22,25], soccer cleats have historically been designed for and validated against male mechanics. Research suggests that female landing mechanics are affected by footwear more so than males [15]. Queen et al., assessed forefoot loading patterns during cut tasks across cleat variations [86]. Significant differences in forefoot regional force-time integral and maximum force between bladed, firm ground and hard ground cleats could only be discerned in female athletes, suggesting the sensitivity threshold to traction may be lower in the female athlete [86]. Similar sex-cleat interactions can be observed in female neuromuscular control strategies. Butler et al., [13] found higher traction footwear to reduce peak knee flexion angles of only female athletes during a jump landing task. Despite evidence suggesting an effect of traction on female loading mechanics, there is a strong scientific narrative that mechanically available traction may have no substantial impact on the lower extremity mechanics that result in injury [42,50,96]. This general assertion, however, is based on male data. To better understand the etiology of female injury patterns in cleated footwear, it is necessary to assess sex differences in whole-foot plantar loading response during cutting tasks.

Previously formulated conclusions regarding the effect of traction on joint loading have been based upon data collected in controlled laboratory settings with limited external validity. Of note, is the lack of methodological consideration for mechanical variability occurring from first to final whistle on the playing field. Evidence suggests the incidence of traumatic injuries increase at the end of each half [34], likely associated with the progression of fatigue. Internal workload measured by perceived exertion was found to predict non-contact injury among elite soccer players [65]. Systemic fatigue has numerous effects on athletic performance, reducing strength [35,10] power [35], and joint stability [35]. More directly, fatigue induces postural sway among soccer players [44]. The effect of localized fatigue of ankle evertor muscles has been evaluated through in-cleat pressure sensors during lateral jumps [91]. Between three cleat models, no significant differences in loading pattern were found before and after evertor fatigue. These data were limited to male subjects and only targeted localized fatigue. Yet, female athletes are suggested to be more consequentially affected by fatigue [5,41,69]. Parallel research involving runners found systemic fatigue to increase peak force, impulse, and plantar pressure in the forefoot and midfoot [106]. From these observations, it appears that changes in pressure distribution could be a marker of systemic fatigue. Since soccer cleats are not primarily designed for impact absorption, pressure increases could identify regions most susceptible to overload, and COP deviations may indicate pathological instabilities underlying on-field injury. To better inform traction parameters for the female athlete, it is necessary to measure loading patterns across fatigued states.

This is an investigation into the effect of sex and fatigue on plantar pressure distribution and COP excursion in cleated footwear of differing stud geometries. Based

on the increased risk of non-contact injury with fatigue progression, this study evaluated plantar pressure distribution patterns of a lateral cutting movements during a field-based running and cutting protocol. Understanding plantar loading patterns across elliptical and bladed cleat conditions may give insight into the stud characteristics best suited to the female athlete. Aligning with previous cleated plantar pressure findings by Queen et al. [87], it is hypothesized that female athletes will have greater lateral midfoot loading, resulting in greater mediolateral COP (COP_x) excursion. Additionally, it is hypothesized that females may have a more posterior COP (COP_y) position at initial contact. The tendency for female athletes to generate greater knee valgus moments may be the result of a more posteriorly directed COP position at initial contact. As elliptical cleats offer lower rotational and translational resistance, it is predicted that this lower traction cleat condition will result in lower peak plantar pressure compared to the bladed, higher traction cleat condition. Systemic fatigue is predicted to increase COP excursions in both the mediolateral and posterolateral axes and increase pressure across the plantar surface. These analyses are exploratory in nature and may offer information about sex differences contributing to injury etiology.

Methods

Participants

Twenty college-aged soccer athletes participated in this study, ten females (age: 19.9 ± 1.7 years, mass: 60.4 ± 6.3 kg, height: 165.3 ± 4.6 cm), and ten males (age: 22.0 ± 2.2 years, mass: 73.7 ± 7.4 kg, height: 175.6 ± 5.5 cm). Participating athletes were between the ages of 18 and 26, with a history of competitive play, ranging from current

NCAA Division III athletes to university club team or local league members. Participants had no lower limb injury in the past year, no history of ACL injury, and wore a shoe size of women's 8-9 (\pm half a size) or men's 10-11 (\pm half a size) to comfortably fit into the provided footwear. Informed written consent was provided by each participant in accordance with the University of Oregon's Ethics Committee requirements.

Footwear Conditions

Participants completed two data collections scheduled within a window of 4-40 days. This time frame allows participants to recover from the first visit, while still maintaining similar physical fitness levels across sessions. Participants were assigned a different, randomized cleat condition each visit. Chosen cleats were the adidas Copa Sense .3 cleat, with traction characterized by an elliptical stud shape, and the adidas Predator Edge .2, with traction characterized by a bladed stud shape (Figure 5.1). While these are different footwear models, tooling materiality, stud length, and stud placement are comparable. Data collection procedures between laboratory visits were identical aside from the cleat condition worn for testing.



Figure 5.1. Elliptical condition [left] assessed using adidas model Copa Sense .3, bladed condition [right] assessed using adidas model Predator Edge .2.

Surface

Data collections were performed at the Moshofsky Center at the University of Oregon (Eugene, OR), an indoor fieldhouse with a regulation-sized American football field. This third-generation synthetic surface features FieldTurf Vertex Core, a hybrid (monofilament and slit-film) fiber construction with a three-layer sand/rubber infill. Beneath the turf surface is a polypropylene shock pad, installed to increase surface compliance.

Data Collection

Participants were provided with a randomized footwear condition upon arrival. Pedar pressure insoles (Novel, Munich, Germany, sampled at 100 Hz) were inserted inside the cleat, in place of the sock liner. Before the collection, insoles were calibrated to 6 bar according to manufacturer specifications, as well as calibrated to the user once cleats were worn. A heart rate monitor (Garmin, Olathe, Kansas, USA) was affixed around the chest and synchronized via Bluetooth to a wrist-worn watch (Garmin, Olathe, Kansas, USA), for the purpose of tracking relative physical workload throughout the protocol.

Participants performed a multi-stage fatigue protocol after completing a standardized warm-up, progressing from a light jog to speed work. This fatigue protocol was an adapted version of the Gauntlet Test, a validated assessment of cardiorespiratory fitness used to predict aerobic performance of collegiate soccer players [12]. The adapted Gauntlet Test consisted of five running stages, each involving a series of intermittent lateral cuts across the length and width of the football field. Suited to the constraints of

the field, the Gauntlet Test was modified to consist of 1607-, 799-, 401-, 208-, and 100-m stages, each separated by one-minute of rest (previously visualized in Figure 4.2). This fatigue protocol was designed to be performed at maximal effort; therefore, participants were instructed to complete the stages in the least amount of cumulative time. At each designated direction change, participants were instructed to perform a 90-degree cut without rounding the corner. Pedar data were recorded throughout the first three stages, as part of a larger study. Cutting steps were simultaneously dictated using voice recordings and temporally synced with Pedar data. Completion time and heart rate at the end of each of the five stages were reported.

Identical methodologies were followed for the second visit, aside from the cleat condition worn.

Data Analysis

Cutting steps during the initial 400 meters of the 1607-m stage were chosen to represent the on-field pre-fatigue condition. Cutting steps during the final 190 meters of the 401-m stage were chosen to represent the on-field post-fatigue condition. Similar routes were followed during these two stages to compare cutting steps. The mean of four cutting steps following a run across the full width of the field were chosen for the analysis of each participant and condition. Each mean contained both left and right cuts when possible; however, six out of eighty conditions contained fewer than four cuts due to equipment failure. Data were filtered using a dual-pass fourth-order Butterworth filter at 25 Hz, and stance phase was defined when the vertical ground reaction force exceeded 50 N. Pressure data were normalized to body weight and subdivided into eleven regions,

reflective of cleat stud placement (Figure 5.2). The heel was subdivided into four masks: Heel Upper Medial (HUM), Heel Upper Lateral (HUL), Heel Lower Medial (HLM) and HLL (Heel Lower Lateral). The forefoot was subdivided into seven masks: Forefoot Upper Medial (FUM), Forefoot Upper Lateral (FUL), Forefoot Center Medial (FCM), Forefoot Central (FC), Forefoot Center Lateral (FCL), Forefoot Lower Medial (FLM) and Forefoot Lower Lateral (FLL). As ACL injury is most likely to occur during initial contact [54], peak plantar pressure masked to stud locations was analyzed within the first 0.05 seconds of stance.

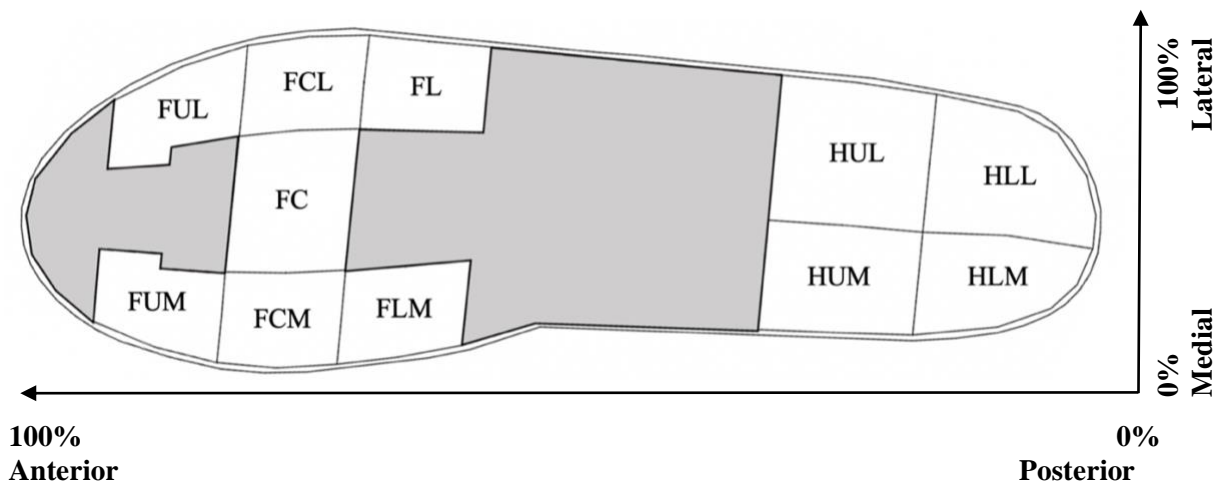


Figure 5.2. Eleven footwear mask regions, corresponding to stud locations. Center of pressure position visual legend is overlaid.

The mean COP position at initial contact and 0.05s after initial contact, as well as the COP excursion during stance and the first 0.05s of stance were analyzed along the mediolateral (COP_x) and anteroposterior (COP_y) axes with a custom MATLAB script (Mathworks Inc., Natick, MA, USA). The COP position was normalized to the dimensions of the plantar pressure insole, with 0% representing medial-most or posterior-most positions, and 100% representing lateral-most and anterior-most positions (Figure

3). Temporal waveforms of COP_x and COP_y excursions across the full cutting stance were interpolated to establish participant and condition-specific means.

Statistics

Statistical analyses were performed using R-Studio (RStudio Inc., Boston, MA, USA). Two-way univariate analyses of variance (ANOVA) statistical tests ($\alpha = 0.05$) were used to assess the effect of sex and cleat on the time to complete the fatigue protocol. Additionally, three-way mixed model ANOVA statistical tests ($\alpha = 0.05$) were conducted to compare heart rate recorded at the end of the 1607-meter and 401-meter stages between sex, cleat, and fatigue state conditions.

Three-way mixed model univariate ANOVA statistical tests ($\alpha = 0.05$) were also conducted to compare the effect of sex, cleat condition and fatigue state on peak pressure for each of the 11 masked regions during initial stance (defined as within 0.05 seconds of initial contact). Mixed-effects ANOVAs were conducted on COP_x and COP_y positions and excursions during the initial 0.05s of stance, and across full stance. If statistical significance was found, post-hoc pairwise t-tests were performed with a Bonferroni correction.

Statistical Parametric Mapping (SPM) was used to independently assess differences in the time series waveforms of COP_x and COP_y excursion based on the effects of sex, cleat condition and fatigue state during the entirety of the cutting stance [82,83]. The t-statistic among conditions was compared on a continuous level, and the null hypothesis was rejected if the critical test statistic values exceeded the critical threshold ($\alpha = 0.05$).

Results

Gauntlet Test

Two-way ANOVA tests examined the main and interactions effects of sex and cleat condition on stage completion time. There was a significant effect of sex ($p < 0.01$) on the time to complete the running stages, finding male athletes to complete the stages in a shorter duration regardless of cleat condition. Three-way mixed-effects ANOVAs examined the main and interaction effects of sex, cleat condition and fatigue on heart rate. There was a significant effect of fatigue ($p < 0.01$) on heart rate, with greater values across both sexes and cleat conditions in the 401-meter stage compared to the 1607-meter stage (Table 5.1).

Table 5.1. Completion time and final heart rate (mean \pm standard deviation) for male and female participants during the Gauntlet Test at 1607-m (pre-fatigue) and 401-m (post-fatigue) stages across two cleat conditions.

Condition	Time (min:sec)			Final Heart Rate (beats/m)	
	1607 m Stage	401 m Stage	Full Protocol	1607 m Stage	401 m Stage
Male					
Bladed	7:15 \pm 0:46	1:41 \pm 0:13	13:35 \pm 1:24	170 \pm 10.07	177 \pm 9.45
Elliptical	7:10 \pm 0:33	1:41 \pm 0:13	13:25 \pm 1:14	168 \pm 12.02	173 \pm 12.17
Female					
Bladed	8:22 \pm 1:01	2:01 \pm 0:18	15:35 \pm 1:54	172 \pm 17.37	179 \pm 12.81
Elliptical	8:18 \pm 0:47	1:53 \pm 0:14	15:26 \pm 1:31	170 \pm 11.71	180.4 \pm 6.75

Peak Plantar Pressure

Mixed model ANOVAs examined the main and interaction effects of sex, cleat condition and fatigue state on peak plantar pressure during initial cutting stance. The mean and standard deviation of peak pressure within the 11 footwear masks are

summarized by condition in Table 5.2, and significant effects are illustrated in Figure 5.3. Four masked regions revealed statistically significant main or interaction effects.

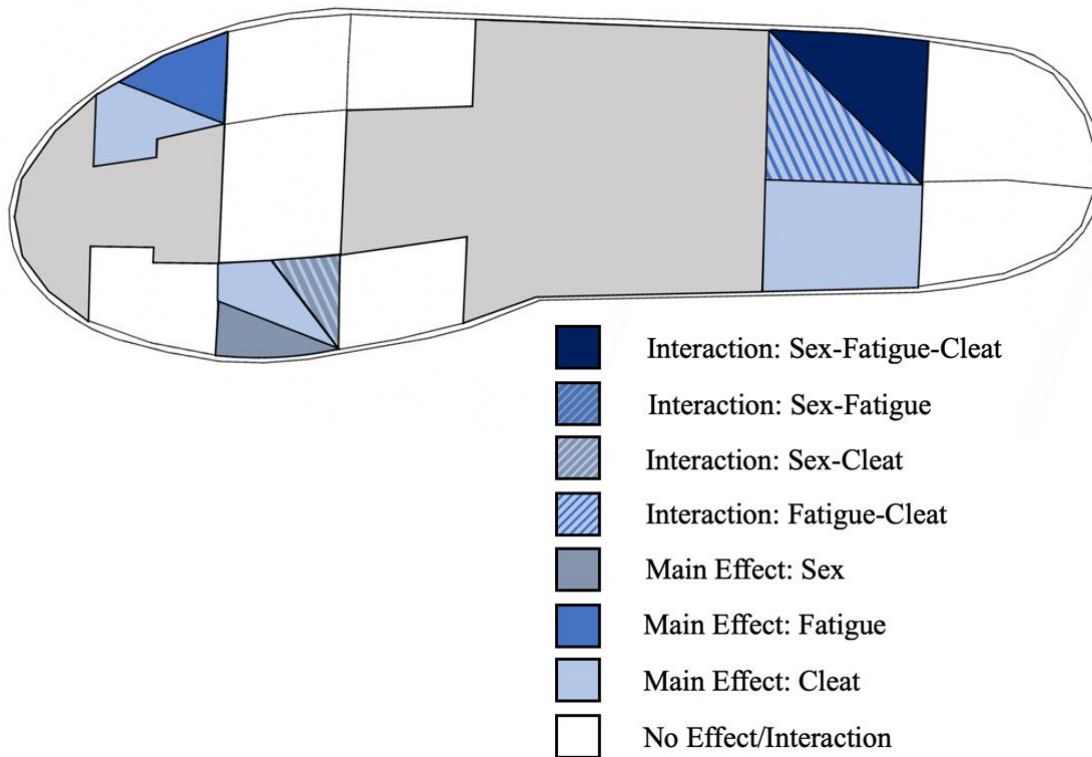


Figure 5.3. Significant main and interaction effects of peak pressure during the initial 0.05 seconds of the cutting stance within the 11 regions corresponding to stud location.

At the forefoot, FUL peak pressure was significantly affected by cleat condition ($p < 0.01$), with elliptical cleats found to generate 18% higher peak pressure than bladed cleats. Furthermore, FUL peak pressure was significantly affected by fatigue state ($p < 0.05$), with lower peak pressure generated in the post-fatigue state. Differences in medial forefoot pressure existed at region FCM, with observed main effects of sex ($p = 0.05$) and cleat ($p < 0.001$), as well as a sex-cleat interaction ($p < 0.01$). At this stud location, males experienced 40% higher peak pressure than females, and the elliptical cleat condition achieved 13% higher peak pressure than the bladed cleat. Post-hoc condition comparisons

using a Bonferroni correction indicated the male elliptical condition was significantly greater than the male bladed condition ($p < 0.001$), and the male elliptical condition was significantly greater than the female bladed condition ($p < 0.001$).

At the heel, significant main effects of cleat condition were found at the HUM mask, with elliptical cleats generating 14% higher peak pressure than bladed cleats. Significant interaction effects were found at the HUL mask, both a two-way interaction effect of cleat condition and fatigue state ($p < 0.05$) and a three-way interaction between sex, cleat condition, and fatigue state ($p < 0.01$). However, post-hoc condition comparisons did not find significant results.

Table 5.2. Mean \pm standard deviation of peak plantar pressure at initial contact of the cutting stance within 11 pressure masked regions correspond to stud location, sorted conditionally by sex, cleat condition and fatigue state (kPa/kg).

Region	Bladed		Elliptical	
	Pre-Fatigue	Post-Fatigue	Pre-Fatigue	Post-Fatigue
Male				
FUM	0.90 \pm 0.50	0.89 \pm 0.59	0.91 \pm 0.62	0.86 \pm 0.68
FUL †, ‡	0.24 \pm 0.13	0.21 \pm 0.12	0.28 \pm 0.15	0.23 \pm 0.12
FCM *, †, ¶	1.74 \pm 0.47	1.76 \pm 0.68	1.82 \pm (0.50	1.79 \pm 0.56
FC	1.02 \pm 0.38	1.03 \pm 0.29	1.06 \pm 0.36	0.99 \pm 0.17
FCL	0.34 \pm 0.19	0.37 \pm 0.18	0.38 \pm 0.15	0.36 \pm 0.12
FLM	0.84 \pm 0.45	0.81 \pm 0.54	0.88 \pm 0.51	0.85 \pm 0.60
FLL	0.38 \pm 0.16	0.39 \pm 0.19	0.40 \pm 0.12	0.37 \pm 0.14
HUM †	1.60 \pm 1.01	1.75 \pm 0.85	1.83 \pm 0.96	2.05 \pm 0.77
HUL ✕, §	1.29 \pm 0.85	1.49 \pm 0.79	1.41 \pm 0.77	1.67 \pm 0.76
HLM	1.65 \pm 1.17	1.67 \pm 0.95	1.77 \pm 1.22	1.76 \pm 0.88
HLL	1.73 \pm 1.16	1.70 \pm 1.01	1.63 \pm 0.97	1.67 \pm 0.82
Female				
FUM	0.49 \pm 0.26	0.46 \pm 0.32	0.64 \pm 0.35	0.63 \pm 0.32
FUL †, ‡	0.21 \pm 0.19	0.23 \pm 0.22	0.34 \pm 0.26	0.19 \pm 0.15
FCM *, †, ¶	1.12 \pm 0.55	1.09 \pm 0.57	1.38 \pm 0.53	1.49 \pm 0.79
FC	0.95 \pm 0.49	0.96 \pm 0.52	1.03 \pm 0.40	1.06 \pm 0.58
FCL	0.31 \pm 0.12	0.34 \pm 0.18	0.41 \pm 0.14	0.38 \pm 0.20
FLM	0.53 \pm 0.32	0.55 \pm 0.40	0.63 \pm 0.42	0.55 \pm 0.36
FLL	0.35 \pm 0.14	0.44 \pm 0.26	0.44 \pm 0.12	0.42 \pm 0.18
HUM †	1.58 \pm 0.97	2.15 \pm 1.04	2.09 \pm 1.25	2.08 \pm 1.36
HUL ✕, §	1.29 \pm 0.74	1.90 \pm 0.95	1.70 \pm 0.97	1.75 \pm 1.19
HLM	1.91 \pm 1.23	2.06 \pm 1.04	2.26 \pm 1.23	2.00 \pm 1.16
HLL	2.00 \pm 1.30	2.30 \pm 1.18	2.06 \pm 1.12	1.96 \pm 1.28

* Significant main effect of sex

† Significant main effect of cleat

‡ Significant main effect of fatigue

¶ Significant interaction of sex and cleat

✕ Significant interaction of fatigue and cleat

§ Significant three-way interaction

Center of Pressure

Discrete Values

Mixed model ANOVAs examined the main and interactions effects of sex, cleat condition and fatigue state on COP positions, excursions and contact time across the different phases of cutting stance. The mean and standard deviation of COP_x and COP_y metrics and contact time are summarized by condition in Table 5.3. Main and interaction effects on COP position were not detected at initial ground contact or 0.05 s after ground contact. A significant main effect of sex on contact time was found ($p < 0.001$), observing female participants experiencing 19% longer contact time than male participants. Fatigue was found to have a main effect on mediolateral excursion during full stance ($p < 0.05$), increasing excursion post-fatigue.

Table 5.3. Mean \pm standard deviation of mediolateral (COP_x) and anteroposterior (COP_y) center of pressure positions and excursions during the cutting stance, sorted conditionally by sex, cleat condition and fatigue state (% width, % length).

	Bladed		Elliptical	
	Pre-Fatigue	Post-Fatigue	Pre-Fatigue	Post-Fatigue
Male				
COP _x Position: 0.05s Stance	45.89 \pm 5.88	45.78 \pm 6.73	46.04 \pm 3.93	45.86 \pm 4.71
COP _y Position: 0.05s Stance	51.44 \pm 12.10	51.91 \pm 10.68	51.55 \pm 10.24	51.62 \pm 8.99
COP _x Excursion: 0-0.05s Stance	6.13 \pm 2.94	6.18 \pm 3.35	7.75 \pm 2.54	7.87 \pm 2.52
COP _y Excursion: 0-0.05s Stance	16.76 \pm 7.20	15.36 \pm 6.76	15.89 \pm 5.89	16.93 \pm 5.61
COP _x Excursion: Full Stance ‡	19.08 \pm 5.44	21.12 \pm 4.78	19.93 \pm 4.01	22.13 \pm 4.45
COP _y Excursion: Full Stance	39.21 \pm 17.51	40.79 \pm 14.68	37.44 \pm 14.68	41.09 \pm 11.37
Contact Time (ms): Full Stance *	26.73 \pm 2.75	25.50 \pm 3.06	26.45 \pm 3.68	25.20 \pm 3.32
Female				
COP _x Position: 0.05s Stance	49.02 \pm 6.66	50.61 \pm 7.21	48.33 \pm 5.32	48.66 \pm 7.45
COP _y Position: 0.05s Stance	47.03 \pm 12.62	44.76 \pm 12.43	49.65 \pm 13.40	48.96 \pm 13.80
COP _x Excursion: 0-0.05s Stance	6.50 \pm 3.35	5.03 \pm 2.86	6.45 \pm 3.35	6.26 \pm 4.11
COP _y Excursion: 0-0.05s Stance	15.46 \pm 8.69	16.48 \pm 4.95	13.43 \pm 6.52	15.25 \pm 8.04
COP _x Excursion: Full Stance ‡	12.21 \pm 8.37	24.28 \pm 6.31	21.82 \pm 7.82	24.15 \pm 7.85
COP _y Excursion: Full Stance	45.38 \pm 15.46	47.07 \pm 15.04	45.25 \pm 17.64	43.47 \pm 18.43
Contact Time (ms): Full Stance *	29.90 \pm 3.54	30.93 \pm 4.57	31.95 \pm 5.08	30.53 \pm 5.08

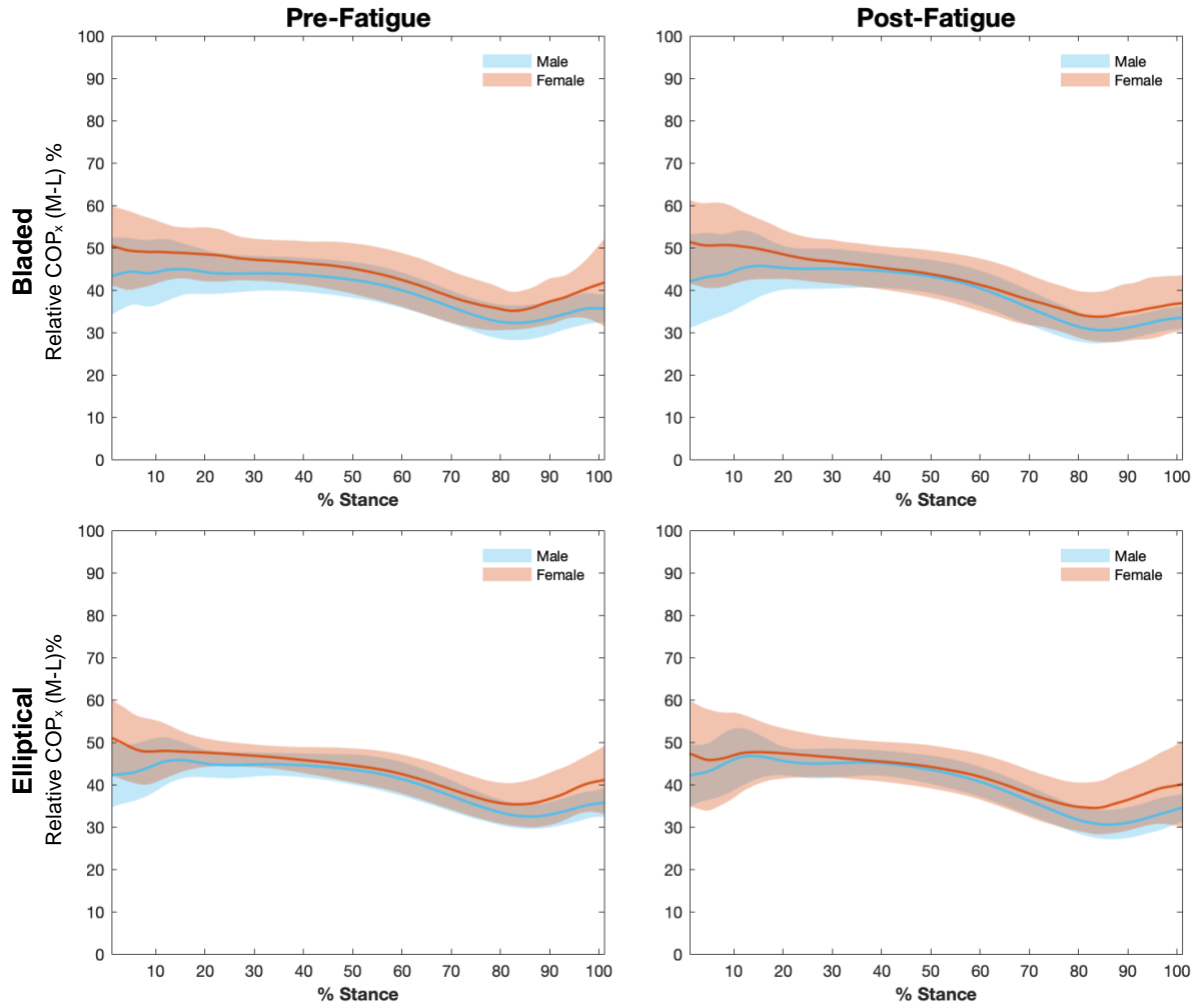
* Significant main effect of sex

‡ Significant main effect of fatigue

Time Series Data

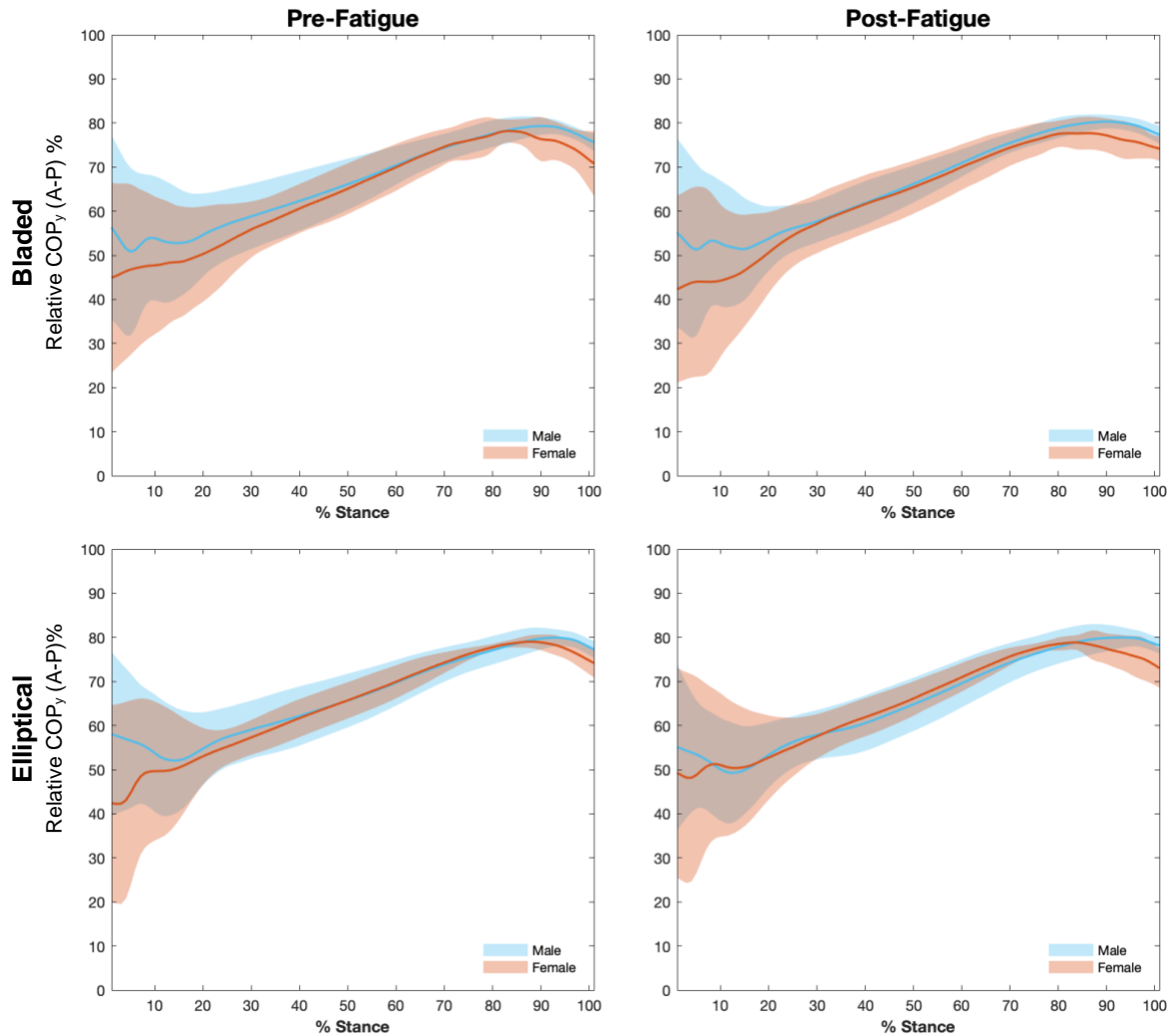
Statistical parametric mapping identified experimental differences between fatigue states on COP_x from 95.7-100% of cutting stance ($p < 0.05$; Figure 5.4).

Additional differences across sex were determined for COP_y from 96.6-100% of cutting stance ($p < 0.05$; Figure 5.5). No detectable differences were characterized during the initial 0.05s of cutting stance.



MAIN EFFECT: Fatigue from 95.7-100% stance ($p < 0.05$)

Figure 5.4. Mean (solid line) and standard deviation (shaded area) of mediolateral (COP_x) trajectory during cutting stance between male (blue) and female (red) participants. A greater value on the y-axis indicates a more lateral position (50% representing the midline of the foot). Top row summarizes bladed footwear condition, bottom row summarizes elliptical footwear condition. Left column presents pre-fatigue time series data, right column presents post-fatigue time series data. Significant fatigue effects were found from 95.7-100% stance.



MAIN EFFECT: Sex from 96.6-100% stance ($p < 0.05$)

Figure 5.5. Mean (solid line) and standard deviation (shaded area) of anteroposterior (COP_y) trajectory averaged across male (blue) and female (red) participants. A higher value on the y-axis indicates a more anterior position (50% representing the halfway point between heel and hallux). Top row summarizes bladed footwear condition, bottom row summarizes elliptical footwear condition. Left column presents pre-fatigue time series data, right column presents post-fatigue time series data. Significant sex effects were found from 96.6-100% stance.

Discussion

The purpose of this study was to understand how soccer cleat stud shape, a known moderator of ground-cleat rotational resistance, may influence the loading patterns of

male and female athletes as fatigue progresses. Experienced soccer players performed a fatiguing running and cutting protocol in soccer cleats of bladed and elliptical stud type, where plantar pressure data were analyzed during anticipated 90-degree cuts. This research sought to better understand how soccer cleat stud parameters may uniquely affect the in-cleat loading patterns of fatiguing female athletes on the playing field, and what this may tell us about the etiology of female ACL injury.

Cleat Condition

The results of this study suggest that the resistance offered by studs of different shapes have significant effects on peak plantar pressure at key stud locations in both the forefoot and heel during initial stance (first 0.05s of stance). Across significant forefoot (FUL and FCM) and heel (HUM) masks, elliptical-style cleats generated greater peak pressure than bladed-style cleats during initial cutting stance. This main cleat effect is counter to what was originally hypothesized, in that the elliptical studs caused greater peak plantar pressure than bladed studs within the temporal window of when ACL injuries are considered most likely to occur [54]. While previous research conducted in unfatigued male athletes [10] identified bladed models to increase pressure and impulse across the lateral plantar surface, this same study also determined elliptical models to increase plantar pressure and force time integrals on the medial plantar surface. In the present study, cleat condition had a significant main effect in two key masked regions along the medial plantar surface, FCM and HUM, thus corroborating aspects of previous research. Bentley et al., [10] had reasoned this medial loading pattern to follow a more natural center of pressure progression, suggesting elliptical-style studs to be a safer

alternative. The COP_x analyses in the present study, however, did not identify any discrete nor continuous main effects of cleat condition to support or refute this deduction. Located in the most anterolateral stud position, the FUL mask also had a main effect of cleat condition. This stud position is approximately aligned with the 5th phalanx. Peak pressure across the lateral plantar surface is generally estimated to be lower than peak pressure across the medial plantar surface during cutting, with the lateral toes comprising only about 5% of total peak pressure across the entire plantar surface [32]. While differences in FUL peak pressure may be significant, its' relevance may be minor when considering the fraction of total pressure distributed to this lesser loaded region.

Previous prospective research on the incidence of ACL injury among high school football players found a positive relationship between the rate of injury and available traction [55]. However, in the current study, the cleat condition with lower available traction resulted in several regions of higher peak pressure. This may be attributed to the in-shoe pressure measurement system only being capable of recording normal forces. Movement patterns associated with ACL injury risk during jump landings demonstrate increased lateral [100] and posterior [79,80] ground reaction force components. Simplifying pressure analyses to uniaxial vertical force will omit pressure generated by shear forces during lateral cutting. It is possible that the higher traction generated by the bladed-style cleat may yield lower normal forces due to increased shear components; this would ultimately explain the comparatively lower peak pressures.

Sex

A main effect of sex was found on contact time. Duration of cutting stance was shorter for male participants than female participants across all conditions. Similarly, significant differences in the completion time of Gauntlet Test stages were found between sex. Male athletes were significantly faster than female athletes both overall and across individual stages.

Sex differences could only be found at one medial forefoot mask (FCM), where male athletes generated 40% higher peak pressure during initial cutting stance. This observation aligns with previous works, where male athletes have been found to have significantly greater maximum force beneath the medial midfoot [87] and peak pressure beneath the middle forefoot [93] than female athletes during lateral cutting. Queen et al. [87] also reported greater lateral column loading among females. Though not statistically meaningful, trends in the COP_x position during cutting stance in the present study are consistent with this observation. Scaled to the width of the instrumented insole, COP_x average initial contact position was 5-10% more lateral in females than males when conditionally matched. This trend continues throughout the remainder of cutting stance. A lateral shift in center of pressure can increase valgus knee joint moments [45]. Similar observations can be made about COP_y position. While not statistically significant, the average COP_y position at initial contact is 4-14% more posterior in females than males when conditionally matched. Over the full course of stance, female COP_y excursion is 6-21% greater than males, showing that females cover a greater anteroposterior distance from initial contact to toe off. Trends suggest there may be differences in landing strategy between males and females. Neutral stance in cleated footwear encourages heel

depression, as body weight is posteriorly shifted through the calcaneal studs [7,104]. As shod foot posture is slightly dorsiflexed when wearing cleats [7,104], there is a tendency for athletes to land in a rearfoot contact pattern [104]. Trends in the current study suggest that female contact patterns may be more adversely affected by shod foot posture than males. Constrained ankle range of motion during high impact activities would reduce eccentric, dissipative activity of the dorsiflexors, placing significantly higher mechanical demand on the knee joint [30]. Traction moderation at the heel may be warranted for female athletes.

An interaction involving sex and cleat condition was found at the FCM mask. Post-hoc analyses revealed that the male elliptical condition had greater pressure than both male and female bladed conditions. For the female athlete, trends suggest elliptical stud types generate greater peak pressure than bladed stud types at FCM during initial stance. Previous works have found elliptical studs to generate higher medial forefoot pressure in male athletes [6], yet lower maximum midfoot force in female athletes [86]. While current study findings mostly align with previous works from Queen et al., [86] and Bentley et al., [6], the female response to stud shape does differ.

Fatigue

Systemic fatigue progression had a significant effect on heart rate, increasing relative physical workload throughout the fatigue protocol. This evidence supports the notion that athletes are in a comparatively fatigued state between the start of the first and the end of the third running stage, enough to induce potential musculoskeletal adaptations.

The progression of fatigue was found to affect mediolateral loading patterns. Fatigue significantly increased mediolateral excursion across full stance; in the case of female participants in the bladed cleats, COP_x excursion doubled from pre- to post-fatigue exposure. Increased mediolateral excursion could indicate some degree of instability across cutting stance. In parallel, significant effects of fatigue were found on two laterally located masks, a main fatigue effect on FUL, and fatigue-cleat and three-way interactions on HUL. In the FUL mask, fatigue significantly decreased peak plantar pressure at initial stance. Yet, in the HUL mask, trends suggest that fatigue increases peak plantar pressure. Paralleling COP_x excursion, this too is most apparent in the female bladed condition. Between the posterolateral pressure shift during initial stance, and the greater mediolateral excursion, bladed cleats may adversely affect female athletes when fatigued. This aligns with supplemental analyses of footstrike angle within this broader, unpublished data set, observing a 10-degree rearfoot shift in footstrike angle among fatigued females in the bladed cleats.

This study has several limitations worth noting. Lateral cutting occurred at anticipated locations during the fatigue protocol. While participants were encouraged to make sudden 90-degree cuts, they may have altered their mechanics in anticipation. This limits the external validity of these results. Footwear used in this study were chosen to represent bladed and elliptical conditions, as stud locations were identical between models. However, the cleats were not identical in construction, most notably in upper material. This may have altered participant fit and feel within the shoe. Lastly, the surface used for testing was an artificial grass and not an outdoor firm ground with natural grass. Firm ground cleats, like those worn in this collection, are designed to be worn on outdoor

grass. However, to perform data collections year-round, an indoor facility was required. Furthermore, female collegiate athletes must often wear firm grass cleats on turf surfaces, thus reducing the impact of this limitation.

Conclusion

This study evaluated the effect of sex and fatigue on peak plantar pressure and COP trajectories in cleated footwear of differing stud geometries. Significant main and interaction effects were found across the anterior heel, medial forefoot, and lateral toes. Results suggest elliptical stud shape increases peak pressure during initial cutting stance, compared to bladed stud shape. Systemic fatigue increased posterolateral pressure and mediolateral excursion, particularly among female participants in the bladed condition. This could be an adverse indication. While this research does not provide definitive conclusions on optimal stud shape according to female athlete loading patterns, it does offer evidence that male and female cutting mechanics may be affected differently by both cleat properties and induced fatigue. Results suggest the need for improving both the lateral and posterior geometry and arrangement of studs on a female-informed cleat design.

Funding Sources: This work was supported by the Wu Tsai Human Performance Alliance and the Joe and Clara Tsai Foundation. Footwear was generously donated by adidas.

Bridge

The goal of this chapter was to understand the effects of soccer cleat stud shape and fatigue on the plantar loading response of male and female soccer athlete during predictive cutting. Results of this study highlight regional pressure differences between sex, cleat condition and fatigue in the anterior heel, medial forefoot, and lateral toes. Evidence in center of pressure trajectories highlight the unique sex-based response to cleat stud shape and induced fatigue. Data in this chapter and previous chapters offer important insight on preferred stud length and shape design choices for the mechanics of the female soccer athlete. This next chapter is in collaboration with industry partner, Puma SE. Traction plate iterations were co-designed utilizing results from Chapter III-V and manufactured for concept validation. Chapter VI determines the effect of the proposed traction plate designs on lower extremity energetics, foot strike contact patterns, and knee mechanics across fatigue states. This chapter will provide evidence that modified traction plates reduce the high-risk mechanics otherwise observed in market-available control cleats.

CHAPTER VI
VALIDATION OF DATA-DRIVEN TRACTION DESIGN FOR THE FEMALE
SOCCER ATHLETE

This chapter is currently in preparation for publication. Footwear iterations were co-developed by PUMA SE innovation team in collaboration with Emily C. Karolidis, Alex N. Denton and Michael E. Hahn. Emily C. Karolidis designed the study and collected and analyzed the data. Michael E. Hahn provided mentorship and aided in study design, general oversight, and editing and finalizing the final manuscript.

Introduction

Emerging epidemiological evidence highlight differences in the prevalence of lower limb injuries between sexes [28,71]. In organized sport, severe knee and ankle ligament injuries are elevated among females [11,48]. Most notably, injuries of the anterior cruciate ligament (ACL) have been estimated to occur at a three-time higher rate in female than male athletes [3,85]. Underlying differences in female knee joint laxity, anatomical alignment and neuromuscular control strategies are significant factors contributing to this sex-based injury discrepancy [22,25]. High agility tasks such as cutting, running, and landing illustrate the adverse mechanical strategies of female athletes, characterized by less knee flexion, lower hamstring muscle activation, greater quadriceps activation, and greater valgus positioning on landing [21,22,25,53,62]. The landing mechanics of female athletes have been shown to worsen with systemic fatigue progression [5,41,69]. Likely associated with the frequency of unplanned cutting and

landing maneuvers over the course of game play, female soccer athletes exhibit the highest rate of ACL injury incidence across all collegiate sport [2].

Due to the compliance of both natural and synthetic grass surfaces, soccer athletes wear high-traction cleated footwear. When a normal load is applied, studs on the outsole of soccer footwear depress into the grass surface, resisting slippage and improving agility during change-of-direction maneuvers [105]. Neutral stance in cleated footwear encourages heel depression, as body weight is posteriorly shifted through the calcaneus [7,104]. Shod foot posture is therefore slightly dorsiflexed when wearing cleats [7,104]. Cleated outsoles generate both translational and rotational resistance [96]. Excessive rotational resistance has been associated with a greater risk of lower limb non-contact injury, disconnecting momentum between the fixed foot and the whole-body in motion [96]. Support structures of the knee, such as the ACL, become particularly vulnerable to this torsional strain. Considering female athlete predisposition to high-risk landing and cutting strategies, unsuitable traction may heighten existing susceptibility to ACL injury. However, market available soccer cleats are predominately designed and validated according to male mechanics. Soccer cleat traction could hold a key role in moderating female athletes' exposure to ACL injury.

Traction parameters such as stud length, geometry and positioning can adapt outsole resistance to axial rotation [7]. Longer studs may increase the magnitude of force required to release the foot from the ground [4]. Sharper geometries such as bladed studs increase both translational and rotational resistance compared to a rounder, elliptical geometry [58,94]. Changes to stud configuration can alter movement strategies and joint dynamics during change-of-direction tasks [72]. Research suggests that female landing

mechanics may be affected by footwear more so than males [15], though individual effects of traction design changes are not as well known.

To address this, previous works by this research team identified how individual stud parameters affect female movement mechanics. This series of research studies first looked to stud length effects, finding stud length reductions to improve relative knee flexor muscle contributions compared to knee extensor musculature during sprint stops and cuts, seen in Chapter III. This work suggested that a reduction of 50-75% of market-available firm ground stud lengths may moderate some of the high-risk landing mechanics observed with longer length studs. To understand the effect of stud shape, Chapter IV identified elliptical style studs to reduce fatigue-induced knee valgus angles observed with bladed style studs. This, in combination with previous research efforts by Butler et al., [13] suggest that outsoles with less available traction may improve the landing kinematics of female athletes. Complimentary research in Chapter V also identified female athletes to trend a more posterolateral directed center of pressure at initial contact than male athletes. Considering ACL rupture is estimated to occur within 50 milliseconds of ground contact [54], and knee mechanical work is higher in rearfoot contact patterns than forefoot contact patterns [30], traction at the heel stud should be carefully considered for female athletes.

In partnership with a PUMA SE, cleat prototypes were developed based on previous research findings. Two cleat plate iterations were constructed off a market-available model, a traction plate iteration characterized by ‘moderate’ changes, and a more boundary-pushing ‘novel’ iteration. Changes to the cleat plate involved reducing stud length, particularly at the heel studs, and the introduction of rounded studs with

lower available rotational traction. This culminating aim is a mechanical validation of traction plates designed for the female athlete. This investigation seeks to determine the effect of the proposed traction plate designs on lower extremity energetics, foot strike contact patterns, and knee mechanics across fatigue states. It is hypothesized that the moderate and novel cleat iterations will improve the lower extremity performance profile of female soccer players compared to the market-available control.

Methods

Footwear

Proof of concept samples were designed and manufactured with preferred stud parameters in collaboration with PUMA SE. To isolate the influence of chosen traction parameters on female knee mechanics, cleat prototypes were based upon a market-available women's model, Women's Future Ultimate FG/AG (Puma SE, Herzogenaurach, Germany). This control model uses a size 8.5 Women's last, validated to measurements of the female foot. Aside from tooling specifications, prototypes were identical to the base model in materiality and technology. Cleat uppers were constructed of an engineered stretch knit and dual mesh, and overlaid by bonded PWRTAPE to increase lateral support and stability (Puma SE, Herzogenaurach, Germany). Two unique sets of tooling were developed around the traction parameters guidelines, a moderate version, and a novel version (Figure 6.1). Outsoles were constructed of an identical thermoplastic polyurethane, yet cleat plate design criteria such as stud length, stud shape, and configuration were altered between cleat conditions, as recommended by data collected in Chapters III-V. While not informed by data collected in this dissertation, the midfoot shank was also modified across cleat conditions. This design decision adjusted

the directionality of the outsole plate at the midfoot, with the intent of encouraging a medial contact pattern. The footwear properties between models are summarized in Table 6.1. Resultant athlete mechanics were evaluated across the proof-of-concept samples and compared against the market-available footwear control.



Figure 6.1. Footwear condition outsoles. From left to right: Women's Future Ultimate FG/AG, "Moderate" prototype, "Novel" prototype

Table 6.1. Comparison of traction properties between control, moderate and novel cleated pairs.

Parameter	Control	Moderate	Novel
Stud Shape			
Heel	Diamond	Elliptical and half-moon	Elliptical and half-moon
Forefoot	Diamond & bladed	Elliptical, half-moon & bladed (chevron)	Elliptical, half-moon & bladed (straight)
Stud Length			
Heel	14 mm	10.5 mm	8.5 mm
Forefoot	Medial forefoot: 12 mm Lateral forefoot: 12 mm Toes: 11.5 mm	Medial forefoot: 10.5 mm Lateral forefoot: 10.5 mm Toes: 8 mm	Medial forefoot: 8.5 mm Lateral forefoot: 5 mm Toes: 5 mm
Stud Position			
Heel	Two anterior, two posterior	No change from original	No change from original
Forefoot	Two anterior toes, three medial forefoot, two lateral forefoot	Medial forefoot studs oriented around 1 st MTP pivot point	Medial forefoot studs oriented around 1 st MTP pivot point
Shank			
Midfoot Shank	Anterolateral heel to medial forefoot	Midline of anterior heel to midline of forefoot	Anteromedial heel to lateral forefoot

Participants

Six female college-aged soccer athletes participated in this study (age: 19.8 ± 1.3 years, mass: 60.6 ± 4.9 kg, height: 168.0 ± 6.3 cm). Participating athletes were between the ages of 18 and 26, with a history of competitive soccer, ranging from NWAACC community college team, current university club team or competitive local league members. Participants had no lower extremity injury in the past year, no history of ACL injury, and wore a shoe size of women's 8 (\pm a size) to comfortably fit into the provided

cleats. Informed written consent was provided by each participant in accordance with the University of Oregon's Ethics Committee requirements.

Protocol

Participants performed three data collections. Each visit, the participant was assigned a different, randomized cleat condition to wear, the control model, the 'moderate' prototype, and the 'novel' prototype, defined previously. In-laboratory procedures were identical between visits, aside from the double blinded cleat condition worn for testing. Cutting task mechanics were compared between male and female participants across cleated conditions, before and after completion of a systemic fatigue protocol.

Data collection was performed at the Marcus Mariota Sport Performance Center located at the University of Oregon (Eugene, OR, USA). This biomechanics facility is equipped with artificial turf, simulating a typical ground-cleat interaction for female collegiate soccer. Installed in the laboratory is 1.25" UBU Sports FT38 artificial turf with slit-film monofilament thatch fibre construction. Beneath the turf surface attaches a 5/8" Armcell Nitrile rubber pad, and a ProPlay-Sport 23D 23 mm closed cell polyethylene shock pad, installed to increase surface compliance. To increase the area of approach, an additional strip of turf was aligned with the installed turf, offering a ten-meter runway into the data collection space. A 19-camera motion capture system (Vicon Motion Systems, Oxford, UK, sampled at 100 Hz) was time-synchronized with ground reaction force data, collected using four AMTI surface embedded force platforms, positioned in a 2x2 square (Advanced Medical Technologies Inc. Watertown, MA, USA, sampled at

1000 Hz). Retroreflective markers were placed on the pelvis and lower extremities of the participants in accordance with the Qualisys CAST lower body marker set [14]. Skin glue was used to attach thigh and shank markers in clusters, ensuring marker fixation throughout the entire data collection. A static neutral trial of the complete marker set was first recorded, then the set was reduced to 28 markers for dynamic trials.

Participants were tasked with performing unanticipated cutting tasks prior to, and immediately following a systemic fatigue protocol. Participants were instructed to run at 80% of their self-selected maximum speed into a 120-degree directional cut (Figure 4.1). Cut direction was randomized by the researcher, signaled to the participant two meters in advance of the force platform deck. For each cut to be considered admissible, the foot opposite the direction of cut must have been planted on one of the four force platforms. Six unanticipated cuts were recorded (three in each direction) to represent mechanics observed in a pre-fatigued state.

Following pre-fatigued cutting task completion, participants were taken to a nearby indoor regulation-sized American football field (The Moshofsky Center, University of Oregon, Eugene, OR) and instructed on the multi-stage fatiguing protocol. This facility is equipped with a third-generation hybrid synthetic surface (FieldTurf Vertex Core) with a three-layer sand/rubber infill. To best mimic fatiguing activities observed in a soccer game, this study implemented an Adapted Gauntlet Test, where each stage consists of a series of intermittent cuts across the length and width of a football field. Suited to the constraints of the field, this study modified the Gauntlet Test to instead perform 1607-, 799-, 401-, 208-, and 100-meter stages, each separated by 1 minute rest, as seen in Figure 2. This is an adapted version of the original Gauntlet Test,

which is a validated assessment of cardiorespiratory fitness used to predict aerobic performance of collegiate soccer players [12]. This fatigue protocol is designed to be performed at a maximal effort to induce systemic fatigue. Differences in mechanics pre- and post-fatigue, such as those states observed at the beginning and end of a soccer match, can then be assessed.

Following completion of the fatigue protocol, participants were immediately returned to the biomechanics facility. To prevent recovery, this facility transition was performed hastily, with the time taken between the final stage of the fatigue protocol and the start of motion capture recording to be under ten minutes. At this time, six unanticipated cuts were repeated (three in each direction) to represent mechanics observed in a fatigued state.

Identical procedures were followed on the second and third laboratory visit. The second and third visits were scheduled within a range of 4-10 days after the previous visit.

Outcome Measures

Low-pass fourth-order Butterworth filters were applied to marker coordinate and force plate data at 6 Hz and 16 Hz, respectively. Stance phase was defined when the vertical ground reaction force exceeded 50 N. Standard inverse dynamics and joint kinematics were calculated using Visual3D v5 (C-Motion Inc., Germantown, MD, United States).

Peak knee flexion angle (PKFA), knee flexion at initial contact (KFIC), peak knee valgus angle during initial stance (KVA), peak internal knee extensor moment (KEM), peak knee valgus moment (KVM) and peak anterior tibiofemoral shear force (ASF) were

analyzed to reflect movement patterns indicative of ACL loading. Metric means across cutting trials pre- and post-fatigue were calculated for each subject per footwear condition.

Hip, knee, and ankle sagittal plane joint power and footstrike angle were calculated from initial contact through toe-off. Peak negative hip, knee and ankle joint power were calculated for each trial and averaged across cleat condition and fatigue state. Temporal waveforms of footstrike angle and joint power were calculated for each trial and interpolated to establish participant and condition-specific means.

Statistical Analysis

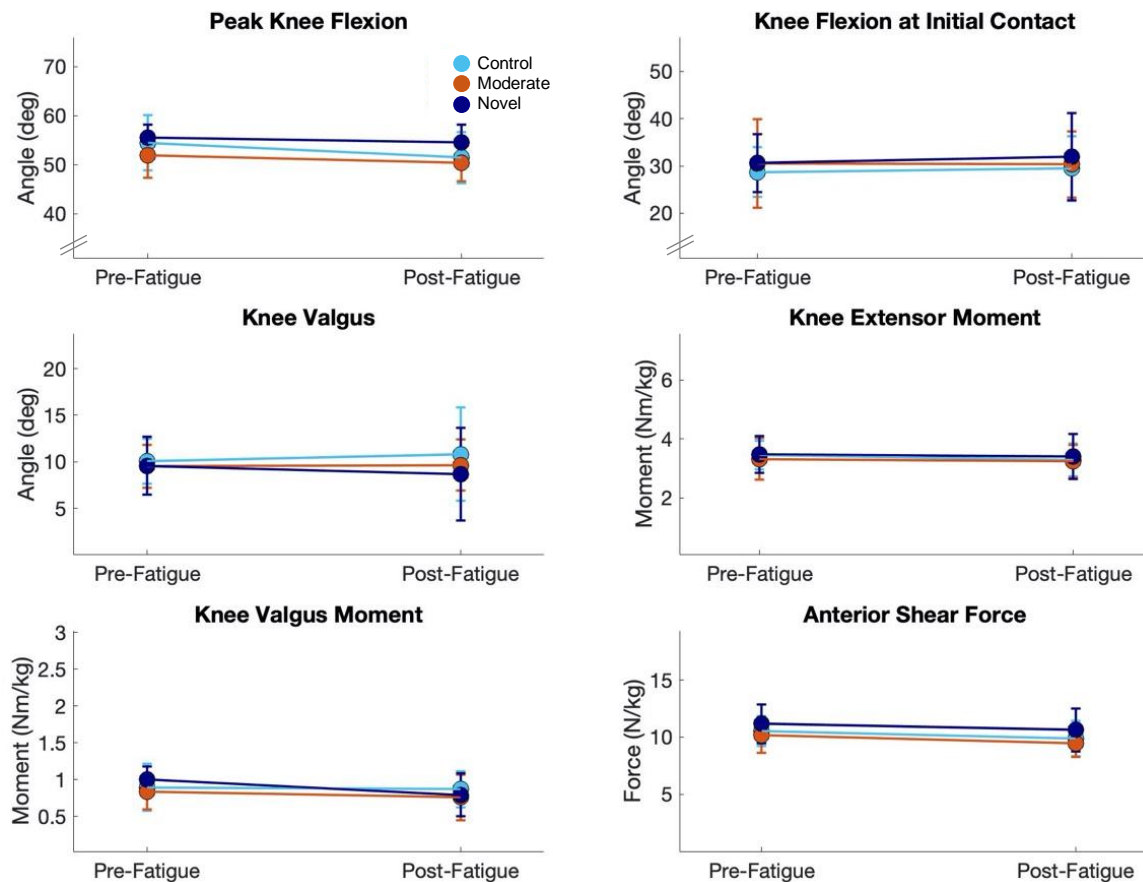
Statistical analyses were performed using R-Studio (RStudio Inc., Boston, MA, United States). Two-way univariate analyses of variance (ANOVA) with repeated measures statistical tests ($\alpha = 0.05$) were conducted to compare the effect of fatigue and cleat on the discrete knee kinetics and kinematics. If statistical significance was found, post-hoc pairwise t-tests were performed with a Bonferroni correction. One dimensional, two-way repeated measures (fatigue state) Statistical Parametric Mapping (SPM) ($\alpha = 0.05$) was used to independently assess differences in the time series waveforms of knee, ankle and hip joint powers and foot strike angle [82,83].

Results

Discrete Kinetics & Kinematics

Multiple two-way ANOVA tests with repeated measures were used to examine the main and interaction effects of cleat condition and fatigue state on cutting mechanics. The mean and standard deviation of peak knee flexion angle, knee flexion angle at initial

contact, knee valgus angle at peak knee flexion, peak knee extensor moment, peak knee valgus moment and peak anterior shear force are summarized by cleat condition in Figure 6.2. A significant main effect of fatigue ($p < 0.05$) was observed on KVM, identifying fatigue to reduce KVM across all cleat conditions. This is a favorable response to fatigue. While not statistically significant, trends across PKFA, KFIC and KVA favor the novel cleat condition both before and after systemic fatigue. Similarly, trends across KEM, KVM and ASF favor the moderate cleat condition both before and after systemic fatigue.



MAIN EFFECT: Fatigue on KVM ($p < 0.05$)

Figure 6.2. Interaction plots of knee mechanical parameters averaged across cleated condition and fatigue state.

Joint Power & Footstrike Angle

Statistical parametric mapping assessed the effect of cleat condition and fatigue on time series ankle, knee, and hip joint power (Figure 6.3), and footstrike angle (Figure 6.4). Footstrike angle can distinguish rearfoot versus forefoot strike patterns based on values below or above zero, respectively. Significant experimental differences between cleat conditions were found on footstrike angle from 11.9-27.6% of cutting stance ($p = 0.01$), observing the control shoe to encourage a more plantarflexed, forefoot contact pattern during this phase of gait.

A cleat-fatigue interaction effect on ankle joint power trends towards significant at 9% of cutting stance. Discrete variables calculated from joint power timeseries data were independently run through two-way repeated measure ANOVA tests. A main effect of fatigue trends towards significance ($p = 0.066$) in peak negative knee power, with trends supporting a decrease in peak negative knee power with systemic fatigue.

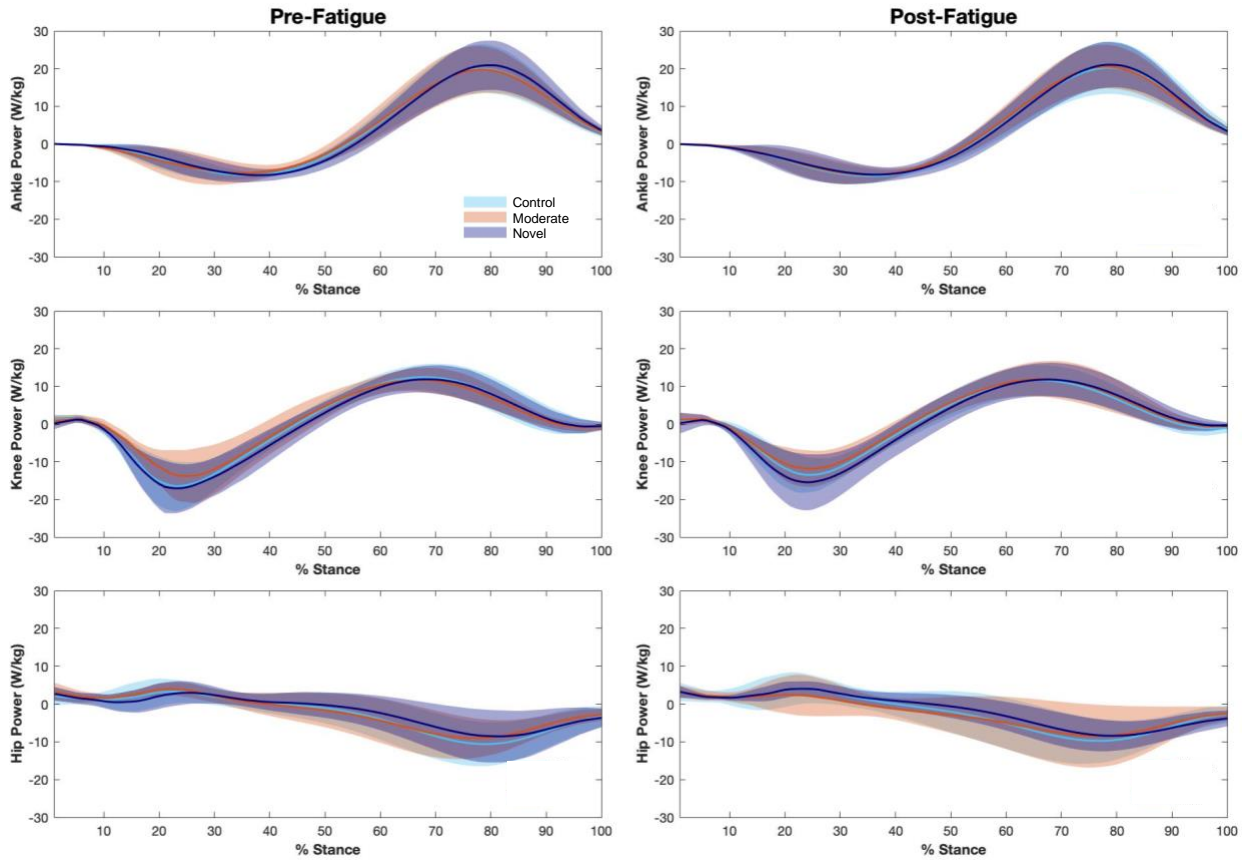
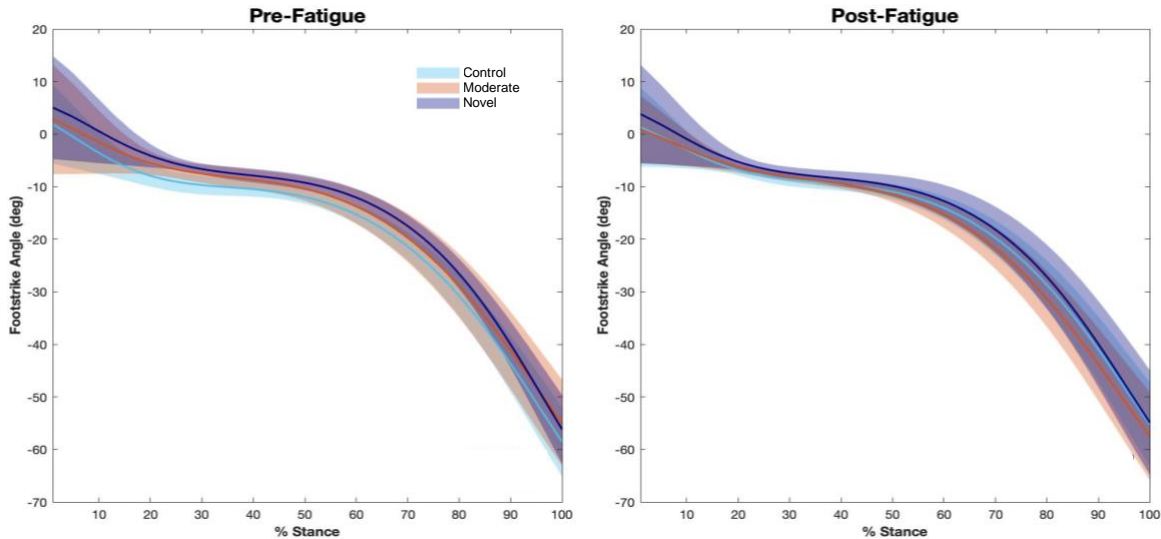


Figure 6.3. Mean (solid line) and standard deviation (shaded area) of ankle, knee and hip joint power between control (blue), moderate (red) and novel (purple) cleat conditions between pre- (left) and post-fatigue states.



MAIN EFFECT: Cleat condition from 11.9-27.6% stance ($p < 0.05$)

Figure 6.4. Mean (solid line) and standard deviation (shaded area) of footstrike angle between control (blue), moderate (red) and novel (purple) cleat conditions between pre- (left) and post-fatigue states. A value above zero on the y-axis indicates a rearfoot (dorsiflexed) strike pattern, a value below zero on the y-axis indicates a forefoot (plantarflexed) strike pattern. Significant cleat effects found from 11.88-27.63% stance.

Discussion

This culminating aim is a mechanical validation of soccer cleat prototypes designed according to female athlete mechanics. Two cleat plate iterations were assessed against a market-available model; the first traction plate prototype characterized by ‘moderate’ changes, and a more boundary-pushing ‘novel’ prototype. This investigation seeks to determine the effect of the proposed traction plate designs on lower extremity energetics, foot strike contact patterns, and knee mechanics during unanticipated cutting tasks before and after fatigue.

A significant effect of fatigue was found on KVM, identifying fatigue to decrease knee valgus moment across all cleat conditions. This fatigue effect is counter to what was initially expected. Previous research saw fatigue progression to negatively alter female landing strategies [20,52,69]. Authors McLean et al. [69] identified fatigue to increase

valgus moment at both initial contact and during peak stance of landing tasks in female athletes. Similarly, authors Collins et al., [20] found fatigue to increase peak valgus moment among female athletes during lateral cutting tasks. This small sample finds joint protective effects with fatigue. Opposing research has found that kinetic and kinematic adaptations to fatigue may encourage a more neutral frontal plane [5]. Fatigue also trended towards significance in peak negative knee power, with fatigue similarly decreasing peak negative knee power across all cleat conditions. Within this limited sample size, fatigue did not appear to amplify female susceptibility to injurious mechanics; comparable mechanics could be observed across the pre- and post-fatigue states. This is different than trends observed among female athletes in Chapter III. Footwear worn by athletes in this aim were developed using female lasts, unlike the footwear worn in previous aims. In part, proper shoe fit could be considered a factor contributing to this observation, though caution is warranted as sample sizes are small.

Time series data identify a significant difference in footstrike angle between cleat conditions from 11.9 to 27.6 percent of cutting stance. Further investigation into this significant difference identifies the control cleat to promote a more plantarflexed, forefoot strike pattern during this weight acceptance phase of cutting stance than either cleat prototypes. The ‘novel’ cleat prototype demonstrates a 5-degree more posterior strike pattern than the control cleat, presenting the opposite of what was intended. A previous study has suggested that shod foot posture is approximately 7 degrees more dorsiflexed in cleated footwear compared to running shoes, both in static posture and during weight acceptance of running [104]. This functional restriction of ankle range of motion has potential repercussions on landing strategies, namely, joint work distribution up the

kinetic chain [7]. To discourage dorsiflexion during initial contact, studs at the heel of both the ‘moderate’ and ‘novel’ prototypes were shortened in length. In this thought process, a shorter heel stud would act similarly to a sprint spike in track and field, implementing a negative heel-toe drop height to naturally encourage a mid-foot to forefoot strike pattern. However, the ‘novel’ prototype functionally achieved the opposite. The ‘moderate’ cleat appears to encourage a similar footstrike pattern to the control cleat, while simultaneously moderating negative knee power most effectively. The subtle variation in heel stud length between ‘moderate’ and ‘novel’ seems to represent a fine line between a lower-risk and higher-risk landing strategy. If athletes are natural rearfoot strikers, the minimal heel-toe drop height in the shortest stud length prototype could encourage an even larger initial dorsiflexion angle.

Across the discrete knee mechanics reported, no statistically significant effects of cleat condition could be reported. However, trends across all knee metrics favored either the ‘moderate’ or ‘novel’ cleat condition. According to PKFA, KFIC and KVA both pre- and post-fatigue, the ‘novel’ cleat condition presented with the lowest risk knee angles. According to KEM, KVM and ASF both pre- and post-fatigue, the ‘moderate’ cleat condition effected the lowest knee forces and moments. The design decision to reduce stud length, most notably at the heel and lateral forefoot, may be at root of the mechanical changes observed with the ‘novel’ prototype. Data also aligns with Chapter IV results, suggesting the less rotationally resistant elliptical stud shape may have reduced KVA and KVM in both ‘novel’ and ‘moderate’ prototypes.

The cleat conditions assessed have a notable limitation worth noting. The ‘novel’ and ‘moderate’ prototypes changed features such as stud length and stud shape- as were

recommended by data collected in Chapters III-V, in addition to changing features about the midfoot shank- which was not directly informed by data collected in this dissertation. This collective decision to alter the position of the midfoot shank was designed to deter any interference at the midfoot in promoting a medial strike pattern. The control cleat has a shank that connects the lateral heel to the medial midfoot, with the intention of promoting a medial strike pattern. However, the stiffness of this shank effectively encourages the opposite. Adding stiff material along the intended rotational plane is likely to increase torsional stiffness, increasing force required to move in the intended direction. It was decided that the shank would also see moderate and novel adjustments to improve this design. This design change may have confounded the results otherwise observed in stud length and stud shape, alone. Further mechanical testing is concurrently being collected by Puma SE to determine torsional stiffness and longitudinal bending stiffness as affected by this design change.

Conclusion

In partnership with PUMA SE, this aim introduced cleat prototypes informed by female athlete data. Data-driven traction patterns were evaluated against the Puma Future Ultimate FG/AG market-available cleat. Female soccer players performed unanticipated lateral cutting tasks before and after a fatigue protocol, assessing differences in knee mechanics, joint power and footstrike angle across cleat conditions and fatigue states. A significant main effect of fatigue was observed on knee valgus moment, and a significant cleat effect was found on footstrike angle from 11.9-27.6% of cutting stance. While not statistically significant, all discrete knee metrics favored either the ‘moderate’ or ‘novel’ cleat condition both before and after fatigue. While cleat prototypes require further

refinement, data suggest that a reduction in stud length and an elliptical stud shape may improve knee mechanics otherwise observed in market-available cleat options.

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CHAPTER VII

CONCLUSION

Summary of Results and Findings

This dissertation sought to determine soccer cleat traction parameters best suited to the mechanics of the female athlete. Utilizing data collected from Chapters III-V, culminating aim VI mechanically evaluated female-specific traction prototypes that were co-designed with and developed in partnership with sportswear brand Puma SE.

Female soccer athletes are affected by ACL injuries at a staggering rate, estimated to have a two to threefold increase in injury incidence compared to male soccer athletes [103]. Female mechanics during unanticipated lateral cutting and deceleration exhibit high-risk landing strategies, featuring patterns of lower knee flexion angles, increased ankle eversion angles, increased knee valgus angles, and greater relative knee extensor muscle activation [21,22,25,38,53,62]. While cleated footwear is advantageous for maneuverability by generating high shear loads at the sport surface, traction in excess has been associated with lower limb torsional strain and injury risk [33]. Unsuitable soccer cleat traction could contribute to elevated female ACL injury incidence. A systematic review covering the mechanical implications of soccer cleat geometries has suggested that female athletes may be more sensitive to traction than male athletes [15]. However, very few studies have attempted to understand the implications of specific traction parameter modifications on female ACL injury etiology. To address these gaps, this dissertation investigated the effect of various modified stud characteristics on female cutting mechanics, with the intent of identifying traction properties that promote ACL-

protective mechanics. An unanticipated cutting protocol was performed to understand the effect of changing stud length and stud shape on knee metrics. Plantar pressure data were supplementally evaluated across stud shape variations, providing complementary analysis of footstrike pattern and plantar pressure loading behaviors during a fatiguing running and cutting protocol. In culmination, preferred traction properties were combined in cleat prototypes manufactured by Puma SE, and cutting mechanics were mechanically evaluated against a market available model.

Chapter III revealed that a reduction in stud length is associated with trends in improved female knee mechanics in both sprint stop and cutting tasks, confirming our hypothesis. While no statistically significant results were conclusively identified, trends in peak knee flexion angle, peak internal knee extensor moment, peak external knee abduction moment, peak anterior tibiofemoral shear force, and normalized ratios of vastus lateralis to biceps femoris muscle activity all demonstrated favorable outcomes in the 50% and 75% stud length conditions. The results from this study are novel, as no previous works have evaluated the effect of varying stud lengths on male nor female knee mechanics. These findings support the notion that market-available soccer cleats may have unsuitable stud properties for the mechanics of the female athlete. A shorter stud length is likely advised for the female athlete.

Chapter IV investigated the effect of soccer cleat stud shape, on both knee mechanics and traction utilization in male and female athletes before and after systemic fatigue progression. Given the conflicting viewpoints in previous research regarding the effect of stud shape on torsional injury patterns [15,31,39,67], this study included both male and female athletes to assess potential sex differences that could challenge

conclusions drawn solely from male data. While no interaction effects were noted to be statistically significant on knee mechanics, main effects of sex and fatigue were observed on knee valgus angle and knee flexion angle, respectively. Increased frontal plane knee motion in female participants is well-established in literature [62,95]. Additionally, elliptical cleats appeared to moderate the fatigue-induced knee valgus observed with bladed cleats. A significant three-way interaction on the rate of utilized traction at initial contact suggested fatigue and cleat condition to uniquely moderate the male and female landing response. This aligns with previous findings suggesting female athletes to have a unique mechanical response to increasing traction [13,86]. While initial predictions thought bladed cleats would induce highest knee loading among the fatigued female participants, data did not fully support this hypothesis. However, results do suggest that reducing traction with an elliptical style stud may be advantageous for the frontal plane mechanics of the fatigued female athlete.

Utilizing data collected from the same broader stud shape study, Chapter V looked to determine the effect of this traction modification on the plantar loading response of male and female athletes, before and after systemic fatigue. The results from this study identify significant main and interaction effects in peak pressure across the anterior heel, medial forefoot, and lateral toes. Trends across center of pressure find increased posterolateral pressure and mediolateral excursion with systemic fatigue progression, particularly among female participants in the bladed condition. This aligns with previous research, which has identified male athletes to land more medially than female athletes during lateral cutting [87,93]. Results suggest improving both the lateral

and posterior arrangement of studs on a female-informed cleat design to encourage a more anteromedial strike pattern.

Together with PUMA SE (Herzogenaurach, Germany), data-driven female soccer cleats were designed and developed into manufactured prototypes. Results from Chapters III-V indicated that traction patterns for female athletes should feature studs that are shorter in length, with lower rotational traction, and particular emphasis on reduced available traction at the heel and lateral forefoot. Female knee mechanics during lateral cutting demonstrated favorable trends with the cleat prototypes. However, footstrike pattern and negative knee joint power appeared to be negatively affected by the ‘novel’ prototype featuring more severe traction adjustments. Results suggest that moderate adaptations to female soccer cleat traction may reduce the high-risk knee mechanics otherwise observed in market-available unisex cleat options.

Taken together, the results of this dissertation reveal that traction properties have important implications on the risk of female athlete torsional injury mechanisms. With biological susceptibility to higher risk landing mechanics, cleated footwear for the female athlete should be appropriately moderated to prevent supplemental ACL loading. While results from Chapter III do not find statistically significant differences between stud lengths, trends across all assessed metrics favor a reduction in stud length to 50-75% of original stud length. Results from Chapter IV-V identify fatigue to be a critical consideration in the ACL injury risk assessment of female athletes, particularly. Higher translational and rotational resistance offered by bladed studs’ reveal adverse trends in mechanical implications for females, encouraging greater valgus angles, and higher posterolateral center of pressure deviations. Proposed traction designs in Chapter VI

incorporated shorter, rounder studs, featuring a prominent reduction in stud length at the heel. Data suggest that the proposed prototype designs trend favorably, presenting with greater knee flexion angles, less knee valgus, and a reduction in forces and moments at the knee. However, the more significant adjustments to traction on the 'novel' prototype design resulted in increased negative knee power, likely due to encouraging a rearfoot strike pattern. Further development on the threshold of adjustments needed to optimize traction for the female athlete is warranted. The results of this dissertation illustrate how relatively minor modifications to traction parameters can encourage lower risk cutting strategies in female soccer athletes.

Limitations

There are limitations in this dissertation that may have affected the reported outcomes. Spanning laboratory constraints, to participant recruitment, to cleat condition comparisons, there are several factors that must be recognized when reporting the results of this body of work.

Across Chapters III, IV and VI, kinetic and kinematic data were collected in a turf biomechanics facility. This surface is an artificial turf without infill, considered less effective at absorbing impact than artificial grass with infill or a natural grass. The turf utilized for biomechanical analysis in the lab is better suited to a turf shoe than the firm ground cleats selected for testing. However, it was critical to evaluate these firm ground cleats in a complete laboratory environment, with the capacity to track three-dimensional movement mechanics and estimate tri-axial force generation during dynamic activity. As it was unrealistic to install an alternative turf with infill in this laboratory, and

out-of-laboratory tools are unable to collect the comprehensive data required for this project, the research team decided to move forward with firm ground cleats on artificial turf. While not optimal, the data collected still captures distinguishable effects of outsole modifications. The common practice of high-level female soccer players reverting to firm ground cleats in turf stadiums reduces the impact of this limitation. However, differences in kinetics and kinematics are possible with changes in surface.

To establish a basis of how traction parameter adaptations may influence ACL loading, Chapters III-V utilized market-available product to draw generalizable conclusions about the effect of stud length and shape on female athlete mechanics. In Chapter III, studs were manually trimmed using a caliper and Dremel hand tool. Stud lengths were individually measured to not only achieve the target length, but also tapered to maintain stud cross-sectional area. However, as this was performed with a hand tool, the accuracy is not fully reliable. Without having the ability to manufacture customized cleats, this was the most viable alternative at a stud length intervention. There is a possibility that the stud surface area is not perfectly maintained across conditions. Cumulative stud surface area is reported to directly affect plantar pressure [86]. In chapter IV and V, adidas off-the-shelf cleats were acquired to assess differences in utilized traction, knee mechanics and plantar pressure across stud shapes. Chosen cleats were two unique models, the adidas Predator .2 and the adidas Copa Sense .3 (adidas, Herzogenaurach, Germany). There are numerous differences between these cleat models aside from stud geometry. Most notably the cleat pairs differ in upper materiality, a synthetic knit versus a synthetic leather. This is not uncommon across bladed and elliptical models; outsoles with elliptical style studs are often paired with traditional

leather uppers. To account for the changes in material thickness, the Copa last is slightly narrower in the toe box (adidas, Herzogenaurach, Germany). This change in fit may have offered increased proprioceptive feedback within the cleat, or in contrast, may have decreased mediolateral stability due to the smaller contact area. Ideally, these would be identical cleats aside from stud geometry. However, this was not feasible, as customizable product was not an available option at this point in the project.

In Chapter V, plantar pressure data was compared between cleat conditions across two distinct fatigue states: before and after systemic fatigue progression. As plantar loading relevant to ACL injury risk is most relevant during lateral cutting, analyzed cutting steps were chosen at the beginning of the 1600-meter phase and at the end of the 400-meter phase. This aligns with the first and third legs of the five-phase protocol. As there were no cuts included in the 100-meter phase, no steps in this phase could represent the post-fatigue state. The 200-meter phase did not follow the same running and cutting route as the 1600-meter phase, rendering it unsuitable for comparison with the cutting steps taken during the 1600-meter phase. Therefore, the cutting steps chosen to represent the systematically fatigued state are two phases earlier than the complete protocol. While it is reasonable to assume that the athletes are systemically fatigued by the end of the 400-meter phase as proven by their heart rate, this stage in the protocol cannot be validated against a maximum cardiorespiratory effort.

Lastly, across all Chapters, athlete inclusion was restricted by shoe size. It would have been ideal to examine the relationship of traction across a range of athlete shapes and sizes. Particularly in the context of stud length, where the length of studs is rarely

scaled to shoe size in market-available product. Larger sample sizes would also likely develop trends into statistically significant differences across cleat conditions.

Recommendations for Future Work

This dissertation sets an important stage for the necessity of designing and developing data-driven female footwear. Historically, research on female athletes has been significantly underrepresented. As a result, research on sports product has been heavily biased towards male athlete data. This dissertation presents a foundation of female soccer athlete research that has direct application to cleated footwear design. Future research in this project space should look to the effect of stud number and stud positioning on female athlete landing and cutting mechanics. Both stud number and positioning have critical implications for plantar pressure distribution, and by association then loading patterns. Material property is also a point of interest for this work. Outsole rigidity may require adjusting to optimize torsional bending stiffness to the mass of the female athlete.

Inclusion criteria for this research excluded athletes with a history of ACL injury, whether that be a minor strain to a complete tear. This was, in part, out of safety for the athlete, but also as a controlling factor for cleat interaction effects. In the case that athletes return to play, which is often, they will still require cleated footwear. It is arguably more imperative to have appropriate traction for the ACL-recovered athlete than the non-injured athlete to prevent catastrophic re-injury. An extension of this project should include athletes fully recovered from ACL-reconstruction, who remain involved in high-level league play. It may be the case that the moderated traction on the existing

female cleat is suitable, but it may also be the case that further traction modifications could better protect the compromised limb.

In conversation with Puma SE, future iterations will be developed based on the results of the first prototype validation. An important consideration for industry innovation teams is the marketability of a product. As it stands, the length and circumference of the studs are quite small. This may not appeal to high level soccer players, if they fear this reduction in traction may compromise performance. However, this may appeal to the parents of young female soccer athletes, looking to lower traction alternatives capable of encouraging proper mechanics. This introduces the notion that soccer cleats could be designed for different age and development levels. At a young age, cutting and running mechanics should not rely on available traction at the cleat bed. A lower traction model with tapered stud lengths at the heel could encourage young developing players to land in a lower-risk forefoot strike pattern. Future work into the developing young player could be an important intervention point in preventing future ACL injuries.

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