5-1-2020

Impact of shoe design on basketball performance and the application of soft sensors to improve dynamic fit.

Anthony Lee Luczak

Recommended Citation

Luczak, Anthony Lee, "Impact of shoe design on basketball performance and the application of soft sensors to improve dynamic fit." (2020). *Theses and Dissertations*. 2605.
https://scholarsjunction.msstate.edu/td/2605

Impact of shoe design on basketball performance and the application of soft sensors to improve dynamic fit.

By

Anthony Lee Luczak

A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Human Factors Engineering
in the Department of Industrial and Systems Engineering

Mississippi State, Mississippi

May 2020

Impact of shoe design on basketball performance and the application of soft sensors to improve dynamic fit.

By

Anthony Lee Luczak

Approved:

Reuben F. Burch, V
(Major Professor)

John Lamberth
(Committee Member)

Daniel W. Carruth
(Committee Member)

Brian Smith
(Committee Member)

Linkan Bian
(Graduate Coordinator)

Jason M. Keith
Dean
Bagley College of Engineering

Name: Anthony Lee Luczak

Date of Degree: May 1, 2020

Institution: Mississippi State University

Major Field: Human Factors Engineering

Major Professor: Reuben F. Burch, V

Title of Study: Impact of shoe design on basketball performance and the application of soft sensors to improve dynamic fit.

Pages in Study: 104

Candidate for Degree of Doctor of Philosophy

This dissertation is composed of four different studies focused on using Human Factors Engineering (HFE) assessment tools traditionally used in industrial settings to evaluate personal protective equipment (PPE) footwear of basketball athletes and assessment of compressible soft robotic sensors to evaluate pressures.

The first study developed a Basketball Shoe Taxonomy (BST) designed to categorize shoes using a combination of design factors and effects on performance. The second study investigated the influence of basketball shoe design on jumping performance. Using four jumping patterns, six male and ten female basketball National Collegiate Athletic Association (NCAA) Division I student-athletes completed 16 trials wearing two different Adidas basketball shoe designs. There was no significant difference in effect of shoe type on jumping performance ($p > 0.05$). The third study examined each athlete's perception of comfort and quality of fit of the shoes used in the second study using a visual analog scale (VAS) and Likert scale survey. One student-athlete out of 16 reported that one of the shoes tested was their favorite and the most comfortable basketball shoe they had ever worn. Results indicated an average overall comfort

rating below 60% for both shoes and there was not a significant difference in perception of comfort or quality of fit between the shoes ($p > 0.05$).

The final study was designed to validate the use of compressible Stretchsense™ sensors (CSSs) to ground reaction pressures. Participants performed three repetitions of squatting, shifting center of pressure between the right foot and left foot, and shifting center of pressure forward and back between the toes and heels. Performance was evaluated using CSSs, BodiTrak Vector Plater™ (BVP), and Kistler Force Plates™ (KFPs). The results indicate that CSSs are an acceptable replacement to ground reaction pressure mats. In addition, the use of an Autoregressive Integrated Moving Average (ARIMA) model resulted in average R^2 values greater than 90%. High R^2 values in the ARIMA modeling indicates that the software accurately models the human 3D foot-shoe interaction pressures used in the development of the ground reaction pressure socks (GRPS) for sport applications and for fall detection in elderly and balance impaired individuals.

DEDICATION

This work is dedication to my family, Nicki Luczak, Taylor, Drew, and Jack, my mother Betty Lou Luczak, in memory of my father Daniel M. Luczak, my father in-law, Lou Fratesi, and in memory of my mother in-law, Brenda Fratesi for their love and support.

ACKNOWLEDGEMENTS

The writing of this dissertation would not have possible except for the relentless support, rewriting, and understanding my stream of consciousness, thank you Nicki, I love you! To Dr. John Lamberth who started and supported my initial efforts in going back to school and opening the door to educational enlightenment, thank you. To Dr. Ed Lewis who suggested I pursue my Ph.D. instead of chasing professional golf, thank you. Special thanks to Dr. Teena Garrison who introduced me to a world that I always wanted to be in and to Dr. JohnEric Smith who made the connection to Industrial and Systems Engineering Professor Dr. Burch.

Special thanks to the members of my committee – Drs. Daniel Carruth, Brian Smith, John Lamberth – and major professor Dr. Reuben Burch, for your support, guidance, and the opportunity to pursue the ideas and research involved in athlete engineering.

A special thanks to the Department of Kinesiology faculty and for your support in allowing me to build out the Cognitive and Motor Control Lab and your continued collaboration. Special thanks to the faculty and staff of the Industrial and Systems Engineering Department, who made my transition to Engineering seamless, especially Alisha Bennett and Tammy Carroll, who had to manage all the paperwork of my travels and research, thank you.

Thanks to the Men's and Women's MSU Basketball student-athletes for volunteering in the study. A special thanks to Coach Collin Crane and Coach Ben Howland, and Coach Marci Hoppa and Coach Vic Shaefer for your continued collaboration with Athlete Engineering working group and making my dissertation possible.

TABLE OF CONTENTS

CHAPTER

III. EFFECT OF SHOE DESIGN ON JUMPING PERFORMANCE 20

IV. PERCEPTION OF COMFORT RELATED TO JUMPING PERFORMANCE 44

APPENDIX

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

DISSERTATION OVERVIEW

1.1 Introduction

Elements of industrial ergonomics, or human factors engineering (HFE), can be universally applied to any system from three basic goals of HFE; to enhance performance, increase safety, and increase user satisfaction [1]. The HFE discipline brings together a holistic perspective from science, technology, design, biomechanics, cognition, and engineering to develop methods and systems to support and enhance human capabilities. One HFE domain has been in the development of personal protective equipment (PPE). The purpose of PPE is to protect the worker from the hazards that occur in the workplace [2]. PPE is specially made clothing, materials, garments, and tools which prevent harm to the worker in hazardous environments [3]. The focus on footwear PPE is of high importance due to constant foot to ground interactions. However, PPE is often uncomfortable leading to poor compliance and work-related injuries due to repetitive altered biomechanics [4]. Specific shoe design features should be based on the work environment. An example of altered biomechanical output has been studied in determining the effect of footwear PPE on firefighter's movement patterns. Wearing appropriate footwear PPE is necessary to protect firefighters from the dangers from the environment. However, due to the size and weight of PPE, additional strain is placed upon the firefighter's body which may negatively impact performance. Footwear PPE can reduce ankle range of motion resulting in impaired force dissipation and altered lower body kinematics [2].

Additional work-related injuries have been linked to altered movement patterns because shoe PPE increases the physical load placed on the body [5]. To improve worker compliance with PPE, HFE assessments of footwear include: safety, traction, comfort, biomechanical performance, microclimate management, and fit [6-10]. As HFE researchers have examined which PPE parameters have the greatest influence on performance, consideration of applying HFE assessments in sports equipment design should be explored.

The parallel relationships between the industrial worker (industrial athlete) and the sport athlete provide support for applying HFE principles in both settings [11]. For example, Sevier et al. reported that a sports medicine model for rehab has shown greater improvements in employee return to work compared to traditional industrial treatment of musculoskeletal injuries [11]. Prevention, providing PPE to industrial athletes, is the least expensive of [11]'s four key elements in the sports medicine model: (1) prevention; (2) conditioning; (3) early intervention or identification and (4) progressive treatment for the industrial athlete[11]. As footwear PPE is found, both in the workplace and in the sports arena, this dissertation will focus on using HFE and PPE principals and sensor technology to establish a basketball shoe dynamic fitting protocol.

1.2 Dissertation research aims

The goal of this dissertation is to use HFE assessment tools traditionally used in industrial settings to evaluate athlete's PPE basketball shoes. By quantifying the impact of shoe design on kinetic output, comfort and fit, and assessing in-shoe pressure sensor solutions, this study will help to develop a performance basketball shoe cause-and-effect chain which can be used to understand causal stressors that stem from ground up.

1.2.1.1 Study 1: Establishment of a Basketball Shoe Taxonomy

The purpose of this chapter is to establish a user-based Basketball Shoe Taxonomy (BST, Figure 1.1) to inform practitioners, coaches, and athletes about the contextual understanding of basketball shoe features. Generally, the decision to wear a specific branded model basketball shoe may be linked to brand loyalty, corporate contracts, or personal style. Defining what type of shoe is best for an individual can be based on a combination of subjective and objective factors. This section applies human factors engineering (HFE) principles based on Garvin's 'product quality' [12] to basketball shoe aspects with the goal to improve performance and mitigate non-contact foot-ankle injury. Actual shoe design recommendations are beyond the scope of this paper.

1.2.1.2 Study 2: Effect of Shoe Design on Jumping Performance

Emphasized in the first study, the decision to wear a specific basketball shoe is often based on an athletes' personal preference, corporate contracts, or suggestive marketing hype from the shoe manufacturer. Basketball shoes are built within three broad categories: low-cut, mid-cut, and high-cut, depending on how much of the malleolus can be seen [13]. Conventional rationale for which type of shoe to wear has post positional athletes, centers and forwards, and those with recurring ankle injuries opting to wear high-cut shoes for protection while guards have opted to wear low-cut shoes for quickness [14]. However, lateral ankle sprains are still a common injury for athletes and the effectiveness of high-cut shoes to prevent lateral ankle sprains has been brought into question [15]. Previous studies examining high-cut shoe design have revealed a negative effect on biomechanical compensations due to restrictions in foot-ankle range of motion resulting in altered kinematics in the lower limbs, pelvis, and torso [14, 16, 17]. Another example of the negative impact from shoe design was seen in a study of a National

Basketball Association (NBA) player which reported a higher jump height while barefoot over eight different styles of basketball shoes [17]. For the athlete determining the proper type of basketball shoe to enhance performance and mitigate injuries isn't clear and should be evaluated. The purpose of this study is to compare the effect of two different styles of basketball shoes on basketball specific jumping performance.

1.2.1.3 Study 3: Perception of Comfort Related to Jumping Performance

There are many shoe characteristics defined by basketball shoe design, but broadly, a shoe can be broken down into four main components, the upper, insole, midsole, and outsole. Configuration of the four components create specific shoe styles and characteristics. Conventional evaluation of proper shoe fit is based on both the perceived level of comfort and the static two-dimensional foot length and width measurements which are matched to a manufacturers shoe specifications [18]. Determination of whether a shoe fits is based on the athlete's comfort expectations compared to past experiences [9, 19-21]. Comfort and fit factors include shock attenuation, the amount of shock a player feels is increased with the stiffer heel confinements [14], fit, the size and geometry of the foot into the shoe [22], plantar pressure distribution onto foot and insole [23], foot sensitivity [24], fatigue, and performance [25, 26].

Given that shoe comfort and fit has multidimensional characteristics, assessing fit based on a static state, length and width, leaves gaps in effectively determining proper fit [18]. Dynamic movements occurring in a basketball game create high vertical and shear GRFs placing severe foot-ground interaction stressors on the athlete that are sometimes powerful enough to cause injuries [27]. Based on the need to determine comfort and fit from a dynamic perspective, the purpose of the second study is to use a basketball specific course survey to gain insight on what determines a comfortable fit for basketball shoes for NCAA Div. I basketball student-athletes after performing eight basketball specific jumps.

1.2.1.4 Study 4: Development of Pressure Sensitive Sock Utilizing Soft Sensors

Discussed in study three, dynamic assessment of basketball shoe comfort and fit is left to the individual athlete. Presented in study one, the development of a BST to improve the decision making process of shoe selection by focusing on the characteristics of the game, player movement patterns, shoe design, kinematics, kinetics, and psychophysical factors may improve a team's and player's decision in selecting a type of basketball shoe to wear. A challenge arises when basketball shoe testing is moved from a lab setting to game-like scenarios to assess GRFs. Presented in studies two and three, the use of force plates and surveys in a lab setting provide insights into acute measurement of jump kinetics and foot-shoe interactions. However, the game of basketball involves competition, adrenaline, and a multitude of foot-ground interactions. To improve the capture of functional data on the court, collecting data using embedded sensors in a ground reaction pressure sock (GRPS) could infer accelerations and forces to determine dynamic shoe fit and be used to mitigate injuries and improve performance. Study four will investigate the use of compressible soft sensors by validating changes in pressure and force to changes in capacitance during three closed kinetic chain dynamic movements of squats, shifting center of mass right to left, and toes to heels.

CHAPTER II

ESTABLISHMENT OF A BASKETBALL SHOE TAXONOMY

2.1 Introduction

Applying human factors engineering (HFE) principles to develop a Basketball Shoe Taxonomy (BST) is derived from a user-based approach originating out of Garvin's seminal work "What Does 'Product Quality' Really Mean?" Garvin defined five approaches that define product quality; (a) the transcendent approach of philosophy; (b) the product-based approach of economics; (c) the user-based approach of economics, marketing, and operations management; (d) the manufacturing-based and (e) the value-based approaches of operations management [12]. Of the five approaches, the focus to develop product quality from a user-based approach is a multicultural and multidimensional approach as compared to focusing on manufacturing quality products from a statistical process control perspective [28]. A user-based approach better identifies the individual consumer's wants and needs for specific products; the consumer determines what is quality [12, 29].

Garvin discussed in his user-based approach that individuals consider "goods that best satisfy their preferences are those that they regard as having the highest quality" [12, 29, 30]. Challenges exist in a user-based approach due to the multitude of individual preferences and concerns as to whether a product is optimal for the intended use even though it may be identified by the user as the preferred option.

From a user-based approach on product quality, Garvin recommended characteristics of quality need to be identified through customer segment research [12]. Once the consumer has expressed their wants, manufacturing can develop product features that match the need of the consumer. This perspective is in harmony with Juran's operational management concept of "fitness for use" [31] which shifts the design process to incorporate new technology, consider past experiences, optimize functional specifications, engage the customer, and understand their requirements [32]. The involvement of customers in the product development cycle has provided positive outcomes in "the quality of the product, the financial success of new products, the quality of the new product development process, and the inexpensiveness of new product ownership" [33]. Developing business customer relationships is a critical component to building constructs of trust, commitment, and satisfaction [33-35]. For example, companies working with professional athletes in defining shoe design is common is one way these components with customers in this market is developed. However, while the intentions are good, working with professional athletes does not translate well at the lower levels of the sport. Personally designed shoes for the thousands of collegiate and high school athletes, to whom the majority of lower limb injuries occur, is extremely uncommon [36].

Expanding the concept of a Garvin's user-based approach should include accounting for these collegiate and high school athletes' user experiences, compiling data of thousands of injuries, and their interactions with the product and company [37]. One instance regarding the need to apply a comprehensive user-based approach to basketball shoes stems from one of the most public displays of product failure involving an athlete. During the highly anticipated Duke – North Carolina NCAA basketball game, Feb. 20, 2019, millions watched as one of Zion Williamsons' shoes "blew out" during an attempt to stop during a quick lateral move. When

Zion Williamson planted his foot, it broke through the side of the shoe, resulting in the star player being injured. The fallout of the defective shoe resulted in a financial loss of over $1 billion dollars in Nike's stock value the following day [38]. As Nike began its investigation into the incident, the question of whether Zion Williamson was wearing the proper shoes was brought into question. Due to the status of Zion Williamson's #1 National Basketball Association (NBA) draft position, Nike re-engineered a different brand name shoe, Kyrie Irving 4, with new reinforced features designed for Zion Williamson's style of play [39]. This type of personalization of shoe design and fit is extremely rare below the professional level.

Additional evidence regarding the impact of shoe quality being a concerning issue in sports was confirmed during our series of interviews with strength & conditioning coaches (S&CCs) and athletic trainers (ATs) as part of the National Science Foundation (NSF) I-Corps Program [40]. Concerns about the negative biomechanical impact of shoes have been regularly raised from S&CCs and ATs. Due to the number of non-contact foot and ankle injuries, these professionals have postulated that one contributing factor is shoe design [41]. These concerns create challenges for manufacturers to design basketball shoes to satisfy the numerous subjective parameters which not only include shoe size but the athlete's positional playing requirement, forefoot and heel fit, protection, and comfort.

To help manufacturers overcome the challenge of subjectivity and develop product quality, Garvin provided a framework of eight dimensions of product quality: (a) Performance; (b) Features; (c) Reliability; (d) Conformance; (e) Durability; (f) Serviceability; (g) Aesthetics, and (h) Perceived Quality [12]. The use of the eight-dimensional framework integrated into the specific requirements of the athlete and playing the game of basketball serves as the foundation of the Basketball Shoe Taxonomy which can provide insight for manufacturers, S&CCs, and ATs for designing and selecting the optimum shoes to be worn for the athlete.

2.2 Basketball Shoe Taxonomy

The goal of the BST (Figure 2.1) is to facilitate the approach in designing and selecting a basketball shoe based on integrated multidimensional parameters. The BST is comprised of four categorical strategies that describe the overall contextual interactions between shoe features and their influences on the athlete. These segmentations include: (a) brand and model, (b) dynamic categorization, (c) biomechanical impact, and (d) dimensions of quality. Specific situational influences include defining type of play, shoe design, injury mitigation, performance, and features. Within each situationally defined segment, the interplay between the eight dimensions of quality are applied to the manufacturers shoe design characteristics. This allows the wearer to fully understand the situational effectiveness of a specific basketball shoe based on quantitative and qualitative assessments. The BST is designed as an assessment tool to provide coaches and athletes a system to improve decision-making in footwear choices which may mitigate injuries and optimize performance.

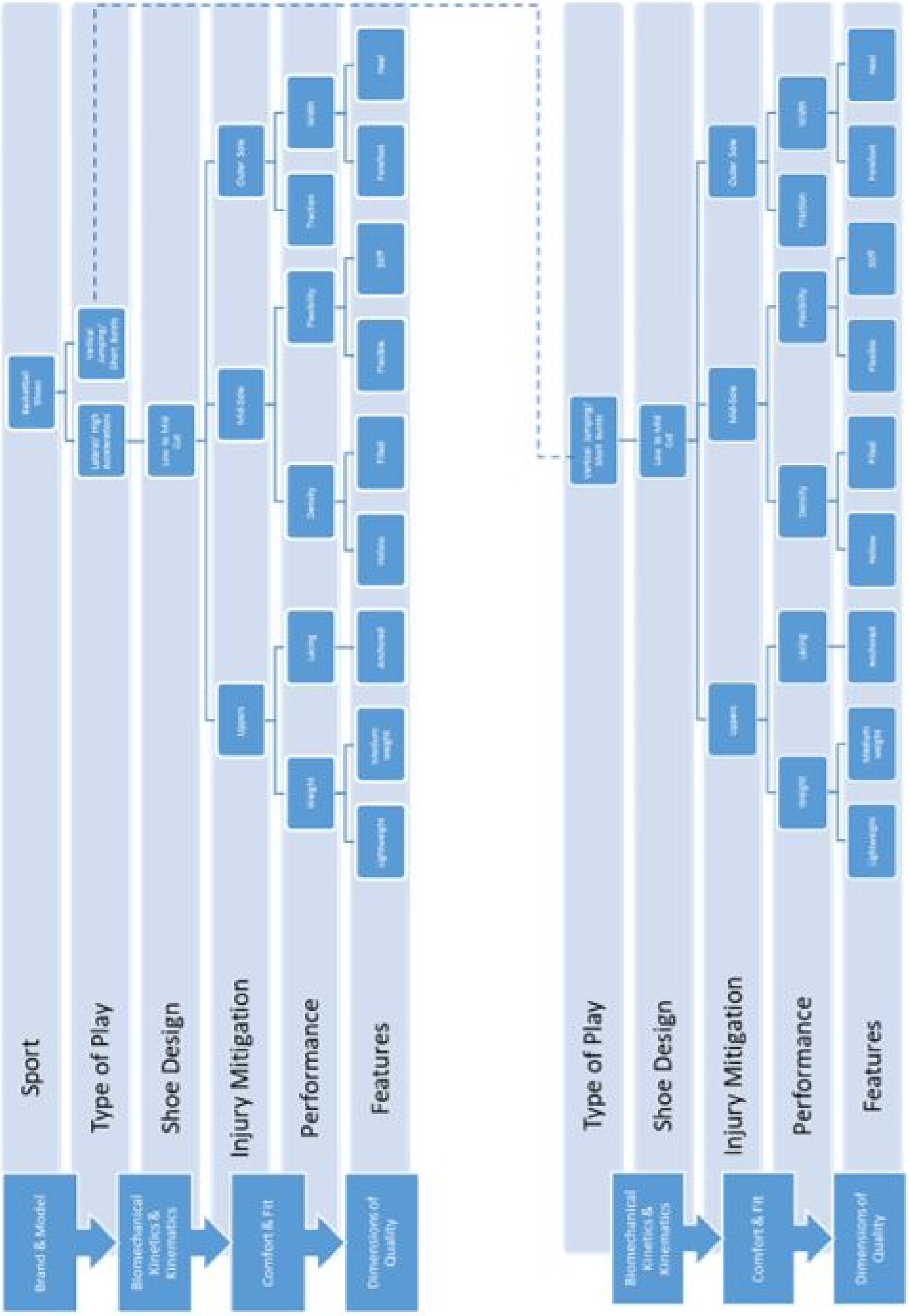


Figure 2.1 Basketball Shoe Taxonomy Hierarchical Tree.

2.2.2 Brand and Model

2.2.2.1 Basketball Shoes

Many of the basketball shoes sold today are branded models derived from an elite player's designs under contract with the manufacturer. For example, Nike created the Nike Air Jordan brand designed for basketball great Michael Jordan [42].

Nike is the current leader in the athletic shoe industry and is prominently seen on each uniform of NBA players [43]. Top competitors to Nike include Adidas, Under Armour, ANTA, and new comers to basketball specific shoes like Puma and New Balance [44]

2.2.3 Dynamic Categorization

2.2.3.1 Type of Play

Positional requirements on the court have traditionally been labeled as guards, forwards, and centers, with centers playing closer to the basket and guards further away. However, the game is changing and positional identifications do not represent the type of play each athlete is performing [13]. Taller, center-like players such as NBA player Kevin Durant (205.74cm) are now handling the ball like guards which changes his lateral acceleration and the demand of his shoes. Based on the athlete's mass and acceleration rates, defining an athlete's force production may offer an improved application to establish type of play profiles and shoe selection [45]. An example of this can be seen in comparing two different athletes that have the same quickness (acceleration) but differ in weight by 30 lbs. This creates different ground reaction forces (GRFs) with the same movement pattern given that force equals mass times acceleration (F=M x A) [46].

2.2.3.2 Shoe Design

Basketball shoe construction is comprised of an upper, insole board, midsole, and outsole built around a last which is a three dimensional model of a foot [47]. The fit of a shoe is determined by toe box height, instep height, heel width, ball width, ball to heel width ratio, and overall length [47]. The upper is comprised of the various materials and panels that cover the toes, mid-foot and heel regions. The insole board lays over the midsole to protect this part of the foot and provides attachment points for the upper in the cement lasting process. The midsole can be designed to reduce the negative shock effects of GRFs during movement, while the outsole is designed for traction and stability. Components of the basketball shoe are assembled together in the lasting process using various methods of cement, slip, and Strobel lasting [47]. Proprietary designs and materials are then engineered to achieve specific performance characteristics.

2.2.4 Biomechanical Impact

2.2.4.1 Injury Mitigation

The goal of a basketball shoe should be to mitigate injuries and improve performance. Shoes have been engineered to reduce lateral ankle sprains, anterior cruciate ligament (ACL) injuries [48], hamstring injuries [49], and over-use injuries [22] representing the more common non-contact athletic injuries experienced in basketball. Due to the demands of basketball, knee and ankle injuries are the most common [50]. These injury types cause shoe designers to focus on protecting the athlete by providing a multidirectional stable base and cushion to support movements with high GRFs [51-53]. Research has reported peak shear GRFs to exceed 1.5 times body weight during forward and sideways cutting movements [50]. In lateral ankle sprains, excessive supination of the foot places high strain upon the anterior-talofibular ligament resulting in injury [54]. ACL injuries have been identified by conditions when the internal tibial torque is paired with increases in knee adduction and coupled with rotation [55]. The balance to maximize safety and optimize performance determines what type of shoe an athlete will want to wear [52].

Preference for specific basketball shoe design is personal; however, guards and forwards have trended toward low to mid cut shoes, while centers have preferred high-cut shoes [13]. This is in part to the belief that the higher cut shoe provides greater ankle support, reducing the chance of lateral ankle sprain. Basketball athletes who have previously suffered lateral ankle sprains or play in congested areas of the court, have opted for the higher cut shoes. Lafortune's assessment of lateral stabilization between two basketball shoes, one with special support/stability features and one without, resulted in significant differences in heel control index, pressure, and lateral support with the support/stability feature shoe [51]. However, Brizuela et al. has questioned the effectiveness of a high-cut shoe to reduce the chance of injury and in fact, their research has indicated that high-cut shoes may increase the amount of lateral inversion due to heel cup stiffness [41]. This is in-line with Lafortune who reported "a smaller lateral displacement of the heel counter indicated better performance" [51]. As further research is needed to define optimal shoe design, Lake has recommend that biomechanical assessments of the athlete during game like scenarios and mechanical testing be evaluated to optimize basketball shoe design [52].

GRF intensity during running and jumping has been reported to reach "2 to 10 times body weight in less than 35ms" [50, 52, 56]. Mitigating the repetition and volume of shock to the lower limbs have been a goal in shoe design to improve comfort. Two areas of shoe design to reduce shock onto the lower limbs are found in the outsole and midsole materials and design [52]. Assessments of materials and designs have been evaluated on force platforms; however due to the lack of sensitivity of the force platforms, specific shoe cushioning properties between shoes have been difficult to obtain [52]. This could be in part to the biomechanical adjustments made by the participants responding to differences between shoe designs [51] and sole hardness [57]. As high GRFs occur during the landing phase of running and jumping, understanding landing mechanics from the athlete and interaction on the athlete's biomechanics from the shoe will be required to properly address the effect of shock on the athlete's lower limbs.

2.2.4.2 Performance

As previously discussed, the influence of shoe design to protect an athlete may have an inverse response to performance. Restrictions in the foot-ankle complex may reduce the chance of excessive strain; however, reduction of joint range of motion has shown to negatively affect vertical jumping height and influence a players performance [16, 17]. This was seen when a NBA player created maximum jump height while barefoot compared to eight different pairs of basketball shoes [17]. The foot-ankle joint complex allows the foot to move through a wide range of motions (ROMs) which include: inversion, eversion, dorsiflexion, plantarflexion, pronation, and supination [54]. In addition, torsion within the foot is described as the movement of the forefoot against the calcaneus [53, 58], allowing the foot-ankle complex to respond to perturbations occurring in ground-shoe interactions while also enabling propulsion [58].

The impact of shoe effect on foot-ankle ROM is not limited to just the ankle joint, these compensations resonate upward affecting movement in the knee, pelvis, and torso in compensation to GRFs Abnormal alterations in biomechanics of jumping and landing kinematics and lateral cutting may result in over-use injuries [16].

2.2.5 Basketball Shoe Dimensions of Quality

To improve upon the user-based approach in developing a taxonomy for basketball shoes, the application of Garvin's eight dimensions of quality can be applied and establish baselines between various types of basketball shoes. The following sub-sections will apply the dimensions of quality to generalized shoe features. Future work can define specific dimensions of quality relationships to product features.

2.2.5.1 Performance

Defining the dimensions of quality to basketball shoes can improve the comparison between shoes. Current basketball shoe descriptions are generally driven to exemplify the marketing creativity not always the true shoe performance factors behind the engineering. For example, basketball shoes from two sport shoe manufacturers have highlighted their shoes as being "inspired by moon craters," and another offers a "full-length speed plate that keeps you on your toes so you can blow right by defenders." Developing performance correlations between moon craters and how a speed plate keeps you on your toes, is not explained and left to the imagination of the consumer [59]. To improve the description of shoe performance, the use of quantitative assessments from biomechanical analysis associated with player feedback would represent a realistic objective rating of the performance features.

2.2.5.2 Features

An example of a product feature is the "rolling responsiveness" of the Nike Kyrie 5, which explains that the insole is curved with the shape of the outsole, to improve energy return. This is a product quality description improvement over the moon crater inspiration, but still leaves doubt as to any biomechanical benefits that may improve performance or mitigate the chance of injury.

An improved product quality feature is Nike's E.A.R.L. (electric adaptable reaction lacing), which is promoted as an adjustable lacing that contours to the wearers foot. The importance of this feature is that different shoe lace construction and systems can provide an improved "fit" [60] and alterations in lacing can increase the comfort level for players with abnormal foot profiles such as high arches and narrow heels [61]. Providing and matching contextual relationships of lacing features to the individual's foot is a good example of an improved product quality feature.

2.2.5.3 Reliability

Understanding reliability or meantime to first failure of a shoe would possibly have altered Zion Williamson's shoe rotation schedule and potentially averted the "blow out." Since professional basketball players go through dozens of shoes throughout the season, the question of how long a shoe lasts may be a double-edged sword for manufacturers. Consumer research will need to be conducted to determine what level of reliability is expected contrasted with shoe price.

2.2.5.4 Conformance

Conformance measures established by manufacturers can determine the frequency of shoe breakage during play and assist in developing manufacturing standards that will improve product quality. After the Zion Williamson incident, Nike reportedly flew to China to investigate the assembly process of their basketball shoes and quickly took measures to design a new pair for Williamson. The question of whether this was a one-off incident or issues with their manufacturing product quality have yet to be released to the public.

2.2.5.5 Durability

Related to reliability is the durability of basketball shoes. According to [40], professional basketball players often wear new shoes for each game, while NCAA basketball players may only have limited number of pairs for the entire season. Thus, defining a shoe's durability will help to establish a proper rotational schedule for wear. Footwear durability is generally determined by the robustness of the midsole and insole [47]. The amount of force and frequency of use will also impact the durability of the shoe. Understanding playing style, anthropometrics, and number of repetitions will go into establishing a shoe's durability [60]

2.2.5.6 Serviceability

Serviceability for basketball shoes can be tied to the manufacturer's willingness to talk to players about shoe preference and design. As basketball shoes are not repaired, the customer satisfaction component of knowing that the manufacturer is listening and more importantly responsive to a player's concerns may improve wearer perception of a shoe's product quality. One growing trend that manufacturers may improve customer relationships is through the development of online communities which would be an example of attuning to the "voice of the customer" (VOC)[32]. Under Armour and Nike have developed large running and fitness on-line communities, the development of basketball communities may offer manufacturers the opportunity improved product serviceability by having access to consumer date, preference trends, and community members' real world experiences or problems not anticipated or tested during research and development [62].

2.2.5.7 Aesthetics

Aesthetics are often based on the likes and dislikes of the individual athlete. Colors, patterns, and materials are just some of the few components that make up the look of basketball shoes. The creativity of the designer to establish marketing “ideal points” that match the preferences determined by the consumer is important component in the market acceptance of a shoe [12]. Based on the BST, functional competence will need to support the aesthetics to optimize product quality.

2.2.5.8 Perceived Quality

The final dimension of perceived quality contains both subjective and objective perceptions of basketball shoe product quality. Perceived quality occurs when a marketing goal to define brand awareness and establish product line strategies to build the manufacturers reputation is a higher priority than a shoe’s true characteristics. An example of this can be seen in Nike’s PG 3 basketball shoes (Paul George, NBA player) with moon crater inspired traction control [59]. The circle rings may provide excellent traction-control but true engineering principles that support multidirectional control are not presented. Instead, listening to VOC should be utilized to assess the true characteristics and the functional cause and effect aspects of shoe design.

2.2.6 Future Research

To properly assess dynamic forces during practice and game scenarios, new technologies in wearable technologies and video are being developed to improve contextually relevant data. A video solution to quantifying forces are being explored by Second Spectrum (www.secondspectrum.com), official video tracking technology provider for the NBA [63].

Sensors measuring movement parameters have been featured in Nike, Under Armour, and Adidas shoes, but Adidas has decided to discontinue the initiative [64], instead relying on third party companies design user-based community apps. Limitations with older technology may be replaced by self-generating power sources, liquid metal and soft sensors, usable data to improve performance, and mitigate injuries [40, 45, 65, 66].

2.3 Conclusion

The goal of developing the domain specific BST is to provide a hierarchical structure that identifies characteristics of the game, player movement patterns, shoe design, and psychophysical factors to assist in improving a team and player decisions in selecting a type of basketball shoe. Based on the user-based approach, the four categorical strategies, brand and model, dynamic categorization, biomechanical impact, and dimensions of quality, describe the overall contextual interactions between shoe features and their influences on the athlete. Specific situational influences include defining type of play, shoe design, injury mitigation, performance, and features. Within each situationally defined segment, the interplay between the eight dimensions of quality to promote product quality are applied to the manufacturers shoe design characteristics. This will allow the wearer to fully understand the situational effectiveness of a specific basketball shoe based on quantitative and qualitative assessments.

CHAPTER III

EFFECT OF SHOE DESIGN ON JUMPING PERFORMANCE

3.1 Introduction

Applying HFE assessment tools to athletic PPE footwear can begin to quantify and define the impact of sport-specific shoe design on positive and negative performance parameters. Discussed in the first study (BST), the evaluation of basketball shoe design should focus on personal preferences, mechanical shoe structures, and dynamic cause-and-effect characteristics of design and performance. The importance of evaluating dynamic foot-ground interactions in determining shoe selection can be traced back to shoe's ability to mitigate injuries and affect performance. This was recently witnessed in collegiate athletics when in February 2019, Zion Williamson, former basketball player for Duke University and the number one pick in the 2019 NBA draft, made a move during competition and, quite literally, blew out his shoe in front of the one of the largest watched games in NCAA history. Unfortunately, Zion suffered a knee injury which continues to negatively impact his 2019/2020 NBA playing season and resulted in Nike losing over $1 billion of stock value the day following the event [36]. To assess a shoe's effect on basketball jumping performance, understanding the design factors that influence kinematic and kinetic output during basketball specific jumps are discussed below.

3.1.1 Basketball Shoes

Basketball shoe design can be broken down into four main components: (a) upper, (b) insole, (c) midsole, and (d) outer-sole (Fig. 3.1). A basketball shoe must support the repetitive

GRF movements including forward and backwards sprinting, quick changes in direction, and jumping. Basketball shoes have been traditionally designed based on how much the malleolus of the ankle is covered by the upper, “Low to Mid cut” for guards and small forwards and “Mid to High cut” designed for forwards and centers (Fig. 3.2) [13]. Specific basketball shoe design parameters can include weight, traction, collar height, mid and upper design, sole design, cushioning systems, and many more, but choosing the proper design based on athlete playing style has shown to be preferred [13].

Figure 3.1 Parts of a basketball shoe.

Figure 3.2 Collar height differences of low-cut and mid-cut basketball shoes.

3.1.2 Kinematic Compensations

Based on a basketball shoe's design and its impact on the range of motion in the ankle joint, athletes may unintentionally alter their kinematics in the knee and hip joints creating compensatory movement which have shown to increase the risk of musculoskeletal injuries [4]. The foot to ground interaction is managed by the foot-ankle complex. The foot-ankle complex allows the foot to move through a wide range of motions, including inversion, eversion, dorsiflexion, plantarflexion, pronation, and supination [54]. The foot-ankle complex is comprised of the tibia, fibula of the lower leg, the talus within the ankle joint, and the calcaneus of the foot. Movement is comprised of three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis [67]. Due to the shape of the talocrural joint, the axis of rotation goes through the medial and lateral malleolus at a 42 degree angle and transversely at a 23 degree angle creating a tri-planar motion of pronation and supination [67]. Further stressors on the lateral ligaments can also occur when the lower leg is externally rotated during plantar flexion and ground reaction forces (GRFs) are high [41]. This places the foot-ankle complex as an important shock absorber during initial contact with the ground and maintaining directional forces during a movement.

3.1.3 Kinetic Assessment

Testing for specific type of shoe functionality can be performed on a force plate with basketball specific movement patterns. Force plates measure external forces applied by the athlete during movement in three planes: vertical, medial-lateral, and anterior-posterior [46]. Measures of these movements are supported by Newton's three laws of motion. Law one explains that for an object to move, a force must act upon it; law two provides the equation that force is equal to mass multiplied by acceleration (F=M x A); law three explains that for every force there is an equal and opposite force. The combination of laws two and three explains that when an athlete pushes onto the ground, with friction, the athlete then has a resistive platform that allows their body to move equal to the force being the applied to the ground. This allows for the measurement of work being performed as "GRFs can indicate the intensity and duration of stress the body is subjected to during contact with the ground" [50].

Examining an athlete's lower body biomechanics can shed light on leg strength asymmetry, kinematics, and the effectiveness of training programs which can be identifiers for improved strength or potential injury factors [46, 68, 69]. Force plate jumping variables can include the athlete's rate of force development, peak force, take-off, flight time, and landing [46]. Figure 3.3 illustrates a countermovement jump's kinetic output from the ForceDecks software. The start of the movement is a reduction of GRF due to the downward squatting motion which eccentrically loads the lower limb musculature through the muscle's stretch-shorten cycle which will be followed with a rapid concentric contraction and extension of the foot-ankle, knee, and hip joints [70, 71]. With an arm swing [72], the individual can apply greater GRF producing the ability to overcome gravity. The greater the rate of force developed (RFD), steepness of the slope, and shorter impulse the higher the jump will be [50]. When the force plate measures zero, the athlete is in the air; this is known as flight time. Greater GRFs are produced due to the acceleration of the athlete's mass being applied to plate when landing from their peak jump height. Peak landing GRFs concerns from basketball jumps have shown intensities up six-times body weight, which when repeated may produce stress-related injuries [50]. Based on the athlete's mass and acceleration rates, an athlete's force production may offer an improved application to establish type of play profiles and shoe selection [35]. Comparing two different athletes that have the same quickness (acceleration) but differ in weight by 30 lbs. creates different GRFs with the same movement pattern.

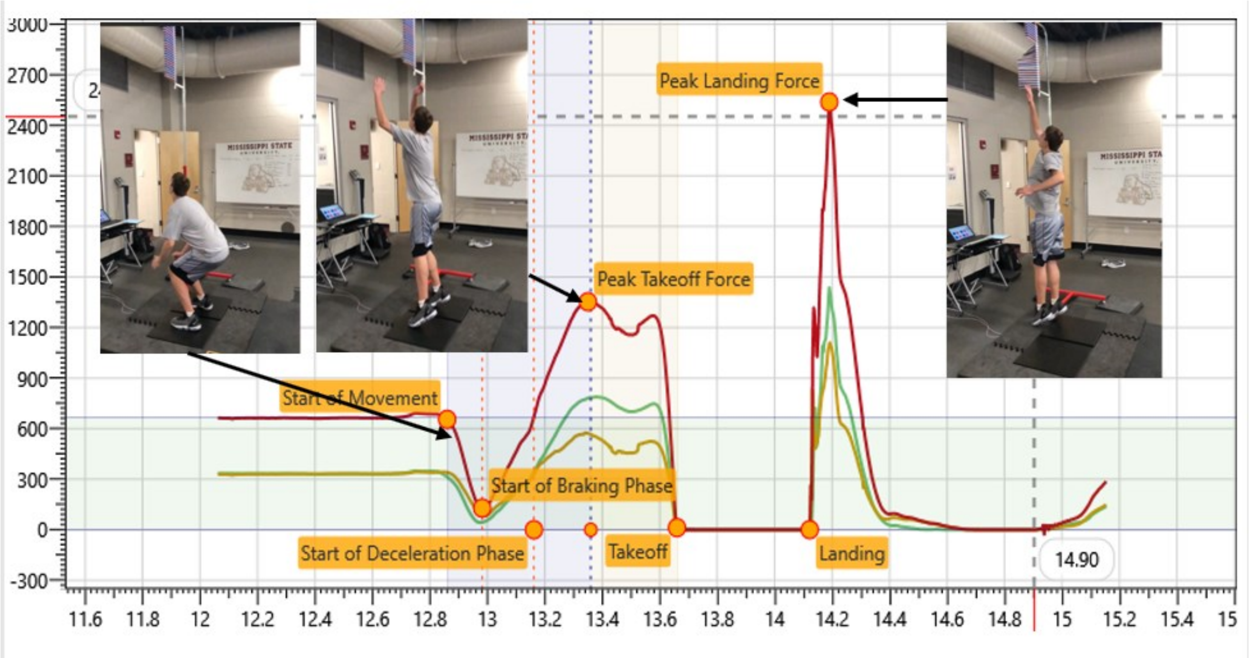


Figure 3.3 Jump measurements taken from ForceDecks software; this image and data were not taken from participant data collection.

3.1.4 Injury Mitigation

Of the many factors in improving basketball shoe design, injury prevention could be considered the “holy grail” for basketball players. The interaction of the foot-ankle complex and lower limbs have with the ground is considered to create a closed kinetic chain [54]. Stressors on lower limbs during the game and practice include impact GRFs, ankle joint inversions, and lower leg rotations. Collectively, research has reported that 70% of knee anterior cruciate ligament injuries (common to female soccer and basketball athletes) occur in non-contact events as a result of high force loads [73, 74]. The type of footwear worn and their contact on playing surfaces, joint alignments of the trunk, and hip all contribute to potential ACL injuries [48]. However, there is insufficient data on the relationship of lower extremity joint alignments to ACL injuries [48]. The knee joint (tibiofemoral joint) is comprised of the femoral condyles that articulate on the superior aspect of the tibial plateau and moves in a combination of hinge (flexion & extension) and rotation [54]. Control during movement of the knee joint is possible due to the medial and lateral menisci, posterior and anterior cruciate ligaments, oblique and arcuate popliteal ligaments, fibular and tibial collateral ligaments, medial and lateral patellofemoral ligaments which allow for flexion and extension while limiting the amount of knee joint rotation [54]. This provides motivation to develop wearable devices that measure the foot-ankle complex and knee ROMs during an athlete’s movement.

Based on the dynamic multi-planar forces placed upon the lower limb during basketball movements, the positioning of joint angles and shear forces on the joints during an athlete’s landing mechanics can lead to an increased chance of soft tissue injuries [45]. Previously, only cadaveric studies have shown that altered movement patterns may lead to increase strain on the ACL. Video has been inconclusive in determining hyperextension as the main cause of strain

[48]. Depending on landing mechanics, NBA players have shown to experience six times their body weight when landing "flat-footed" [50]. Landing force parameters such as the loading rate or time from first contact to peak force, can be used to assess levels of potential stress injuries [16, 75]. To reduce the negative effects of GRFs, basketball midsoles have been designed with various levels of cushioning. The amount of midsole cushioning has an inverse relationship with the performance requirements of basketball [27]. An increase in shoe cushioning under the foot can reduced the negative effects of vertical GRFs [27, 76]; however, with increased cushioning with softer materials, reduced GRFs resulted in lower jump height [16].

Another common sports injury is a non-contact lateral ankle sprain. Lateral ankle sprains can occur when an athlete's foot moves into excessive supination or inversion causing damage to the lateral ligaments [67]. The foot-ankle joint complex allows the foot to move through a wide range of motions, including inversion, eversion, dorsiflexion, plantarflexion, pronation, and supination(Fig. 3.4) [54].

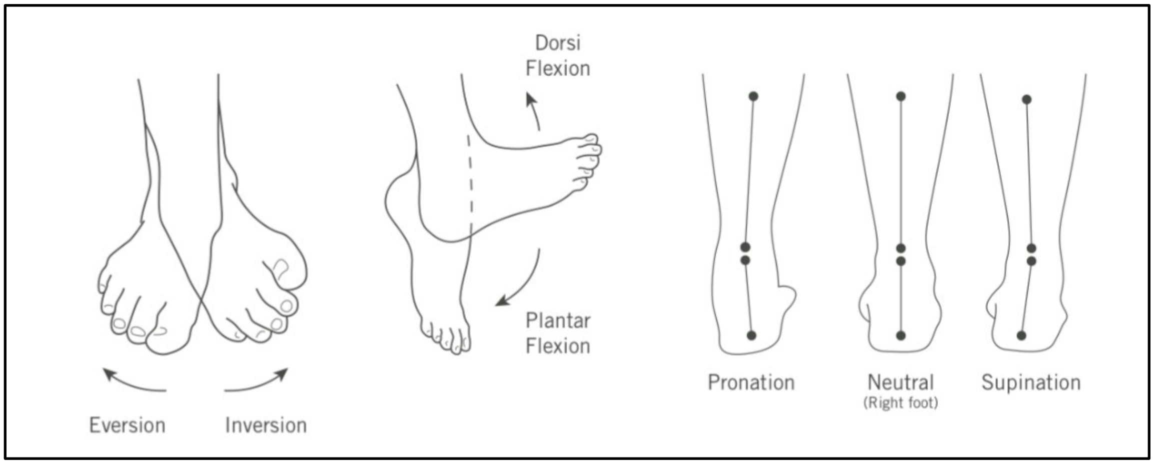


Figure 3.4 Movement patterns of the foot-ankle complex. Source: Adapted from [54].

The foot-ankle complex is comprised of the tibia, fibula of the lower leg, the talus within the ankle joint, and the calcaneus of the foot (Fig. 3.5). Foot-ankle movement is comprised of three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis [67] . Three ligaments support the lateral foot-ankle complex: the posterior talofibular ligament, the anterior talofibular ligament, and the calcaneofibular ligament (Fig 3.6). The weakest ligament, the anterior talofibular ligament, is generally seen as the first ligament to be injured during excessive supination or inversion (Fig. 3.7) [54].

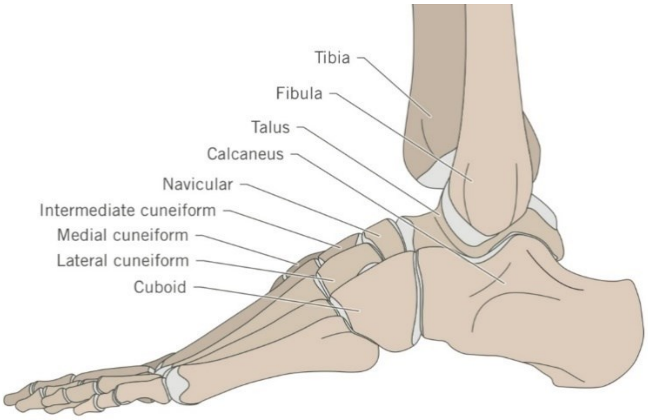


Figure 3.5 Identification of the foot-ankle skeletal complex. Source: Adapted from [54].

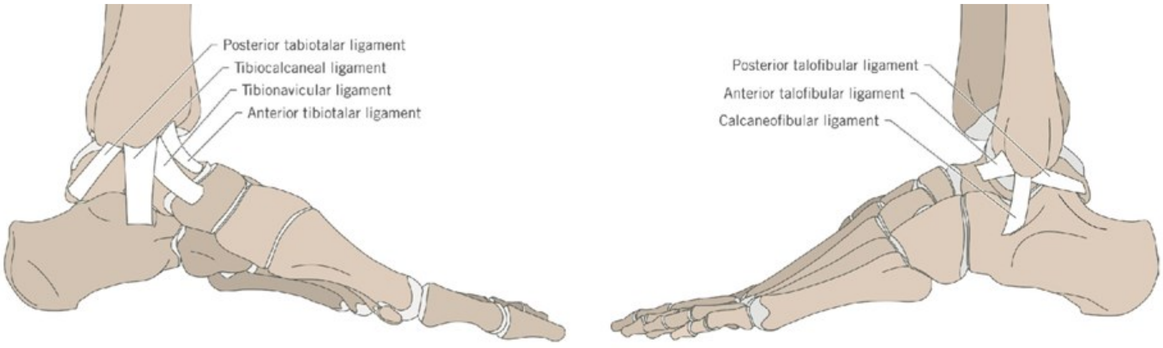


Figure 3.6 Identification of the foot-ankle complex ligaments. Source: Adapted from [54].

To prevent excessive inversion and lateral ankle sprains, basketball shoes are designed with high collars or high tops which have shown to prevent the occurrence and to minimize ankle inversion and external rotation [77]. However, there is conflicting research with shoe design functionality. Depending on the shoe's heel stiffness and design, high tops have been shown to increase lateral ankle inversion, the opposite of their intended design [15]. In addition, heel counters (additional support surrounding the heel upper) have led to an increase lateral ankle inversion and increased shock transmission [14]. Current inconclusive findings make it difficult to determine what type of shoe is best for the athlete.

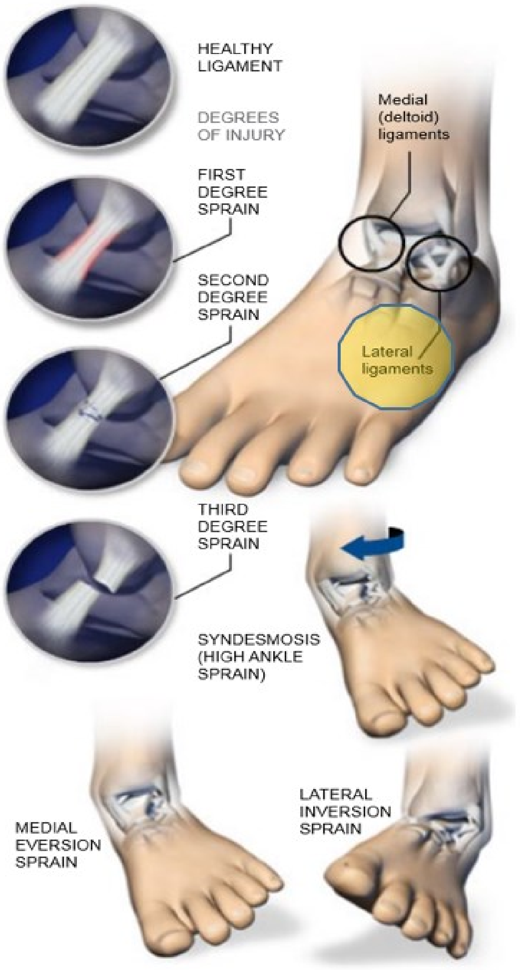


Figure 3.7 Description of medial and lateral ankle sprains. Highlighted anterior-lateral ligament is the most common type of lateral ankle sprain. Source: This Photo by Unknown Author is licensed under CC BY-NC-ND

3.1.5 Performance

The influence of basketball shoes on jumping height, has been examined by Blache et al., with eight pairs of basketball shoes based on the following parameters: height of the upper on the backside of the shoe (high/low), the mass (heavy/light), the flexibility of the upper (flexible/stiff), as compared to jumping barefoot which produced the highest jump [15]. Three parameters (heavier, taller, and stiffer) reduced jumping performance and altered landing mechanics limiting maximum plantar flexion and affected the coordination of the knee and hip joints [15]. Wearing shoes that maximize GRFs allowed the basketball athlete to move quicker but also placed a greater strain on the body [25]. To reduce the chance of injury, a reduction of force placed upon the body during a basketball game requires understanding the impact of shoe design on landing mechanics and vector GRF movement alignments [26, 27].

Fais et al., has shown that landing with shoes set at a positive 3° – 4° of dorsiflexion increased vertical jump height in countermovement jumps (CMJ) and improved landing and jump height during a 15 second continuous jump protocol [78]. In addition, when there was a reduction of ankle plantar flexors upon landing, the ability of the musculature to absorb the vertical GRFs were reduced resulting in higher compressive forces placed upon the spine and lower body [2, 68]. A combination of ensuring the athlete can perform proper landing techniques and basketball shoe designs may allow proper range of motion and should be the goal to optimize performance and safety. This would favor an experimental design that matches conditions of the game and leads to the question: Do different shoes impact men's and women's basketball athlete's jumping performance at the NCAA DI level? To evaluate shoe effect, two different Adidas brand basketball shoes were worn to assess their influence on performing four basketball-specific jumps: (a) countermovement jump, (b) drop jump, (c) step jump, and (d) plyometric jump.

3.2 Materials and Methods

3.2.1 Participants

This study was conducted under the approval of the Mississippi State University's (MSU) Institutional Review Board (IRB protocol #19-351) at Mississippi State University. A total of 16 MSU basketball student-athletes, six from the men's team (198.48cm ± 8.97, 94.48kg ± 15.96, 13.5US Men's ± 2.35) and 10 from the women's team (184.15cm ± 9.29, 78kg ± 10.84, 10US Men's ± 2.35) ages 18 – 22 years of age participated in the study. Before performing the test, student-athletes were informed of the testing protocol and provided a written informed consent form and PAR-Q form to "determine the safety or possible risk of exercising for an individual based on their health history, and current symptoms and risk factors"[79]. Any questions from the participants were addressed at that time. Student-athletes who were not allowed to practice determined by the strength and conditioning coaches (SCCs) were not recruited for the study.

3.2.2 Study Design

All student-athletes were instructed to visit the Mize Center basketball weight room. The study design followed a single day testing protocol with an initial familiarization session conducted before testing. During the familiarization session, student-athletes watched a demonstration by the researcher in how to perform each of the four jump types. The testing station included two force plates controlled by a Microsoft Windows-based laptop, surrounded by a firm foam pad to expand the platform area for safety purposes. Adjacent to the platform was a Vertec jump measurement apparatus set to the student-athletes' dominant side. The Vertec was preset at specific marks on the vertical support for the men's team at 2.896m and 3.048m height and 2.4384m and 2.5908m for the women. Pre-setting the Vertec allowed for consistent time management of measuring vanes reached, record kinetic data, and differences in height and jumping ability. The experimental procedures included measurements of GRFs in two different types of basketball shoes for each team, Adidas shoe A and B for the men's team and Adidas shoe C and D for the women's team. Shoe order was counter balanced to minimize order effect and reduce the impact of fatigue. Each student-athlete warmed up based on their chosen method. Student-athletes then performed jumps onto two ForceDecks Dual Force Plate System (Vald

Performance, Brisbane, Australia) measuring at 1000 Hz, surrounded by rubber matting with a Vertec positioned on their dominant side (upper extremity) for hitting the Vertec vanes with their dominant hand during the jumping tasks (Fig. 2.4). Each participant performed two trials of each jump (Table 3.1). Upon completion, the student-athlete completed a comfort and fit survey and changed shoes. The jump protocol and comfort and fit assessment survey was repeated with the second pair of shoes.

Table 3.1 List of jump types performed.

Jump Tests (1 testing session - 2 trials each):
1. Countermovement vertical jump (CMJ)
2. Depth jump (30cm box) (DJ)
3. Step and jump (STJ)
4. Plyometric jump (PJ)

Figure 3.8 Experimental jump set-up: (1) Laptop running ForceDecks Software, (2) Adidas Foot Scanner, (3) Vertec Jump System, (4) Dual Force Plates, and (5) Drop Jump Box was positioned on platform adjacent to force plates during testing.

3.2.3 Instrumentation and Participant Preparation

Adidas (Herzogenaurach, Germany) shoe selection was determined by the men's and women's strength and conditioning coaches based on the current available supply and student-athlete preference. The men's team chose the Adidas basketball shoe Harden Vol. 3 – shoe A and the Adidas basketball shoe SM Pro Bounce Madness Team – shoe B to assess jumping parameters (Fig. 3.3, Table 3.1). While the women's team choose Adidas basketball shoe Harden

Vol. 3 – shoe C and the Adidas Pro Vision Marvel's Captain Marvel – shoe D (Fig. 3.3, Table 3.1).

Figure 3.9 Men's Shoe – Team Harden (a) and SM Pro (b), Women's Team Harde (c) and Captain Marvel (d).

Shoe dimensions are presented in Table 3.1. Weight of the shoes were measured with an electronic scale (Mainstays™ Slimline Digital Scale). A sliding caliper was used to measure a straight-line difference between reference points on each shoe (Lafayette Instruments, Anthropometer, Model 01291). Previous research has reported that athletes prefer lighter weight shoes [80], wider outsoles provide increased lateral stability [81], and "heavy + high" shoes have shown to decrease vertical jump height [17]. The weight of these shoes are considered medium for the men's team and light for the women's team [17]. Shoe A, B, and C are considered low-cut shoes, while shoe D is a high-cut shoe. Higher collared shoes have shown decreased ankle range of motion and reduced lateral motion in the heel which may lead to increased strain on ankle ligaments [41].

Table 3.2 Sample shoe dimensions for both the men's and women's team.

Men's Team	Weight (g)	Collar Height at Ankle (mm)	Collar Height at Heel (mm)	Collar Height at Top Eyelet (mm)	Insole Thickness (mm)	Heel Sole Height (mm)	Forefoot Width (mm)	Heel Width (mm)	Size
Shoe A	535	88	140	114	4	30	124	98	14
Shoe B	488	95	134	110	3	40	128	97	14
Women's Team									
Shoe C	373	78	121	102	4	30	110	89	7
Shoe D	338	110	129	118	4	34	114	95	7

3.2.4 Experimental Procedures

Each student-athlete was first instructed to read through a participation consent form. Upon agreement to the expectations and signature for approval as per IRB protocol, the student-athlete was instructed on which pair of shoes should be worn first. Additional demographic information was gathered including shoe size, height, and weight. The order of the shoes was counter balanced to reduce bias of shoe type and fatigue in the study. Demonstrations by the test administrator were given to the student-athletes for each of the jumps as follows: (a) jump as high as possible by bending your knees and hit the vanes with your dominant hand (CMJ), (b) step and drop onto the force platform from the 30cm box and immediately on landing, jump as high as possible reaching for the Vertec vanes (DJ), (c) standing off the force plate, take a step forward with one foot, then the other into a counter movement pattern, jump as high as possible reaching for the Vertec vanes (STJ), and (d) jump as high as possible bending your knees, and on landing, perform a series of 4 consecutive CMJ jumps (PJ). Athletes used their individualized arm swings during all jumps attempting to create maximum jump height and touch Vertec vanes. Student-athletes were paired together for motivation in performing maximal effort jumps. Student-athletes completed two trials of each jump and rested while the other participant completed their two trials. Between jumps, the Vertec vanes were reset, this provided the student-athletes rest between jumps. The jump and rest routine were followed until all jumps were completed. Student-athletes then rested to put on the second pair of test shoes and fill out a comfort and fit survey. The exact same protocol was repeated with the second pair of shoes. This marked the completion of the kinetic assessment study.

Figure 3.10 Example of a Vertec Jump Measurement Test. Data from the photo was not used for this study.

3.2.5 Data Processing

Jump force data was collected and processed using ForceDecks software. The Force Decks system auto-detected the CMJ, DJ, and PJ. The STJ was manually saved into the software. Prior to each jump, the athlete stepped onto the force plate to determine weight. Analysis of the jump was accomplished through the auto-analysis feature for the CMJ, DJ, and PJ. The STJ data was post selected into a counter jump movement for analysis. Recognizing the first jump within the PJ is a CMJ, that jump performance is ignored. The highest jump from the remaining three PJ was manually selected as indicated from the ForceDecks analysis. Peak jumps from each athlete was then transferred to a Microsoft Excel (Redmond, WA, USA, ver.

365) program for further analysis. Figure 2.1 provides an example of the auto-analysis from the ForceDecks software.

3.3 Statistical Analysis

A Paired Samples t-Test was conducted using the Statistical Package for Social Sciences (SPSS ver.26, IBM Corporation, New York, NY, USA) to compare the interaction effect of shoe model on calculated jump height (cm) and normalized body weight peak power (W/kg) production (PPr) as presented in Table 2.2. Jump height and PPr were determined using the ForceDecks software and presented in Table 2.1. Independent t-Test was conducted to compare differences in jump types between the men's and women's team as presented in Table 2.3. Two repeated measures analysis of variance (ANOVA) pairwise comparisons were conducted to compare jump types. Results are summarized in the following paragraphs. Statistical significance was set a priori at $p \leq 0.05$.

3.4 Results

This pilot study selected the highest jump from the two trials performed within each jump and of each shoe tested and the highest of the three PJ performed after performing the initial CMJ to minimize any effect of loss of balance and fatigue that can occur in continuous jump protocols [82]. Calculated jump height and PPr was obtained from the ForceDecks software.

3.4.1 Shoe Effect on Jump Height

A Paired Samples t-Test was conducted to compare the effects of shoe types on jump height and PPr for both the men's and women's teams. Jump height was calculated in centimeters, peak power is normalized to body weight (W/kg). Results from the statistical analysis are presented. There was no significant difference in CMJ jump height for shoe A mean

46.85 (SD = 3.91) and shoe B mean 46.32 (SD = 4.52), t(5) = 0.809, p = 0.455. There was no significant difference in CMJ jump height for shoe C mean 28.79 (SD = 4.73) and shoe D mean 29.43 (SD = 4.01), t(9) = -0.863, p = 0.410. There was no significant difference in DJ jump height for shoe A mean 47.50 (SD = 5.61) and shoe B mean 49.78 (SD = 6.45), t(5) = 1.494, p = 0.195. There was no significant difference in DJ jump height for shoe C mean 28.79 (SD = 4.37) and shoe D mean 29.58 (SD = 5.51), t(9) = -1.661, p = 0.131. There was no significant difference in STJ jump height for shoe A mean 53.70 (SD = 6.55) and shoe B mean 54.55 (SD = 7.01), t(5) = 0.809, p = 0.455. There was no significant difference in STJ jump height for shoe C mean 33.46 (SD = 4.27) and shoe D mean 32.51 (SD = 5.36), t(9) = .0785, p = 0.453. There was no significant difference in PJ jump height for shoe A mean 47.37 (SD = 4.24) and shoe B mean 47.13 (SD = 6.08), t(5) = 0.249, p = 0.814. There was no significant difference in PJ jump height for shoe C mean 29.49 (SD = 4.80) and shoe D mean 29.44 (SD = 4.97), t(9) = 0.125, p = 0.904.

3.4.2 Shoe Effect on Peak Power

Normalized PPr (w/kg) was computed, which has shown to reduce the effects of a covariate on the dependent variable in assessing GRFs [83]. Results from the statistical analysis are presented. Pearson correlation coefficients was conducted to compare shoe effect on PPr. There was no significant difference in CMJ PPr for shoe A mean 79.17 (SD = 14.70) and shoe B mean 73.50 (SD = 14.73), t(5) = 1.504, p = 0.193. There was no significant difference in CMJ PPr for shoe C mean 49.87 (SD = 8.91) and shoe D mean 48.20 (SD = 15.00), t(9) = 0.422, p = 0.683. There was no significant difference in DJ PPr for shoe A mean 125.52 (SD = 20.53) and shoe B mean 124.27 (SD = 22.41), t(5) = 0.605, p = 0.572. There was no significant difference in DJ PPr for shoe C mean 95.53(SD = 12.35) and shoe D mean 92.74 (SD = 17.17), t(9) =

1.009, p = 0.339. There was no significant difference in STJ PPr for shoe A mean 94.72 (SD = 12.54) and shoe B mean 99.58 (SD = 10.72), t(5) = -0.876   p = 0.421. There was no significant difference in STJ PPr for shoe C mean 67.83 (SD = 13.73) and shoe D mean 67.21 (SD = 18.91), t(9) = .150, p = 0.884. There was no significant difference in PJ PPr for shoe A mean 96.53 (SD = 22.32) and shoe B mean 91.82 (SD = 23.21), t(5) = 0.661, p = 0.538. There was no significant difference in PJ PPr for shoe C mean 85.62 (SD = 35.99) and shoe D mean 87.47 (SD = 31.37), t(9) = -0.617, p = 0.552.

3.4.3 Male versus Female Jumping Performance

3.4.3.1 Jump Height

An Independent Samples Test was conducted to compare average jump height (cm) and PPr (W/kg) of the male and female student-athletes. There was a significant difference in men's (M = 46.59, SD = 4.04) and women's CMJ height (M= 29.11, SD= 4.28) t(30) = 11.414, p = 0.001). There was a significant difference in men's (M = 48.64, SD = 5.88) and women's DJ height (M= 29.19, SD= 4.86) t(30) = 10.136, p = 0.001). There was a significant difference in men's (M = 54.13, SD = 6.48) and women's STJ height (M= 32.99, SD= 4.74) t(30) = 10.633, p = 0.001). There was a significant difference in men's (M = 47.25, SD = 5.00) and women's PJ height (M= 29.47, SD= 4.76) t(30) = 10.048, p = 0.001).

3.4.3.2 Peak Power

There was a significant difference in men's (M = 76.33, SD = 14.34) and women's CMJ PPr (M= 49.04, SD= 12.04) t(30) = 5.782, p = 0.001). There was a significant difference in men's (M = 124.89, SD = 20.50) and women's DJ PPr (M= 94.14, SD= 14.63) t(30) = 4.949, p = 0.001). There was a significant difference in men's (M = 97.15, SD = 11.41) and women's STJ

PPr (M= 67.52, SD= 16.09) t(30) = 5.578, p = 0.001). There was a nonsignificant difference in men's (M = 94.18, SD = 21.85) and women's PJ PPr (M= 86.55, SD= 32.88) t(30) = 0.713, p = 0.482).

3.4.3.3 Jump Types

Descriptive statistics of jump types within the men's team resulted in CMJ max height mean of 46.59 (SD = 6.48), DJ max height of 48.64 (SD = 5.88), STJ max height mean of 54.13 (SD – 6.48), and PJ max height mean of 47.25 (SD = 5.00). Pairwise comparisons resulted in significant differences of men's STJ max height compared to CMJ max height (p = 0.001), to DJ max height (p = 0.009), and PJ max height (p = 0.001).

Descriptive statistics of jump types within the women's team resulted in CMJ max height mean of 29.11 (SD = 0.96), DJ max height of 29.19 (SD = 1.09), STJ max height mean of 32.99 (SD – 1.06), and PJ max height mean of 29.47 (SD = 1.06). Pairwise comparisons resulted in significant differences in only the women's STJ max height compared to CMJ max height (p = 0.001), to DJ max height (p = 0.001), and PJ max height (p = 0.001).

3.5 Discussion

This pilot study examined the jump height differences of an acute jump assessment performing four different basketball specific jumps while wearing two different pairs of basketball shoes. There were no significant differences in shoe effect in any of the four jumps for either the men's or the women's teams (p > 0.05). Commentary from the student-athletes about various aspects of the shoes seem to indicate a preference for one shoe over the other. Shoe D - Adidas Marvel Captain Marvel shoe, the visual appearance did impact the likelihood of whether the student-athletes would wear the shoe during practice and games. Understanding personal psychological shoe preferences have shown to influence athlete playing performance and should be considered in designing basketball shoes [80].

Significant differences existed in jump height between genders resulting in significantly higher average jump height in all four jumps for the men's team compared to the women's team. There were significant differences in CMJ PPr, DJ PPr, and DJ PPr between genders. Interestingly, there was no significant difference in PJ PPr between the men's and women's teams even though PJ height was significantly different. Differences in jump height between genders may be a result of differences in body dimensions and utilization of potential elastic energy in the musculoskeletal system [71].

The results of this study reported that the STJ produced the highest average jump height in all four jumps for both the men's women's teams. This is due in part to the additional momentum and eccentric loading from the student-athletes mass during the stepping phase and greater velocity of arm swing creating the potential for quicker rate of force development [72].

3.5.1 Limitations

Limitations of this pilot study include the limited number of volunteer student-athletes, the volume of jumps attempted per shoe, and the similarities of the men's shoes tested. Both the men's shoes were low cut and had similar features, but are the shoes worn by the players for their upcoming season. The type of basketball shoes provided by Adidas is limited by decisions of the coaching staff, athlete choice, and the corporate-school contract.

Time to complete the pilot study was a concern of the coaching staff as not to interfere normal practice time. Expansion of the testing methodology was not possible at this time of the basketball season.

3.5.2 Future Research

Several recommendations for future research are the inclusion of using optical motion capture, mechanical testing of the shoes, and video analysis of playing performance in a game or practice. The use of optical motion capture may provide biomechanical assessments that may occur due to different shoes. Mechanical testing of each shoe may provide design parameters that affect biomechanical adjustments. Identifying biomechanical adaptations throughout an entire game or practice because of shoe design may lead to injury mitigation and improved performance.

3.6 Conclusion

The impact of shoe design on acute basketball jumping performance did not significantly affect student-athlete jump height and power production during a countermovement jump, drop jump, step jump, and plyometric jump. It is recommended that higher game-intensities should be used to evaluate basketball shoes on individual athlete performance and physiological factors. Comments from the student-athletes suggested the idea of assessing basketball shoes based on performance was a novel idea and expressed interest in additional information and future testing. Understanding the psychological factors that influence perception about basketball shoe performance should be taken into consideration when designing shoes. Not all colors and styles have the same effect on athletes.

CHAPTER IV

PERCEPTION OF COMFORT RELATED TO JUMPING PERFORMANCE

4.1 Introduction

Utilizing an HFE based assessment tool for athletic shoe comfort and fit, comparisons between shoes can be made within the context of the sport. The purpose of this chapter is to define the parameters that support the assessment of comfort and fit in a basketball shoe in identifying key parameters. Perception of comfort and fit is subjective, yet important for manufacturers to improve shoe design [84]. The following sections of this chapter will apply validated HFE comfort assessment scales to create a categorical based basketball shoe comfort and fit assessment tool to understand the player's perception of comfort during simulated game movement patterns. Contextually linking the subjectivity of a player's shoe comfort to their basketball specific kinetic output, has shown to be an effective means for shoe assessment will be discussed [9]. The objective of establishing a basketball specific comfort and fit assessment tool is to help refine the decision-making process in selecting the appropriate type of basketball shoe based on the individual athlete's style of play. Dynamic cutting, accelerations, decelerations, and jumping volume throughout the season place tremendous amounts of strain, shock, and stress on the athletes lower limbs and shoes[13]. Using an athletic based HFE assessment tool to select the appropriate shoe that supports and mitigates GRFs to optimize performance and reduce the chance of injury would be valued by coaches, trainers, and athletes.

4.1.1 Shoe Comfort

An athlete's choice on shoe selection is often based on the complex culmination of experiences, knowledge, perceptions, environment, and attitude resulting in a "set of principle operations" [85] An important aspect of shoe selection is *comfort* and how well the shoe fits. Comfort has been defined as the lack of discomfort [86] and includes a variety of features including "fit, dynamic stability, vibrations, and early fatigue" [26]. Additional contributions have been made to refine the definition of comfort with descriptors such as relaxation and well-being [87]. The difference between shoe discomfort and shoe comfort can be explained by applying the definition used in chair comfort assessment [88]where discomfort is related to "biomechanics and fatigue factors" and comfort is related to "well-being and aesthetics". To improve the assessment of comfort and discomfort, shoe manufacturers, coaches, trainers, and athletes could utilize qualitative and quantitative methods, such as the BST (Chapter 2) and surveys, to define an athlete's ideal perception of their perfect basketball shoe.

Due to the subjectivity of comfort, the use of ergonomic "discomfort questionnaires", machine testing (ISO 5725-1 and ISO 5725-3, section 8), and personal interviews have shown to be reliable in defining shoe design errors and factors relating to discomfort [89]. Two specific means of assessing footwear PPE comfort and discomfort are visual analogue scales (VAS) and Likert scales [9, 10]. Specific anchor words should be added to categorical ratio-based scales [90] to gain insight on specific parameters that determine shoe preference.

Due to the interrelatedness of shoe features, subjective psychophysical measures such as levels of stiffness, stability, and cushioning, can assist in determining the parameters of shoe design that matches the athlete's anthropometrics, physiological responses, biomechanical influence, psychological factors, and performance [3, 89, 91, 92]. Mündermann et al. used the following shoe aspects to assess inserts and running shoes: overall comfort, heel cushioning, forefoot cushioning, medio-lateral control, arch height, heel cup fit, shoe heel width, shoe forefoot width, shoe forefoot width, and shoe length [10]. Using a sport closer to the movement patterns of basketball, LLana, et. al, measured the discomfort of tennis shoes utilizing a seven-point Likert scale (anchored by “no discomfort” and “intense pain”) and a three-point Likert scale (“little”, “adequate”, and “high”) to assess 14 characteristic of footwear [89]. The characteristics included: footwear floor-hold, front mid-sole height, rear mid-sole hardness, front upper vamp hardness, rear upper vamp hardness, rear height, fastening, length, front width, rear width, flexibility, arch support position, arch support height [89]. The following sections will highlight the specific human factors parameters and scales used in the assessment of footwear PPE and its transferability to basketball shoes.

4.1.2 Shoe Fit

Footwear fit has been defined as “the functional geometrical match of foot and shoe” [9]. How a shoe fits greatly determines whether the shoe is comfortable or causes discomfort. Determining dynamic fit parameters within contextual movement patterns including subjective fit rating, foot-last size difference, and pressure distribution of the foot-shoe interface may improve the perception of comfort[93]. Quantifying fit, Cheng and Hong used a VAS scale correlated to 16 flexible pressure sensors mounted to the top of the subject’s foot. The results indicated a negative correlation of fit rating to pressure [93]. Some sensors were found to record higher pressures due to the folding of the sensors. Another wearable device, a pressure sock, was developed using textile sensors with results indicating the same negative correlation between comfort and pressure [94]. However, the question of how much pressure is uncomfortable is not universal between individuals [94].

General methods in determining fit using a Brannock device includes measurement of foot length and width of the foot [61]. This provides a standing weight bearing method for foot size, which unfortunately, cannot be utilized to define any shape deformation of the foot during movements. Limited to two dimensional measurements, new technology is improving fit through the use of scanners and three dimensional modeling (Fig. 4.1) [95]. A potential solution to capture the dynamics of the foot during gait cycle. Coudert et al., has developed a method to produce 3D digitization of the foot using stereoscopic sensors which produces a surface, scanner-like mapping of the foot during gait cycle [95].

Figure 4.1 Scanned image of a foot.

However, this methodology only produced an upper model of the foot and not plantar pressures. Improvements to Coudert's work were developed by Ito et al. by having participants walk across a glass plate. This allowed for the capture of plantar pressures with 3D surface capture [96]. Findings from this study identified temporal changes in size and pressures throughout the foot during a gait cycle which were different from standing weight bearing measures. When comparing the dimensional foot changes of recreational sprinters versus non-habitual sprinters, aside from temporary changes in overall foot size, the anatomical changes from repeated activities of the recreational sprinters resulted in other significant dimension changes in the foot including heel breadth, toe length, height of navicular, hallux of the right foot, and ball girth circumference [97].

Changes in foot size and shape during walking and running complicates the fitting process. The foot and ankle ranges of motion of nine elite American football players were optically captured then modeled using Open Sim software synchronized with force plates to determine kinematics and kinetics during cutting, jumping, and sprinting movements. The results of this study indicated that the talocrural, subtalar, and metatarsophalangeal joints ranges of motion exceeded physiological limits [98]. Understanding the changes in the foot and the kinetic forces that occur in multidirectional movement patterns can help shoe designer develop a better fitting shoe.

4.1.3 Dynamic Shoe Assessments

The amount of GRF transmitted to the individual's foot and lower limb during standing and movement can determine the levels of shock transmitted and over time may increase the risk of injury [22]. Cushioning can be used to mitigate impact perception between the GRFs and the foot. How the midsole and insole are designed can influence the amount of cushion or lack of force experienced which can alter the perception of comfort. According to Kong et al., walking and running participants preferred lighter weight and cushioned model shoe over the stable shoe [84]. Other force dampening strategies are proprietary cushioning technologies applied in the heel, forefoot, mid-sole, and sole [61]. Preference for comfort has been reported as high as 16 out of 20 recreational basketball players who preferred soft-midsole over the hard-midsole even though mediolateral stability was higher in the hard-midsole shoes [76]. New materials, manufacturing processes, and biomechanics are playing a role in how shoes are designed. The use of air, hemispherical springs, and exotic polymers have been used to improve the comfort of enduring GRF [99]. However, too much cushioning has shown to increase the chance of running injuries due to the inability of recognizing GRFs [100-102] and when repeated, may lead to overuse injuries [103]. This creates a challenge for shoe designers to optimize comfort, fit, and performance.

Another shoe features that may affect perception is shoe weight. There is limited research on the effect of shoe weight on jumping performance [81]. Previous research has reported lower energy output when wearing lighter shoes when running [104], however, Worobets et al., found no difference in jump and reach height in three different weighted shoes [81]. This was further supported in a blind group study, in which the unaware group did not perform significantly different with three varied mass shoes [80]. Interestingly, the aware group which knew of the weight differences, showed an increase in vertical jump height with the lighter shoe indicating a positive psychological effect.

General assessment of shoe comfort and fit is often a simple try on approach. However, this leaves out any dynamic GRF assessment. Lam et al. have recommended that a “Basketball Specific Course” (BSC) be used to refine the assessment of basketball footwear relative to comfort and fit [9]. The design of experiments should use contextual aspects of the game of basketball to help assess shoe safety combined with descriptive assessments. Features of basketball shoes that have an impact on performance have been seen in traction and forefoot bending stiffness [81] A basketball shoe comfort and fit assessment tool (Appendix A.1 and A.2) based on the comfort research tool used by Lam et al. was designed using a 110 mm visual analogue scale with the left end labeled “not comfortable at all” (0 comfort points) and the right end “most comfortable condition imaginable” (11 comfort points) [9]. The scale also included a fit rating scale using a seven-point Likert Scale anchored by “too narrow” and “too wide”, with a score of four for “perfect fit”. Previous evidence supported the integration of assessing comfort and fit during specific shoe use was seen in Brauner et al.’s identification of specific shoe characteristics for playing position demands [13]. In addition, quantitative assessment of the type of shoe being worn has shown that shoe design can influence running speed and jump height [14], which would favor an experimental design that matches conditions of the game. Correlating comfort to performance may provide insight on how cognitive perception influences performance. This was seen in changes in running kinematics that were made in an attempt to reduce heel impact forces [102].

4.1.4 Basketball Cause-and-Effect Chain

The goal in developing a multi-faceted tool to assess comfort and fit brings together various assessment techniques to capture the descriptive user preferences and optimum performance, with dynamic design features of the shoe. These include the shoe’s effect on motor performance, the intensity of the athlete’s performance during the testing, and the athlete’s energy expenditures [78]. Mündermann et al., has recommended that in order to establish a reliable measure of comfort, requirements “to determine valid relationships between comfort and shoe constructions, subject characteristics, and biomechanical variables” should be taken into consideration [10]. Assessing performance intensity can provide a meaningful component to determine the amount of relative force placed upon the shoe which can be used to quantify the subjectivity of the VAS. Shoes which may be comfortable at a lower level of movement intensity, may not perform the same at a higher level of intensity due to construction and design.

In order to accomplish the breadth of investigation, the use of a multidimensional tool assessing performance, kinetics, and perception should prove valuable and would be reflected in a performance basketball shoe cause-and-effect chain (Fig. 4.2). This progression model allows for the prioritization of features that determine optimal dynamic fit and an understanding of the cause-and-effect relationships between aspects of the shoe and the individual [89, 105, 106]. The performance cause-and-effect chain can be utilized to describe the feature relationship of a shoe's interaction with the athlete. Characteristics of the athlete, the shoes being worn, and the type of surface played upon are placed on Level 1. Level 2 is comprised of the biomechanical adaptations or changes in a player's movement patterns in reaction to the functional outcomes of the shoe design. Level 3 indicates either the performance or the injuries suffered as a result of Level 2 adaptations. Developing a measurable performance basketball shoe cause-and-effect chain can provide medical practitioners, strength and conditioning coaches (S&CCs), athletic trainers (ATs), and athletes a better understanding of the impact of shoe features on performance and safety.

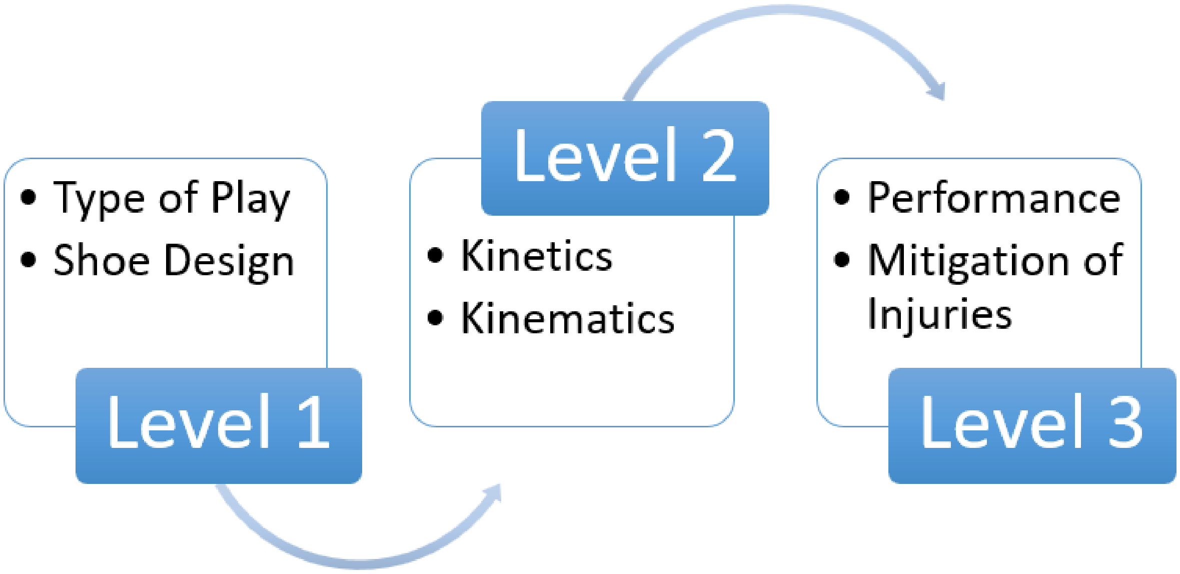


Figure 4.2 Concept of a performance basketball shoe cause-and-effect chain.

4.2 Materials and Methods

4.2.1 Participants

This study was conducted under the approval of the Institutional Review Board (19-351) at MSU. Before performing the test, student-athletes were informed of the testing protocol and provided a written informed consent form. Any questions were answered at that time. Student-athletes included Mississippi State basketball student-athletes on the current academic year's roster including six from the men's team (198.48cm ± 8.97, 94.48kg ± 15.96, 13.5US Men's ± 2.35) and 10 from the women's team (184.15cm ± 9.29, 78kg ± 10.84, 10US Men's ± 2.35) between the ages of 18-22 years. Student-athletes who participated in the previous jump study (Study 1) completed VAS and Likert forms used in this study (Study 2).

4.2.2 Study Design

The study design is a single day testing protocol conducted after each series of jump trials. During the familiarization of the jump protocol, student-athletes were informed that they would evaluate the shoes comfort and fit based against the most comfortable pair of basketball shoes they had ever worn. After completion of the first jump series, student-athletes were handed a multi-page comfort and fit assessment based on a 110mm VAS scale for comfort and seven-point Likert rating form for fit to assess the basketballs used during testing. After rest and changing into the second pair of shoes, student-athletes completed the second series of jumps and were handed a second 110mm VAS scale for comfort and seven-point Likert rating form for fit to assess the basketball shoes worn during testing.

4.2.3 Instrumentation and Participant Preparation

Evaluating the basketball shoes (Fig. 4.1) was completed using a 110mm VAS scale and seven-point Likert fit rating scale. The following comfort factors: arch height, heel cushioning, forefoot cushioning, heel region, collar, medial-lateral control, and overall comfort to the most comfortable pair of basketball shoes ever worn [9] (Fig. 3.1; Appendix A). The fit of the shoe was rated on shoe length, heel region, forefoot width, and collar fit. The 110mm VAS scale was set to a 0-11 cm scale for data analysis and fit ratings were subtracted by four and then transformed into absolute values to assess shoe effect [9]. This identifies values closer to 0 indicating a better fit while values closer to three indicating a poorer fit which follows protocol of previous research conducted by Lam et al [9].

In addition, the student-athletes were handed a visual explanation for all the comfort and fit assessment tool (Appendix A.1). Any questions were answered by using the printed guide as a reference relating back to the shoe that was worn during testing. Any verbal descriptions that were said were read from the printed example directions seen in Appendix A.2.

Figure 4.3 Figure 4.1 – Men's Shoe - Team Harden (a) and SM Pro (b), Women's Team Harden (c) and Captain Marvel (d).

4.2.4 Experimental Procedures

All student-athletes that participated in the previously discussed jump protocol study were included in the comfort and fit assessment study. Upon completion of the first series of jumps, the student-athlete was handed a clipboard and pen to evaluate the shoes. The researcher described the filling out of the form by indicating drawing a vertical line through the horizontal 110mm VAS comfort scale within each of the shoe comfort characteristics. The researcher then described circling the rating value on fit on how well the shoe tested fitted the student-athlete. If there were any questions, the student-athlete was directed to the visual description page and review the questioned area by talking aloud the written description. This process was repeated after the second series of jumps. Upon completion of the surveys, the student-athlete had completed the study.

4.2.5 Data Processing

The vertical markings on the 110mm VAS were manually measured using a 180mm ruler. Using a Microsoft Excel program (Redmond, WA, USA, ver. 365), each deidentified student-athletes' response was recorded in centimeters for each of the comfort parameters: arch height, heel cushioning, forefoot cushioning, heel region, collar, medial-lateral control, and overall comfort Marked fit ratings from the seven-point Likert scale were recorded as absolute values when subtracted from 4 for each of the fit parameters: shoe length, heel region, forefoot width, and collar fit.

4.2.6 Statistical Analysis

A Paired Samples t-Test was conducted using Statistical Package for Social Sciences (SPSS ver.26, IBM Corporation, New York, NY, USA) to compare basketball shoe comfort and fit effects on two different pairs of shoes (Table 3.1). Pearson correlation coefficients was conducted to correlate the quality of fit to the comfort of the shoes as presented in Table 3.2. Repeated measures ANOVA was conducted to investigate the interaction of comfort and fit. Statistical significance was set a priori at $p \leq 0.05$.

4.3 Results

This pilot study evaluated the athlete's perception of comfort and fit on new (less than 2 weeks old) basketball shoes after an acute jumping test protocol. Each athlete rated the comfort of the shoe tested to the most comfortable basketball they have ever worn and how well each shoe currently fits.

4.3.1 Shoe Comfort Comparison

Table 4.1 provides a summary of descriptive statistics of overall rating of shoe comfort and fit in both shoes. The mean comfort from men's team shoe A was 4.69 (SD = 2.54) and shoe B was 5.89 (SD = 2.8) indicating that shoe B was considered slightly more comfortable than shoe A as compared to the student-athletes' most comfortable basketball shoe ever worn. The mean comfort from the women's team shoe C was 5.36 (SD = 2.76) and shoe D was 5.59 (SD = 2.09). Indicating that shoe D was slightly more comfortable than shoe C as compared to the student-athletes' most comfortable basketball shoes ever worn.

Table 4.1 Descriptive statistics of comfort and fit for men's and women's team.

	Men's Team				Women's Team			
	Shoe A		Shoe B		Shoe C		Shoe D	
Comfort	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Arch Height	5.08	3.82	6.65	3.23	5.45	2.48	5.04	1.52
Heel Cushioning	5.23	1.50	5.02	2.66	5.01	2.83	6.58	1.96
Forefoot Cushioning	4.67	2.14	6.60	2.64	5.49	2.96	5.16	1.93
Heel Region	4.23	2.12	5.02	2.96	5.08	3.23	5.72	2.02
Collar	4.18	3.07	5.62	2.74	4.9	2.50	5.64	2.63
Medial-Lateral Control	4.92	2.88	5.80	3.48	5.4	2.57	5.06	2.43
Overall Comfort	4.50	2.98	6.52	2.66	6.22	2.79	5.93	2.16
Fit								
Shoe Length	1.17	1.17	0.67	0.52	0.50	0.71	1.20	1.03
Heel Region	1.00	0.89	0.33	0.52	0.80	0.79	1.10	0.74
Forefoot Width	1.17	0.75	1.00	0.89	0.60	0.70	0.50	0.71
Collar	1.00	1.26	0.50	0.84	1.00	0.82	1.00	0.82

4.3.1.2 Shoe Comfort Characteristic Correlations

A Paired Samples t-Test was conducted to compare the comfort of the two selected shoe models by the men's and women's team. There was no significant difference in arch height comfort for shoe A mean 5.08 (SD = 3.81) and shoe B mean 6.65 (SD = 3.23), t(5) = -0.957, p = 0.382. There was no significant difference in arch height comfort for shoe C mean 5.45 (SD = 2.48) and shoe D mean 5.04 (SD = 1.52), t(9) = 0.508, p = 0.624. There was no significant difference in heel cushion comfort for shoe A mean 5.23 (SD = 1.50) and shoe B mean 5.02(SD = 2.96), t(5) = -0.193, p = 0.854. There was no significant difference in heel cushion comfort for shoe C mean 5.01 (SD = 2.83) and shoe D mean 6.58 (SD = 1.96), t(9) = -1.859, p = 0.096. There was no significant difference in forefoot region cushion comfort for shoe A mean 4.67 (SD = 2.14) and shoe B mean 6.60 (SD = 2.64), t(5) = -1.316, p = 0.245. There was no significant difference in forefoot region cushion comfort for shoe C mean 5.49 (SD = 2.96) and shoe D mean 5.16 (SD = 1.93), t(9) = .291, p = 0.778. There was no significant difference in collar comfort for shoe A mean 4.18 (SD = 3.07) and shoe B mean 5.62(SD = 2.74), t(5) = -1.013, p = 0.358. There was no significant difference in collar comfort for shoe C mean 4.90 (SD = 2.50) and shoe D mean 5.64 (SD = 2.63), t(9) = -1.16, p = 0.294. There was no significant difference in medial-lateral control comfort for shoe A mean 4.91 (SD = 2.88) and shoe B mean 5.80 (SD = 3.48), t(5) = -0.467, p = 0.659. There was no significant difference in medial-lateral control comfort for shoe C mean 5.44 (SD = 2.57) and shoe D mean 5.06 (SD = 2.43), t(9) = 0.335, p = 0.745. There was no significant difference in overall comfort for shoe A mean 4.50 (SD = 2.98) and shoe B mean 6.52 (SD = 2.66), t(5) = -1.371, p = 0.229. There was no significant difference in overall comfort for shoe C mean 6.22 (SD = 2.79) and shoe D mean 5.93 (SD = 2.16), t(9) = 0.260, p = 0.80.

4.3.1.3 Shoe Fit

Descriptive statistics resulted in the mean fit from men's team shoe A was 1.08 (SD=0.63) and shoe B was 0.88 (SD = 0.52) indicating that shoe B provided a slightly better fit. The mean fit from women's team shoe C was 0.073 (SD=0.52) and shoe D was 0.95 (SD = 0.54) indicating that shoe C provided a slightly better fit.

4.3.1.4 Shoe Fit Characteristic Correlations

A Paired Samples t-Test was conducted to compare fit of the two selected shoe models by the men's and women's team. There was no significant difference in shoe length fit comfort for shoe A mean 1.17 (SD = 0.75) and shoe B mean 0.67 (SD = .52), t(5) = 0.889, p = 0.415. There was no significant difference in shoe length fit for shoe C mean 0.50 (SD = 0.71) and shoe D mean 1.2 (SD = 1.03), t(9) = -2.09, p = 0.066. There was no significant difference in heel region fit comfort for shoe A mean 1.00 (SD = 0.89) and shoe B mean .33(SD = 0.52), t(5) = 2.00, p = 0.102. There was no significant difference in heel region fit for shoe C mean 0.80 (SD = 0.79) and shoe D mean 1.10 (SD = 0.74), t(9) = -0.709, p = 0.496. There was no significant difference in forefoot region fit for shoe A mean 1.17 (SD = 1.17) and shoe B mean 1.00 (SD = 0.89), t(5) = 0.542, p = 0.611. There was no significant difference in forefoot region fit for shoe C mean 0.60 (SD = 0.70) and shoe D mean 0.50 (SD = 0.71), t(9) = .318, p = 0.758. There was no significant difference in collar fit for shoe A mean 1.00 (SD = 3.07) and shoe B mean 0.50 (SD = 0.34), t(5) = 1.17, p = 0.296. There was no significant difference in collar fit for shoe C mean 1.00 (SD = 0.82) and shoe D mean 1.00 (SD = 0.82), t(9) = 0.00, p = 1.00.

4.3.2 Relationship between Comfort and Fit to Jump Performance

A trials pooled Pearson Correlation Coefficients was conducted to compare the relationships between comfort and fit.

4.3.2.1 Comfort

The results of the men's team comfort pooled Pearson Correlation Coefficients are presented in Table 4.2. There were significant negative relationships between the men's medial-lateral control comfort and CMJ PPr (r = -0.711, n = 12, p = 0.009), and between overall comfort and CMJ PPr (r = -0.632, n = 12, p = 0.027). There was a significant negative relationship between medial-lateral control comfort and DJ PPr (r = -0.665, n = 12, 0.018).

Table 4.2 Men's team comfort to jumps correlations.

Men's Team Jump Correlations		Arch Height	Heel Cushioning	Forefoot Cushioning	Heel Region	Collar	Medial-Lateral Control	Overall Comfort
CMJ_Peak Power/BW (W/kg)	Pearson Correlation	0.383	-0.488	-0.53	-0.407	-0.492	-.711**	-.632*
	Sig. (2-tailed)	0.22	0.107	0.076	0.189	0.104	0.009	0.027
	N	12	12	12	12	12	12	12
CMJ_Max Height (cm)	Pearson Correlation	0.208	-0.02	-0.198	0.041	-0.209	-0.284	-0.302
	Sig. (2-tailed)	0.517	0.952	0.538	0.899	0.515	0.372	0.34
	N	12	12	12	12	12	12	12
DJ_Peak Power/BW (W/kg)	Pearson Correlation	0.374	-0.488	-0.391	-0.27	-0.278	-.665*	-0.379
	Sig. (2-tailed)	0.231	0.108	0.208	0.396	0.382	0.018	0.224
	N	12	12	12	12	12	12	12
DJ_Max Height (cm)	Pearson Correlation	0.496	-0.454	-0.518	-0.342	-0.383	-0.41	-0.572
	Sig. (2-tailed)	0.101	0.138	0.084	0.276	0.219	0.186	0.052
	N	12	12	12	12	12	12	12
STJ_Peak Power/BW (W/kg)	Pearson Correlation	-0.086	-0.017	0.22	0.237	0.346	-0.038	0.058
	Sig. (2-tailed)	0.791	0.958	0.492	0.459	0.271	0.908	0.858
	N	12	12	12	12	12	12	12
STJ_Max Height (cm)	Pearson Correlation	0.235	-0.309	-0.189	-0.165	-0.152	-0.408	-0.454
	Sig. (2-tailed)	0.463	0.328	0.556	0.607	0.637	0.188	0.138
	N	12	12	12	12	12	12	12
PJ_Peak Power/BW (W/kg)	Pearson Correlation	0.358	-0.274	-0.074	-0.153	-0.081	-0.372	-0.367
	Sig. (2-tailed)	0.253	0.39	0.819	0.635	0.803	0.234	0.241
	N	12	12	12	12	12	12	12
PJ_Max Height (cm)	Pearson Correlation	0.478	-0.455	-0.332	-0.433	-0.425	-0.255	-0.562
	Sig. (2-tailed)	0.116	0.137	0.291	0.16	0.169	0.424	0.057
	N	12	12	12	12	12	12	12

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

The results of the women's team comfort pooled Pearson Correlation Coefficients are presented in Table 4.3. There was a significant negative relationship between the women's collar comfort to DJ PPr (r = -0.457, n = 20, p =0.043). There was a significant positive relationship between heel region comfort and STJ PPr (r = 0.511, n = 20, p = 0.021). There were significant negative relationships between collar comfort and PJ PPr (r = -0.543, n = 20, p = 0.013) and medial-lateral control comfort to PJ PPr (r = -0.502, n = 20, p = 0.024).

Table 4.3 Women's team comfort to jumps correlations.

Women's Team Jump Correlations		Arch Height	Heel Cushioning	Forefoot Cushioning	Heel Region	Collar	Medial-Lateral Control	Overall Comfort
CMJ_Peak Power/BW (W/kg)	Pearson Correlation	-0.167	-0.054	0.044	0.089	-0.203	-0.139	-0.038
	Sig. (2-tailed)	0.483	0.822	0.853	0.709	0.392	0.559	0.874
	N	20	20	20	20	20	20	20
CMJ_Max Height (cm)	Pearson Correlation	-0.009	0.271	0.231	0.38	0.131	0.17	0.388
	Sig. (2-tailed)	0.97	0.247	0.328	0.098	0.583	0.474	0.091
	N	20	20	20	20	20	20	20
DJ_Peak Power/BW (W/kg)	Pearson Correlation	0.018	0.13	0.33	0.056	-.457*	-0.263	-0.045
	Sig. (2-tailed)	0.938	0.584	0.155	0.814	0.043	0.262	0.85
	N	20	20	20	20	20	20	20
DJ_Max Height (cm)	Pearson Correlation	-0.029	0.17	0.127	0.33	-0.036	-0.09	0.159
	Sig. (2-tailed)	0.905	0.474	0.593	0.155	0.88	0.707	0.503
	N	20	20	20	20	20	20	20
STJ_Peak Power/BW (W/kg)	Pearson Correlation	-0.02	0.172	0.221	.511*	0.134	0.183	0.267
	Sig. (2-tailed)	0.933	0.467	0.35	0.021	0.574	0.44	0.254
	N	20	20	20	20	20	20	20
STJ_Max Height (cm)	Pearson Correlation	-0.085	0.077	0.01	0.173	0.07	-0.047	0.175
	Sig. (2-tailed)	0.722	0.748	0.965	0.466	0.77	0.843	0.459
	N	20	20	20	20	20	20	20
PJ_Peak Power/BW (W/kg)	Pearson Correlation	-0.115	-0.037	0.01	-0.216	-.543*	-.502*	-0.194
	Sig. (2-tailed)	0.629	0.876	0.968	0.36	0.013	0.024	0.412
	N	20	20	20	20	20	20	20
PJ_Max Height (cm)	Pearson Correlation	0.13	0.27	0.232	0.35	0.094	0.013	0.253
	Sig. (2-tailed)	0.584	0.249	0.326	0.131	0.695	0.957	0.281
	N	20	20	20	20	20	20	20

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

The men's team was split with three student-athlete average comfort rating higher in shoe A and three in shoe B. The women's team was also split with five student-athlete average comfort ratings higher in shoe C and five in shoe D.

4.3.2.2 Fit

The results of the men's team fit pooled Pearson Correlation Coefficients are presented in Table 4.4. There were significant positive correlations between heel region fit and CMJ PPr (r =0.842, n = 12, p = 0.001) and heel region fit and CMJ PPr (r = 0.636, n =12, p = 0.026). There was a significant positive relationship between heel region fit and DJ PPr (r = 0.675, n = 12, p = 0.016). There was a significant positive relationship in collar fit to DJ max height (r = 0.697, n = 12, p = 0.012). There was a significant positive relationship between heel region fit and STJ max jump height (r = 0.620, n = 12, p = 0.032). There was a significant positive relationship of collar fit to PJ PPr (r = .651, n = 12, p = 0.022).

Table 4.4 Men's team fit to jump correlations.

Men's Team Jump Correlations		Heel Region Fit	Forefoot Width Fit	Collar Fit
CMJ_Peak Power/BW (W/kg)	Pearson Correlation	.842**	0.241	.636*
	Sig. (2-tailed)	0.001	0.45	0.026
	N	12	12	12
CMJ_Max Height (cm)	Pearson Correlation	0.495	-0.063	0.555
	Sig. (2-tailed)	0.102	0.847	0.061
	N	12	12	12
DJ_Peak Power/BW (W/kg)	Pearson Correlation	.675*	0.018	0.276
	Sig. (2-tailed)	0.016	0.956	0.386
	N	12	12	12
DJ_Max Height (cm)	Pearson Correlation	0.545	0.227	.697*
	Sig. (2-tailed)	0.067	0.478	0.012
	N	12	12	12
STJ_Peak Power/BW (W/kg)	Pearson Correlation	0.091	-0.252	-0.114
	Sig. (2-tailed)	0.778	0.43	0.723
	N	12	12	12
STJ_Max Height (cm)	Pearson Correlation	.620*	0.008	0.432
	Sig. (2-tailed)	0.032	0.979	0.161
	N	12	12	12
PJ_Peak Power/BW (W/kg)	Pearson Correlation	0.568	0.179	0.238
	Sig. (2-tailed)	0.054	0.578	0.456
	N	12	12	12
PJ_Max Height (cm)	Pearson Correlation	0.545	0.492	.651*
	Sig. (2-tailed)	0.067	0.104	0.022
	N	12	12	12

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

The results of the women's team fit pooled Pearson Correlation Coefficients are presented in Table 4.5. There were no significant relationships between fit and types of jumps.

Table 4.5 Women's team fit to jump correlations.

Women's Team Jump Correlations		Shoe Length Fit	Heel Region Fit	Forefoot Width Fit	Collar Fit
CMJ_Peak Power/BW (W/kg)	Pearson Correlation	0.125	-0.044	-0.092	-0.013
	Sig. (2-tailed)	0.601	0.855	0.701	0.956
	N	20	20	20	20
CMJ_Max Height (cm)	Pearson Correlation	-0.019	-0.12	-0.022	-0.336
	Sig. (2-tailed)	0.935	0.615	0.928	0.148
	N	20	20	20	20
DJ_Peak Power/BW (W/kg)	Pearson Correlation	0.096	-0.052	-0.385	0.422
	Sig. (2-tailed)	0.686	0.826	0.093	0.064
	N	20	20	20	20
DJ_Max Height (cm)	Pearson Correlation	-0.144	0	-0.092	-0.17
	Sig. (2-tailed)	0.543	0.999	0.699	0.472
	N	20	20	20	20
STJ_Peak Power/BW (W/kg)	Pearson Correlation	-0.184	-0.081	0.105	-0.205
	Sig. (2-tailed)	0.438	0.733	0.659	0.385
	N	20	20	20	20
STJ_Max Height (cm)	Pearson Correlation	-0.194	0.016	-0.036	-0.26
	Sig. (2-tailed)	0.411	0.947	0.88	0.269
	N	20	20	20	20
PJ_Peak Power/BW (W/kg)	Pearson Correlation	0.068	0.199	-0.108	0.163
	Sig. (2-tailed)	0.776	0.4	0.652	0.493
	N	20	20	20	20
PJ_Max Height (cm)	Pearson Correlation	-0.165	-0.047	-0.21	-0.188
	Sig. (2-tailed)	0.488	0.844	0.375	0.428
	N	20	20	20	20

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

The men's team had three student-athletes average fit rating higher in shoe B, one student-athlete rated average fit higher in shoe A, and two student-athletes rated average fit to be the same between shoe A and B. The women's team was split with five players average comfort ratings in shoe A and five in shoe B. In the men's and women's team, the same shoe received higher averaged comfort and fit ratings.

4.4 Discussion

This pilot study used a 110mm VAS comfort assessment tool, it was found that each pair of Adidas basketball shoes evaluated did not score above a 60% average in perceived comfort for the men's and women's MSU basketball student-athletes. No significant comfort difference was found between shoe types for either team. The question of what level of perceived comfort ratings in basketball footwear affects playing performance is individualized. However, extended levels of low comfort may lead to higher levels of discomfort resulting in poor performance and over-use injuries [9, 22]. Of the significant correlations identified, negative correlations were found between medial-lateral control comfort and over-all comfort in men's CMJ PPr and DJ PPr. On the women's team, negative correlations were found in collar comfort related to DJ PPr and PJ PPr, and medial-lateral control comfort to PJ PPr. There was one positive correlated relationship on the women's team which identified heel region comfort to STJ PPr, lending to the potential support of heel comfort to mitigate vertical GRF during the stepping motion in the STJ [16] Caution should be taken on establishing strong meanings behind the correlations due to the small sample size of the men's team, strong jump performers may have skewed the directional relationships. The study did not find any significant shoe comfort characteristics that influenced jump height.

Using a seven-point Likert scale to rate the fit of the shoes, results indicated shoe B having a better fit for the men's team and shoe C for the women's team. Shoe fit was not significantly different between styles for either team or did any of the fit metrics have a relationship to jumping performance.

The purpose of this study was to examine the relationship of comfort and fit to jumping performance. Using an acute basketball specific jump protocol did not yield significant shoe effect on jump performance, however, the survey revealed a concern the student-athletes have on existing Adidas basketball shoes used in practice and during the season.

4.4.1 Limitations

Limitations in this study include the limited number of student-athletes and volume of time each student-athlete spent in the test shoes. In addition, jumping is only part of the game as sprinting forward and backwards and changing direction places additional forces upon the feet. Rating basketball shoes after a practice or game and quantifying movement patterns on the court can help to define the type of forces the athlete places on their feet and quality of shoe comfort and fit.

4.4.2 Future Research

Future investigations into basketball shoe comfort and fit should require longer GRF loading to establish foot-shoe interaction in determining shoe discomfort levels. Understanding how the foot changes shape during high impact movement, and how the shoe responds to game playing styles will influence the level of comfort and fit. Determining equal matching between shoe volume and 3D foot scans may offer a closer fit compared to the use 2d measuring tools. The use of wearable technology to collect on-court data could determine GRFs and assess different shoe types may offer an improved solution to assess in determining proper shoe design and fit.

4.5 Conclusion

Given the complex physical and psychological factors involved in determining levels of shoe comfort and fit the following recommendations can be implemented: (a) use of a VAS comfort assessment tools and Likert rating scales, (b) integrated into the Basketball Shoe

Taxonomy, and (c) correlated to biomechanical loads through the use of force plates or wearable ground reaction pressure sensors can help bring out a clearer understanding of the interplay between shoe comfort and fit to performance and injury mitigation. Feedback from athletes can help manufacturers improve shoe design and provide coaches and trainers insight into the physiological stressors experienced on the court throughout the season. The importance of foot-ground interaction with shoe comfort and fit cannot be overlooked for optimized athletic performance.

CHAPTER V

DEVELOPMENT OF PRESSURE SENSITIVE SOCK UTILIZING SOFT SENSORS

5.1 Introduction

The goal of this study was to develop a wearable solution using compressible soft robotic sensors (C-SRS) to accurately collect data “from the ground up” as defined by the needs of the Strength and Conditioning Coach (S&CC) and Athlete Training (AT) practitioners who commonly rely upon wearable solutions in sports [107] for decisions about health and safety [108]. The aim of this research series was to extend the “Closing the Wearable Gap” paper series where the previous studies used stretchable soft robotic sensors or stretchable SRS to capture both static movements [109] and dynamic movements [110] of the foot-ankle complex as well as to fully quantify gait cycles [111] all through the validation of goodness-of-fit as compared to 3D motion capture. To this point in the paper series, only foot-ankle joint angles from common movements such as plantar flexion (PF), dorsiflexion (DF), inversion (INV), and eversion (EVR), have been evaluated. To fully assess movements occurring in the closed kinetic chain for the lower-body [112] measuring ground reaction forces (GRFs) are critical in determining human performance data “from the ground up” [46].

Research into wearable technology has led to the application of soft sensors applied initially in robotics for use in capturing human movement [107, 109, 113, 114]. Two categories of soft sensors include solid-state and liquid-state sensors, depending on the sensing elements [115]. Regardless of materials, two main types of soft sensors that can be connected to microelectronics include resistive- and capacitive-based sensors [116]. “Resistive sensors convert deformation to change of resistance,” while “capacitive sensors are typically composed of two flat-plate electrodes separated by a dielectric material” [117].

Parameters that soft sensors should be evaluated on include: “sensitivity or gauge factor, stretchability, linearity, hysteresis, response time, drift, dynamic durability, and overshooting behavior” [116]. The importance of sensor linearity and correlation to movement have been reported, and outcomes show that soft sensors can be modeled to measure dynamic human joint kinematics [109]. Resistive sensors have a higher gauge factor but unfortunately show signs of non-linearity as compared to capacitive sensors, which produce high linear outputs [116-122]. The non-linearity of resistive sensors creates challenges in software design to manage and make sense of data output. The use of deep learning neural networks demonstrates promise in taking advantage of the resistive sensors and minimizing their weaknesses [118].

Assessing both resistive and capacitive sensors under a mechanical force have shown that capacitive sensors exhibit greater uniformity across the entire sensor as compared to a resistive sensor, while resistive sensors reported a higher accuracy than the capacitive sensor [122]. Overall recommendations from Marinelli et al. [122] indicate that decisions to use resistive or capacitive sensors for pressure detection should be based on the magnitude of force, relative importance of accuracy, repeatability, and the substrates’ conformity to non-flat surfaces.

Developing a wearable ground reaction pressure sock (GRPS) will require identifying specific pressure points within the foot-shoe interaction. According to Urry, “an ideal force-sensing device will respond identically to two equal forces regardless of either the area over which the force is applied or the point of application of the force” [123]. Various types of pressure insoles are available for athletes to measure the vertical component of the pressure being applied by the foot [124]. F-scan™ system, pedar® mobile system [125], and Loadsol® [126] are products showing promise in improving the portability of capturing human gait. However, a limitation of pressure sensors is the inability to distinguish between normal and directional shear forces [123]. Refinement in capturing 3D deformation during the gait cycle has been achieved using stereoscopic cameras while walking on a glass plate [96]. Ito et al. identified several plantar pressure points including the heel and the ball of the foot as a relevant pressure and strain points during the gait cycle [96]. Placing sensors in these locations can provide the insight necessary to develop the GRPS to measure ground-based movement patterns.

Human Activity Recognition (HAR) is one aspect of the software and hardware integration that uses time-series data from sensors to recognize the movement patterns of the individual [127]. For systems to recognize movement patterns, the use of deep learning software has been shown to be effective. Applying deep learning software to wearable soft sensors can be challenging due to the non-linearity of the stretch and strain properties of sensor types and cost of computing power [118]. A potential solution to the non-linearity problem has been suggested by Miodownik et al., in using a Long Short-Term Memory Neural Network (LSTM) after calibration of a wearable stretch sensor. A solution to reduce the cost of computing power has been identified in the use of an auto regressive-integrated moving average (ARIMA) model in wireless sensor networks [128]. Another benefit of using an ARIMA model is the accuracy of immediate future data estimations; however, model prediction accuracy erodes over extended time [129]. Ma et al. have proposed a solution for erosion over time by using an integrated sliding window feature within the ARIMA model [130]. The use of the sliding window ARIMA model proved effective when used in a mobile Android app to detect driver drowsiness. The app captured the driver’s electrooculography (EOG) signal 0.5 seconds ahead of time, notifying the driver of the potential dozing off while driving. This study uses ARIMA models to predict future data from compressible Stretchsense™ sensors (Auckland, Australia).

5.2 Materials and Methods

In Parts II, III, and IV of "Closing the Wearable Gap" paper series [109-111], the use of stretchable SRS and optical motion capture were used to assess foot-ankle kinematics. Part II captured active range of motion of the four primary foot-ankle joint movements—PF, DF, INV, and EVR—while participants were seated [109]. Part III captured PF and DF during dynamic expected and unexpected slip and trip perturbations [110]. Part IV captured all four foot-ankle joint ranges of motion during multiple gait cycles on flat and tilted surfaces [111]. Given that the primary goal of this continuing research effort is to design a wearable solution that accurately captures data collected at the foot-ankle complex in a non-laboratory environment, developing the GRPS is a continuation of this paper series. This paper, Part V, assesses the use of compressible StretchSense™ sensors to capture foot ground reaction pressures during closed kinetic chain movements in squats, shifting center of pressure right-to-left, and toe-to-heel (anterior to posterior). Therefore, there will be shared similarities in layout, wording, and the goal of developing wearable technology that can measure movement and pressure "from the ground up" originating from the previous papers [109-111].

5.2.1 Participants

Thirteen volunteers participated in this study: eight women (height 165.3 ± 2.2 cm, mass 76.2 ± 13.4 kg, age 32 ± 9.1 yrs.) with a mean U.S. shoe size of 8.6 (SD = 1.12) and five men (height 175.3 ± 6.5 cm, mass 81.1 ± 13.4 kg, age 25.6 ± 4.6 yrs.) with a mean U.S. shoe size of 10 (SD = 1.1). Participant foot sizes are reported in U.S. shoe sizes. This study was approved and conducted under Mississippi State University's (MSU's) Institutional Review Board (IRB; protocol #19-354). Participants reported to the Human Performance Lab (HPL) at the Center for Advanced Vehicular Systems (CAVS). Before performing the test, participants were informed of the testing protocol, they were asked to read and sign an informed consent form, and all their questions about the study protocol were addressed during the pre-test period. All participants reported no recent history of a lower extremity fracture, surgery, or previous ankle sprain in the last six months via a Physical Activity Readiness Questionnaire (PAR-Q) to "determine the safety or possible risk of exercising for an individual based on their health history, and current symptoms and risk factors"[27]. Participant's anthropometric data, including height, weight, age, and shoe size were recorded.

5.2.2 Study Design

The study design followed a single-day testing protocol. A familiarization session was conducted before the experimental testing. All participants were briefed on the procedures and allowed to practice movements prior to testing. In order to effectively validate the C-SRSs, each participant stood on two paper soles allowing for proper placement identification of the calcaneus and ball of the foot, medial aspect of the first metatarsal head, and lateral aspect of the fifth metatarsal head during the experiment. Ten C-SRSs were then placed on a gridded testing platform (TP), transferring boney landmarks from the paper soles to specific cells on the Boditrak Vector Plate™ (BVP, Vista Medical, Winnipeg, Manitoba, Canada). The TP consisted of the ten C-SRSs placed on top of the BVP, which was on top of a 6.35mm rubber flooring surface, which was placed on top of the Kistler™ Force Plates (KFPs, Novi, MI, USA) (Figure 5.1). The TP configuration is based on previous studies validating the use of sensors on pressure mats and force plates, with the additional rubber flooring used to reduce slippage between the

BVP and KFPs [19, 28]. Based on the orientation of the global coordinates defined in The MotionMonitor™ software (Innovative Sports Training, Inc., Chicago, IL, USA), the Z-axis represents the vertical axis, the Y-axis represents the anterior-posterior direction, and the X-axis represents the medial-lateral direction. Figure 5.2 shows the top-down view of the anterior-posterior (A/P) sensor layout and medial-lateral (M/L) sensor layout on top of the BVP.

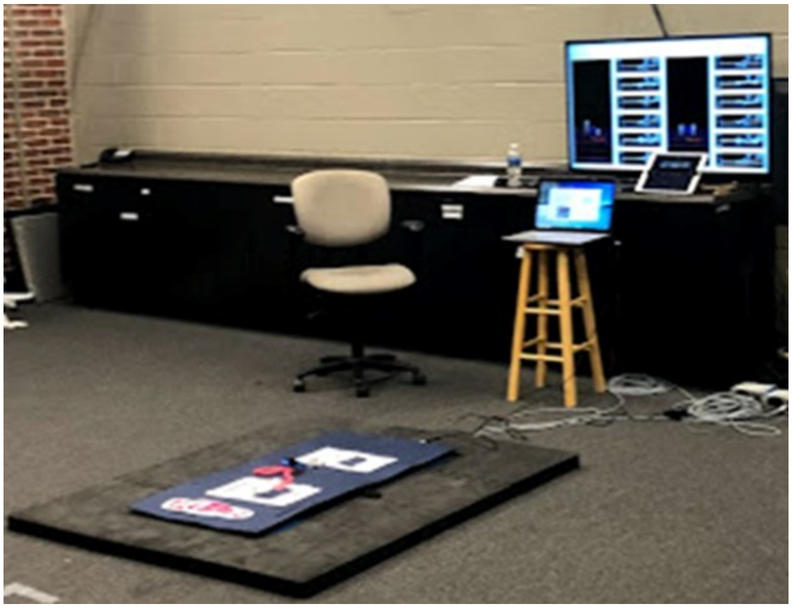


Figure 5.1 Testing platform (TP) consisting of the stacked ten C-SRSs, BVP, and KFPs.

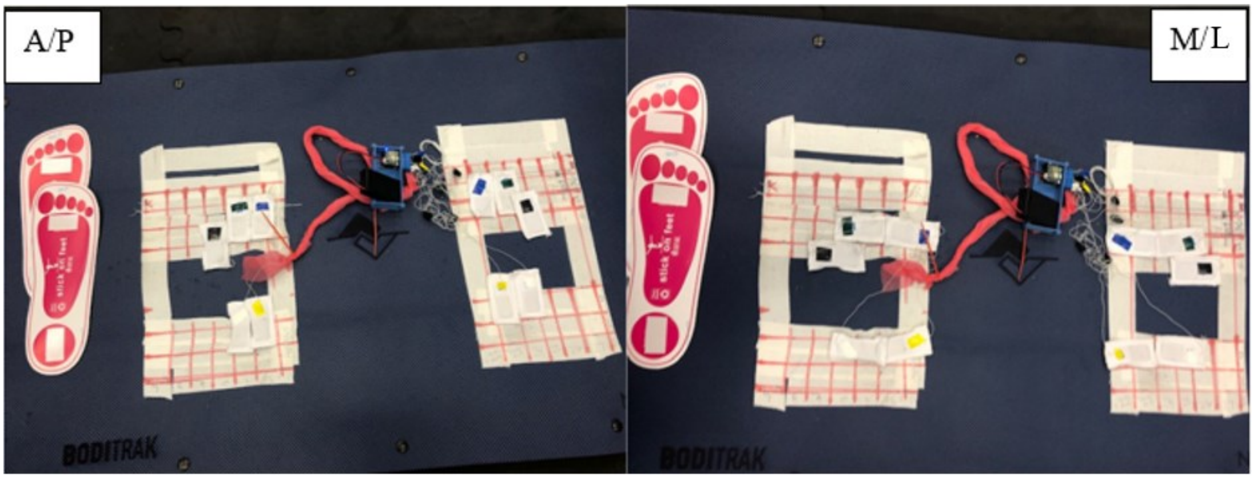


Figure 5.2 Sensor orientation on the gridded BodiTrak Vector Plate. A/P relates to the anterior and posterior direction of the sensors. M/L relates to the medial-lateral direction of the sensors.

5.2.3 Instrumentation and Participant Preparation

The experiment included measurements of ground reaction pressures and forces using a TP consisting of 10 - 32mm x 19mm C-SRSs (Figure 5.2), placed on the BVP which was positioned over a 6.35 mm rubber flooring piece over two KFPs to prevent slipping of the BVP on the KFPs. The BVP is comprised of 512, 2.54 cm2 cells embedded into a ruggedized mat (Figure 5.3). The grid allowed for individual identification of the sensor onto an individual cell of the BVP. The MotionMonitor™ software was used in conjunction with the KFPs to capture, visualize, and record force data.

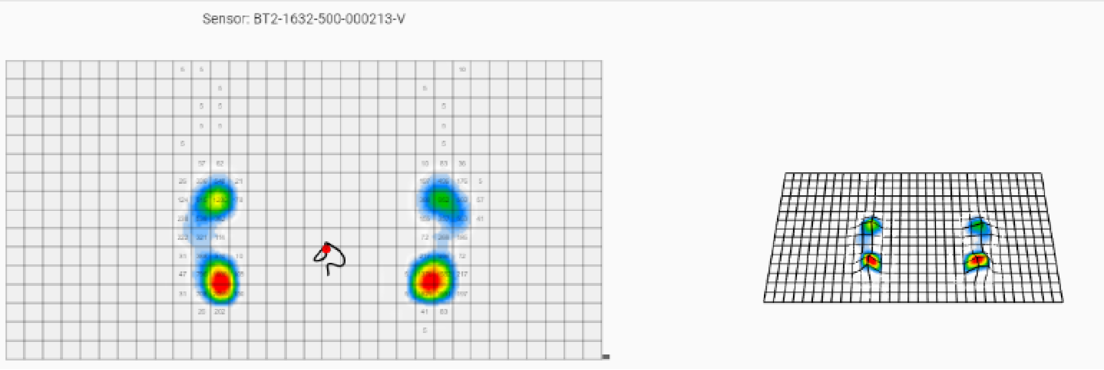


Figure 5.3 Visual heat map of the individual pressure cells and center of pressure output (red dot with trail) from BodiTrak Pro 6.0. White cells indicate 5 mmHg increasing pressures to red indicating 2068.8 mmHg.

5.2.4 Experimental Procedures

All participants were first instructed to read through a participant consent form and freely agree to the intent of the study and methodology. Upon agreement, each participant signed their approval as per the IRB protocol. Participants were asked to take their shoes off and wear socks during the trials. To effectively validate the C-SRSs, each participant was asked to stand on two paper soles allowing for identification of the area of the heel and ball of the foot. Based on the individual's foot size, alignments on the paper soles were then transferred to specific cells on the gridded BVP (Figure 2). Five C-SRSs were placed upon specific cells in the BVP. Placement of the C-SRSs correlated to bony landmarks of the first metatarsal head, second and third metatarsal head (Mid), fifth metatarsal head, and medial and lateral locations under the calcaneus for both feet. The first trial placed the C-SRSs aligned in the anterior-posterior orientation (A/P, Figure 2).

The participant was asked to step on top of the C-SRSs and TP. A validation step was conducted during the first 20 seconds as a baseline and to ensure proper alignment of the sensors under the feet. Upon the researcher's visual validation, three dynamic movements were performed with three repetitions of each movement: squat, shift right to left and shift toe to heel. The participants were instructed to perform the three squats based on their individual and comfortable range of motion. After completion of the squat movement, the participants were instructed to shift right to left, moving their center of mass to the right as the first movement. Upon completion of the second movement, the participants were instructed to shift center of mass forward to their toes and then back onto their heels without losing balance. Upon completion of the first trial, the participant was asked to step off the TP. The researcher then positioned the sensors in the medial-lateral direction within the same BVP cell. The participant was then asked to step back onto the C-SRSs and TP. After the first 20 second validation, the protocol of the three-movement patterns with three repetitions was repeated. After completion of the second trial, the participant was asked to step off which concluded the study. All participants performed the movements in the same order.

5.2.5 Data Processing

C-SRS data was collected via an SS app (ver.3.6) on an iPhone X™ (Apple Inc., Cupertino, CA, USA) at 25 Hz. BBVP pressures were recorded at 25 Hz with a maximum threshold of 2068.8 mmHg on a windows-based laptop operating the BodiTrak™ Pro 6.0 software KFPs were controlled using The MotionMonitor™ software. To compare data from C-SRSs, BVP, and KFPs several steps were taken. First, KFPs data were down-sampled to 25 Hz matching the output from C-SRSs and BVP. C-SRSs output is reported in picoFarads (pF), BVP cell output is reported in mmHg, and KFPs output is in Newtons (N). Second, using Microsoft™ Excel (Redmond, WA, USA, ver. 365) raw data from C-SRS, BVP, and KFPs were trimmed based on locating minimum and maximum values during the movements. Finally, %Δ in C-

SRSs, %Δ BVP and %Δ KFP were calculated based on changes from minimum and maximum values [29, 30] and imported to SPSS™ for statistical analysis. Figure 4 provides an example of overlaid data between two C-SRSs and two individual BVP cells for a participant's left heel during shifting right to left, toe to heel, and squats.

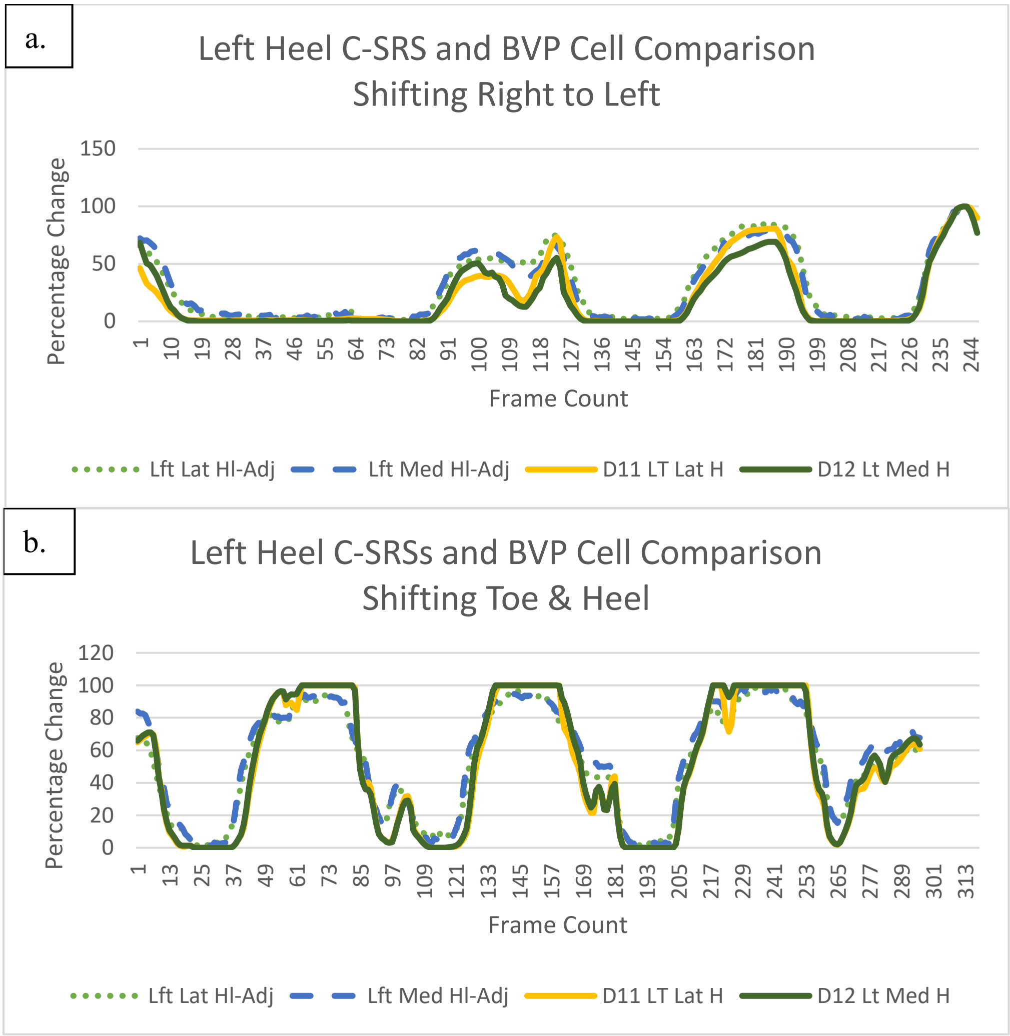


Figure 5.4 Sample data graphed to show percentage change comparisons of BVP cells and left heel C-SRSs in the A/P orientation during (a) shifting right to left, (b) shifting toe to heel, and (c) squatting. The vertical axis represents percentage of change from minimum and maximum over horizontal axis of time. The blue line represents the left lateral heel sensor; the orange line represents the left medial sensor. The grey line represents the individual BVP cell (D11) which correlates to the lateral left heel sensor. The yellow line represents the individual BVP cell (D12) which correlates to the left medial sensor.

c.

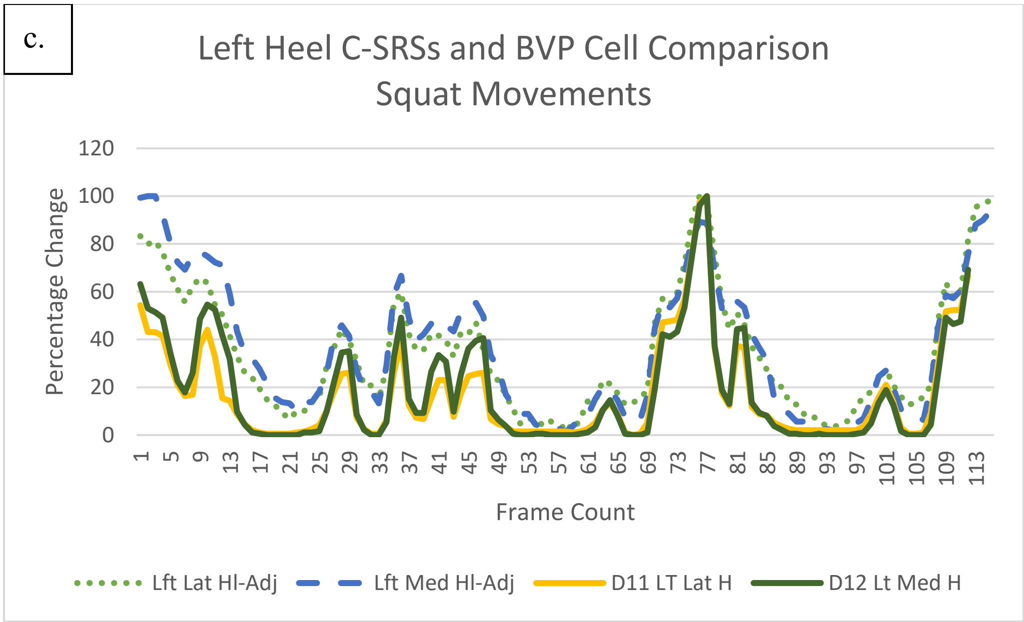


Figure 5.4 (continued)

5.2.6 Statistical Analysis

Each data analysis was performed on a per-sensor basis similar to previous studies [3-5]. In this approach, correlations were generated for each foot %Δ C-SRSs and corresponding %Δ BVP cell, and %Δ KFPs during each type of movement (i.e., Left Lateral Heel C-SRSs compared to D11 BVP cell, Left Medial Heel C-SRSs compared to D12 BVP cell, Left First Metatarsal C-SRSs compared to I12 BVP, Left Mid-Metatarsal C-SRSs compared to I11 BVP, and Fifth Metatarsal C-SRSs modeled toH10 BVP). . Statistical analysis was conducted on %Δ C-SRSs, %Δ BVP, and %Δ KFPs using Pearson Correlation Coefficients, Time Series Expert Modeling, and Paired-Samples t-Test (IBM SPSS™ (ver. 27.0). Results of relationships between C-SRSs to BVP were identified using (a) the shape of the pressure graphs, (b) Pearson Correlation Coefficients, and (c) differences in the coefficient of determination (R2) between percentage changes in pressures.

5.3 Results

5.3.1 Comparison of C-SRS to the BVP

Table 5.1 provides a summary of the descriptive statistics of correlated R values from the thirteen participant's positional C-SRSs and corresponding BVP cells during the three movements of squats, shifting right to left, and shifting toe to heel. A Pearson correlation coefficient analysis was conducted to compare the relationship of C-SRSs to the BVP. Averaged R values greater than 0.70 occurred in 618/780 (79%) of individual sensors. The relative loading of the C-SRSs and BVP varied among participants. The mean correlation for pressure percentage change during the squat was 0.704 (SD = 0.24) for the A/P sensor orientation and 0.682 (SD = 0.222) for the M/L sensor orientation. Trials in the shifting pressure right and left movements resulted in a mean correlation of 0.847 (SD = 0.111) in the A/P sensor position and 0.791 (SD = 0.218) in the M/L sensor orientation. Toe and heel shifting trials resulted in mean correlation of 0.858 (SD = 0.127) for A/P sensor orientation and 0.877 (SD = 0.126) in the M/L sensor orientation.

Table 5.1 Mean and standard deviations of R values from the thirteen participants positional C-SRSs to BVP cells

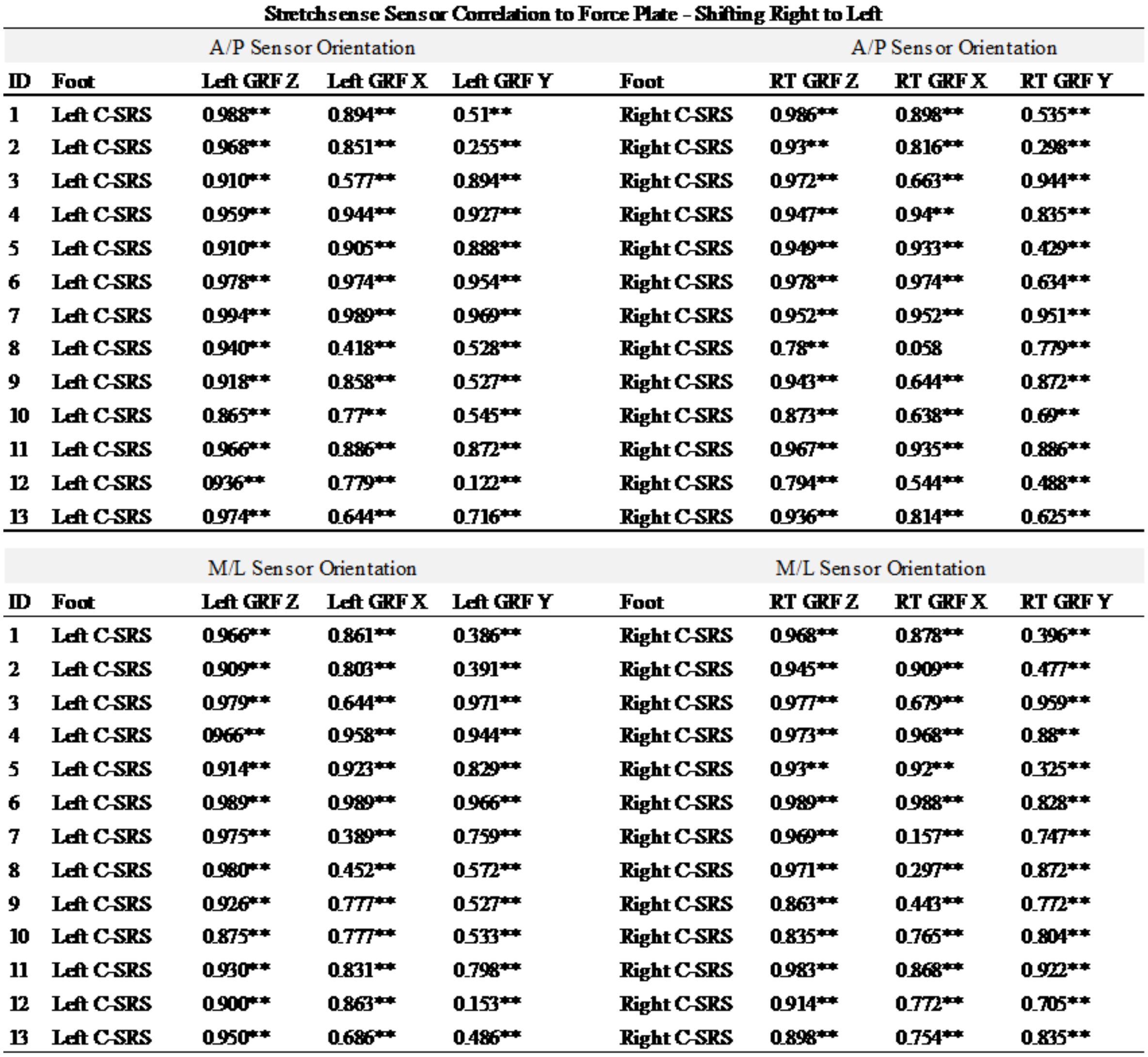
	Left Foot				Right Foot			
	Squat - SSs in A/P Orientation		Squat - SSs in M/L Orientation		Squat - SSs in A/P Orientation		Squat - SSs in M/L Orientation	
	Mean R	SD	Mean R	SD	Mean R	SD	Mean R	SD
Lateral Heel	0.796	0.129	0.789	0.118	0.639	0.312	0.526	0.468
Medial Heel	0.692	0.253	0.659	0.168	0.680	0.336	0.694	0.274
Fifth Metatarsal	0.699	0.258	0.704	0.158	0.690	0.207	0.614	0.255
Mid-Metatarsal	0.681	0.326	0.685	0.224	0.682	0.188	0.753	0.129
First Metatarsal	0.755	0.192	0.652	0.296	0.725	0.195	0.741	0.139
	Right to Left - SSs in A/P Orientation		Right to Left - SSs in M/L Orientation		Right to Left - SSs in A/P Orientation		Right to Left SSs in M/L Orientation	
	Mean R	SD	Mean R	SD	Mean R	SD	Mean R	SD
Lateral Heel	0.9215	0.07602	0.8922	0.22107	0.7853	0.24737	0.8536	0.25175
Medial Heel	0.9272	0.09966	0.8262	0.21608	0.9322	0.02599	0.8369	0.21187
Fifth Metatarsal	0.8949	0.07998	0.8657	0.12188	0.8425	0.10661	0.8193	0.2329
Mid-Metatarsal	0.8345	0.11071	0.7753	0.17819	0.759	0.12235	0.6822	0.25044
First Metatarsal	0.8142	0.078	0.6526	0.2565	0.7612	0.16985	0.705	0.23645
	Toe to Heel - SSs in A/P Orientation		Toe to Heel - SSs in M/L Orientation		Toe to Heel - SSs in A/P Orientation		Toe to Heel - SSs in M/L Orientation	
	Mean R	SD	Mean R	SD	Mean R	SD	Mean R	SD
Lateral Heel	0.932	0.087	0.942	0.058	0.758	0.362	0.810	0.320
Medial Heel	0.911	0.113	0.947	0.031	0.918	0.101	0.945	0.030
Fifth Metatarsal	0.863	0.112	0.859	0.068	0.792	0.086	0.874	0.097
Mid-Metatarsal	0.916	0.075	0.821	0.247	0.874	0.097	0.861	0.159
First Metatarsal	0.861	0.085	0.885	0.092	0.757	0.157	0.826	0.158

5.3.2 Comparison of C-SRS to Force Plates

A Pearson Correlation Coefficients analysis was conducted to compare the sum of pressures [31] %Δ C-SRSs in capacitance to %Δ KFPs during the three-movement patterns (Table 5.2). Determination of center of pressure (COP) changes during movements from C-SRSs was not conducted. Prior to determining COP of movement, validation of C-SRS is required which was accomplished by this study. The complexity of modeling ten different resting values C-SRSs to individual COP movement patterns will be conducted in future work. To obtain accurate understanding of the movement patterns, an absolute value was placed on the correlation values. This is required to recognize that negative values are relating to direction, not decreases in value. The testing platform required the use of rubber flooring to reduce slipping between the BVP on the KFP. Due to the smaller center of mass translations during the squat and shifting toe to heel movement a dampening effect occurred from the rubber flooring reducing the intensity of GRFs. During the shifting in the right to left produced greater translations and magnitudes during the movements resulting in clearer identification of pressure and force changes (Figure 5).

The relative loading of the C-SRSs and KFPs varied among participants. The correlation of pressure and force percentage change during the shifting of center of pressure right to left with sensors in the A/P sensor location resulted in the vertical Z-GRF left foot mean R of 0.947 (SD = 0.038) and the right foot mean R of 0.924 (SD = 0.067). With sensors in the M/L orientation, the shifting of center of pressure right and left resulted in the vertical Z-GRF left foot mean R of 0.943 (SD = 0.036) and the right foot mean R of 0.94 (SD = 0.049). Changes in the lateral X-GRF axis and sensors positioned in the A/P orientation resulted in left foot mean R of 0.810 (SD = 0.168) and right foot mean R of 0.755 (SD = 0.255). In the M/L sensor orientation, changes in the lateral X-GRF resulted in left foot mean R of 0.766 (SD = 0.182) and right foot mean R of 0.723 (SD = 0.264). In the toe and heel direction, Y-GRF axis, with sensors positioned in the A/P orientation, resulted in left foot mean R of 0.670 (SD = 0.279) and right foot mean R of 0.690 (SD = 210). With sensors in the M/L orientation, Y-GRF axis reported left foot mean R of 0.640 (SD = 0.258) and right foot mean of 0.732 (SD = 0.204).

Table 5.2 Pearson Correlation Coefficients comparison of C-SRSs and force plate during right and left shifting.



Stretchsense Sensor Correlation to Force Plate - Shifting Right to Left

		A/P Sensor Orientation				A/P Sensor Orientation		
ID	**Foot**	**Left GRF Z**	**Left GRF X**	**Left GRF Y**	**Foot**	**RT GRF Z**	**RT GRF X**	**RT GRF Y**
1	Left C-SRS	0.988**	0.894**	0.51**	Right C-SRS	0.986**	0.898**	0.535**
2	Left C-SRS	0.968**	0.851**	0.255**	Right C-SRS	0.93**	0.816**	0.298**
3	Left C-SRS	0.910**	0.577**	0.894**	Right C-SRS	0.972**	0.663**	0.944**
4	Left C-SRS	0.959**	0.944**	0.927**	Right C-SRS	0.947**	0.94**	0.835**
5	Left C-SRS	0.910**	0.905**	0.888**	Right C-SRS	0.949**	0.933**	0.429**
6	Left C-SRS	0.978**	0.974**	0.954**	Right C-SRS	0.978**	0.974**	0.634**
7	Left C-SRS	0.994**	0.989**	0.969**	Right C-SRS	0.952**	0.952**	0.951**
8	Left C-SRS	0.940**	0.418**	0.528**	Right C-SRS	0.78**	0.058	0.779**
9	Left C-SRS	0.918**	0.858**	0.527**	Right C-SRS	0.943**	0.644**	0.872**
10	Left C-SRS	0.865**	0.77**	0.545**	Right C-SRS	0.873**	0.638**	0.69**
11	Left C-SRS	0.966**	0.886**	0.872**	Right C-SRS	0.967**	0.935**	0.886**
12	Left C-SRS	0936**	0.779**	0.122**	Right C-SRS	0.794**	0.544**	0.488**
13	Left C-SRS	0.974**	0.644**	0.716**	Right C-SRS	0.936**	0.814**	0.625**

		M/L Sensor Orientation				M/L Sensor Orientation		
ID	**Foot**	**Left GRF Z**	**Left GRF X**	**Left GRF Y**	**Foot**	**RT GRF Z**	**RT GRF X**	**RT GRF Y**
1	Left C-SRS	0.966**	0.861**	0.386**	Right C-SRS	0.968**	0.878**	0.396**
2	Left C-SRS	0.909**	0.803**	0.391**	Right C-SRS	0.945**	0.909**	0.477**
3	Left C-SRS	0.979**	0.644**	0.971**	Right C-SRS	0.977**	0.679**	0.959**
4	Left C-SRS	0966**	0.958**	0.944**	Right C-SRS	0.973**	0.968**	0.88**
5	Left C-SRS	0.914**	0.923**	0.829**	Right C-SRS	0.93**	0.92**	0.325**
6	Left C-SRS	0.989**	0.989**	0.966**	Right C-SRS	0.989**	0.988**	0.828**
7	Left C-SRS	0.975**	0.389**	0.759**	Right C-SRS	0.969**	0.157**	0.747**
8	Left C-SRS	0.980**	0.452**	0.572**	Right C-SRS	0.971**	0.297**	0.872**
9	Left C-SRS	0.926**	0.777**	0.527**	Right C-SRS	0.863**	0.443**	0.772**
10	Left C-SRS	0.875**	0.777**	0.533**	Right C-SRS	0.835**	0.765**	0.804**
11	Left C-SRS	0.930**	0.831**	0.798**	Right C-SRS	0.983**	0.868**	0.922**
12	Left C-SRS	0.900**	0.863**	0.153**	Right C-SRS	0.914**	0.772**	0.705**
13	Left C-SRS	0.950**	0.686**	0.486**	Right C-SRS	0.898**	0.754**	0.835**

** Correlation is significant at the 0.01 level (2-tailed).

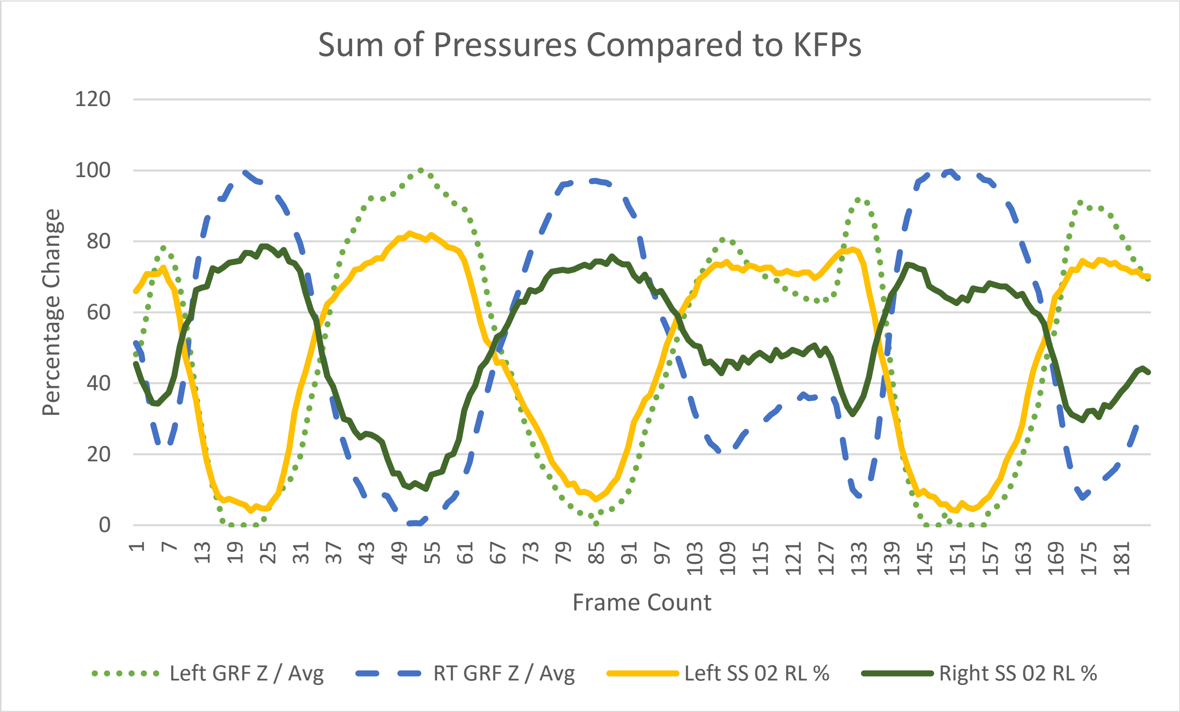


Figure 5.5 Comparison of C-SRSs to KFPs during shifting of right to left with sensors in M/L orientation. The vertical axis represents percentage of change over horizontal axis of time. The blue line represents the sum of pressures percentage changes in the left foot C-SRSs. The grey line represents the vertical (Z-axis) GRFs from the left KFP. The orange line represents the sum of pressures percentage changes in the right foot C-SRSs. The yellow line represents the vertical (Z-axis) GRFs from the right KFP.

5.3.3 Autoregressive Integrated Moving Average

An ARIMA was conducted on the C-SRSs data for the three types of movements, squats, shifting right to left, and shifting toe to heel. This process included an “Expert Modeler that attempts to automatically identify and estimate the best-fitting ARIMA or exponential smoothing model” [131]. The mean squat R^2 value in the A/P sensor orientation was 0.933 (SD = 0.038) and average RMSE was 4.87 (SD = 1.071). The mean squat R^2 value in the M/L orientation was 0.909 (SD = 0.047) and average RMSE value was 5.86 (SD = 1.433) The mean shifting right and left R^2 value in the A/P sensor orientation is 0.956 (SD = 0.043) and average RMSE = 3.61 (SD

= 1.151). The mean shifting right and left R^2 value in the M/L sensor orientation was 0.963 (SD = 0.034) and average RMSE of 3.75 (SD = 0.974) for M/L sensor orientation. The mean shifting toe and heel R^2 value in the A/P sensor orientation was 0.966 (SD = 0.039) and average RMSE = 3.34 (SD = 0.769). The mean shifting toe and heel R^2 value in the M/L sensor orientation an average R^2 is 0.964 (SD = 0.042) and average RMSE of 3.53 (SE = 0.771) for M/L sensor orientation.

5.3.4 Sensor Orientation

A Paired Samples t-Test was conducted to compare C-SRSs orientation on the BVP during all three movements, squats, shifting right to left, and shifting toe to heel. The results of the test indicate no significant difference between A/P and M/L sensor orientations in lateral heel sensor t(77) = 0.076, p = 0.939 and medial heel sensor t(77) = 0.974, p = 0.333. In the metatarsal placed sensors, no significant difference existed in the fifth metatarsal sensors t(77) = 0.292, p = 0.771, the mid-metatarsal sensors t(77) = 1.151, p = 0.253, and the first metatarsal sensors t(77) = 1.446, p = 0.152.

A Paired Samples t-Test was conducted to compare the differences between C-SRSs and KFP GRFs with sensors in the A/P and M/L orientations. The results of the test indicate no significant difference between A/P and M/L sensor orientation in the left foot Z-GRF t(12) = 0.38, p = 0.71, in the X-GRF t(12) = 1.16, p = 0.268, and Y-GRF t(12) = 1.02, p = 0.33. In the right foot, no significant difference existed in the Z-GRF t(12) = -0.8, p = 0.427, X-GRF t(12) = 0.44, p = 0.667, and the Y-GRF t(12) = -1.1, p = 0.301.

5.4 Discussion

The focus of this study was to validate plantar pressure sensor placement, assess the effectiveness of C-SRSs in changes in ground reaction pressure during movement against a pressure mat and force plates, and establish the groundwork for the development a ground reaction pressure sock The results of this study indicate three critical pieces of information: (a) high correlations of R > 0.7 in 79% of the 780 individual cell trials between C-SRSs and BVP for all participant movement patterns indicating that CSRSs can be used to capture normal ground reaction pressures, (b) R2 and RMSE values in ARIMA software modeling of C-SRSs are excellent predictors of future sensor data, and (c) that C-SRSs can be integrated into a wearable sock to capture internal foot-shoe interactions. High R positive values in correlating C-SRSs to the BVP indicates a positive relationship in reactive changes to pressure. High R2 values in the ARIMA modeling indicate a successful ability for software development to model human 3D foot-shoe interaction pressures in the development of the GRPS. RMSE ARIMA model values indicate the absolute measure of error between present and future sensor data. RMSE ARIMA model values in shifting right to left and toe to heel resulted in values below 4% and during the squatting movement below 5%.

The relationship between C-SRSs and the KFPs were inconclusive during the squat movements and shifting from toe to heel. The use of the rubber flooring to improve friction between the BVP and KFPs may have dampened the effect of force transmission during small changes in center of pressure during the movements. Greater translational and magnitude changes in center of pressure occurred during the shifting of right to left resulting in high R values ranging from 0.865 to 0.988 in the 13 participant trials. In developing the GRPS, adjusting calibrations to match the individual will need to be considered. Resting values of the ten C-SRSs were different from each other, requiring software modeling to establish a static baseline for each user as current C-SRSs used are an off-the-shelf solution.

5.4.1 Autoregressive Integrated Moving Average Model (ARIMA)

Using a time series analysis, "ARIMA models predict a dependent variable's present value based on its past values plus values of other explanatory variables" [131]. ARIMA models have shown to be effective with small sample sizes, case studies, and during prevention research in assessing person data monitoring over time [131, 132].

5.4.2 Mean R^2

To determine the goodness of fit of the C-SRSs ARIMA time series modeling, mean R^2 values were calculated from the thirteen participants' time series ARIMA models in both A/P and M/L sensor orientations. Combining all three movements of squats, shifting right to left and toe to heel, resulted in overall mean R^2 value of 0.952 with sensors in the A/P orientation, while in the M/L sensor orientation, mean R^2 value was 0.945. Based on the results, C-SRSs could be aligned in either direction due to the general change in area effect of capacitive sensors [116]. Independently, M/L sensor orientation did have a higher average R^2 value of 0.963 over the A/P sensor R^2 orientation value of 0.956. The relationship of directional forces during the shifting from toe to heel did produce an A/P sensor orientation average R^2 value of 0.966 versus an M/L R^2 value of 0.964. Due to the similar results additional research will need to investigate the relationship between width and length of soft sensors to potentially establish directional pressure and force relationships. To further support the use of C-SRSs in a wearable device, the test reported a strong correlation between the C-SRSs and the KFP during the shifting of right to left, further evidence that using C-SRSs to detect GRF in a wearable can be accomplished but requires further refinement.

5.4.3 Mean RMSE

RMSE values provide insight into the accuracy of the ARIMA time series models. Mean RMSE of the thirteen participants ARIMA models in the A/P sensor orientation resulted in value of 3.94%, while M/L resulted in 4.38%, indicating that sensors in the A/P orientation produced a more accurate model for the three movements in squats, shifting from right to left, and shifting from toe to heel. Due to changes in area in capacitive sensors, directional sensor orientation may not provide the most accurate indication of directional pressures as no significant differences were seen between A/P and M/L sensor orientations.

5.4.4 GRPS Applications and Configurations

The goal of the “Closing the Wearable Gap” paper series is to design a wearable device to replace optical motion capture to measure joint movements and replace pressure mats to capture GRFs. The addition of C-SRSs to the plantar region of the GRPS allows for the measurement of ground reaction pressures providing a solution for the needs of practitioners to accurately capture movement data “from the ground up” [111]. Uses for GRPSs go beyond plantar pressure replacement devices of pressure mats. The development of highly accurate prediction models within the GRPS could also lend itself to potential solutions outside of athletics such as fall detection in elderly and balance impaired individuals. Another application like the ability to alert an individual with poor balance control would be in alerting a driver who is dozing off as previously discussed in the introduction.

In this study, specific plantar pressure regions were identified in the heel and metatarsal heads. Reducing the number of plantar pressure C-SRSs from five to three will reduce the cost of processing and materials in the GRPS. Increasing the size of the plantar pressure sensors will allow for a single heel sensor and two forefoot sensors. To assess lateral and superior shoe pressures, the use of longer and narrower C-SRSs wrapped around the foot can provide specific 3D foot area pressure assessments. Further research will provide specific insight into sensor location and size.

5.4.5 Limitations

Several limitations existed in this study. One limitation was in the frequency at which the C-SRSs operated (25 Hz). Human movement is generally captured at 200 Hz or greater when using optical motion capture and force plates capture data at 1000 Hz. This study examined relatively slow movement patterns. Use of the GRPS during walking, running, jumping, and cutting will require higher data capture rates. Another limitation that existed was with the BVP, which has a 2068.8 mmHg limit per cell. Several times the BVP reached its limit while changes in the C-SRSs were occurring during the movement patterns. To improve upon the study, the C-SRSs could have been placed directly onto the participants' socks identifying center of mass locations of metatarsal heads. Interestingly, few changes in sensor placement relative to the BVP cells were made during the study. This may have been due to the number of participants and closely related foot sizes.

The TP required the use of slip-resistant rubber flooring to prevent the BVP from sliding on the KFPs during movement. The flooring ensured the safety of the participants and allowed for freedom of motion. Due to the dampening effects of the rubber flooring, smaller translational changes in center of pressure were difficult to measure during the squatting and shifting of toe to heel movements. The dampening effect did not affect the shifting right and left as greater translational GRFs were captured. Conducting separate C-SRSs trials on the BVP and KFPs may have provided additional insight into translational center of pressure changes.

5.4.6 Future Research

Additional research is required for the commercial development of using C-SRSs in a gait wearable. Advancements in both hardware and software are needed to achieve a nearly seamless user experience when integrating sensors into garments during real-time play [40]. Increasing the frequency of data captured, determining various size and placements of sensors, and developing improved user experiences are will need to be addressed during the design process. Deep learning techniques can be used to provide individualized assessments of the sensor data to report the wearer’s movements for uses beyond sports such as rehabilitation and prevention of work-related musculoskeletal disorders.

5.5 Conclusion

The results from this study highlight the effectiveness in using C-SRSs to evaluate ground reaction pressures. Correlations, mean R2, and mean RMSE were used to compare the changes in pressure of C-SRSs, changes of pressure on the BVP, and changes in force on the KFPs. Positive linear relationships were identified and visualized between the C-SRSs and BVP in all three movements of squatting, shifting right to left, and shifting toes to heels. Relationships did exist in the shifting right to left between the C-SRSs and KFPs. However, smaller translational GRFs relationships did not exist possibly due to the dampening effect of the rubber flooring used in the TP. Identifying sensor orientation to determine shear pressure changes was inconclusive due to pressure change characteristics of capacitive sensors.

The input of C-SRSs data into an ARIMA model revealed high R2 and low RMSE values (< 5%) indicate a high level of accuracy to predict future outcomes. The rationale for the investigation of applying ARIMA to wearable devices was to identify movement patterns and assess the kinetic frequency and intensity to potentially predict injury thresholds of lower limb kinematics. This study, Part V, builds upon Parts II and IV of the “Closing the Wearable Gap” paper series by adding the capability to measure ground reaction pressures to an in-progress solution with significant potential to accurately capture joint angles of the foot-ankle complex [109, 111].

CHAPTER VI

CONCLUSION OF DISSERTATION

The purpose of these four studies was to use HFE tools to assess basketball shoes as PPEs, specifically their impact on performance, their comfort and fit, and to validate the use of soft sensors for future development of wearable devices in measuring dynamic forces. Conventional research, measuring and collecting data in the lab, is limited compared to the environmental contextual parameters experienced during games and practice.

The first study developed a BST derived from Garvin's "product quality" approach using multidimensional parameters in brand and model, dynamic categorization, biomechanical impact, and dimensions of quality. Understanding the relationship between shoe design and the shoe's effect on injury mitigation and performance can improve the decision-making process in selecting the optimum shoe for each athlete.

The second study examined the influence of shoe design on jumping performance. Using game like jumping patterns, male and female basketball student-athletes completed 16 trials wearing two different pairs of shoes. There was no significant effect of shoes on jump height with either team. Athlete opinion of the shoes varied greatly as some players would never wear one of the shoes tested in practice or a game. The third study involved each athlete completing a survey about the comfort and fit of the shoes worn during the jump test. The test shoes were compared to the "most comfortable basketball shoe they had ever worn". Only one athlete out of 16 considered that one of the shoes tested was the most comfortable basketball shoe they had ever worn. There were two athletes who used orthotics; only one preferred the comfort of their orthotics. Unfortunately, the average comfort rating parameters for both shoes did not exceed 60%. This leaves many unanswered questions as to how the basketball shoes worn truly impact performance or mitigate potential injuries. One participant complained about the shoes that they had worn when first attending MSU and inquired if the shoes could have been a factor in their subsequent lower leg injuries. Future research will need to study the long-term effect of shoes on kinematics and kinetics throughout the season and the addition of motion capture to assess jumping could offer additional insight into altered jump biomechanics.

The final study was designed to validate the use of soft sensors, in this case compressible soft robotic sensors (C-SRSs) during dynamic human movement patterns. Three dynamic movements included three repetitions of squatting, shifting center of pressure between the right foot and left foot, and shifting center of pressure forward and back between the toes and heels were evaluated upon C-SRSs and Boditrak Vector Plate™ (BVP). Applying statistical analysis comparing the C-SRSs to BVP and Kistler Force Plates™ (KFP) provided high average R^2 values which indicate that SSs are an acceptable replacement to systems that measure ground reaction pressures. The use of an Autoregressive Integrated Moving Average (ARIMA) model showed high averaged R^2 values ranging from a low of 90% to a high of 99%. This is encouraging for future research and development of wearable technology in predicting ground reaction pressure movement patterns.

Together, these studies are just the beginning in developing an HFE based dynamic basketball shoe fitting protocol, a performance cause and effect model, and field assessment tools to define optimal performance and safety.

REFERENCES

1. Dul, J., et al., A strategy for human factors/ergonomics: developing the discipline and profession. Ergonomics, 2012. 55(4): p. 377-395.

2. Vu, V., et al., Ankle restrictive firefighting boots alter the lumbar biomechanics during landing tasks. Applied Ergonomics, 2017. 65: p. 123-129 DOI: https://doi.org/10.1016/j.apergo.2017.06.006.

3. Akbar-Khanzadeh, F., M.S. Bisesi, and R.D. Rivas, Comfort of personal protective equipment. Applied ergonomics, 1995. 26(3): p. 195-198.

4. Irzmańska, E., Footwear use at workplace and recommendations for the improvement of its functionality and hygiene. AUTEX Research Journal, 2014. 14(2): p. 89-94.

5. Park, H., et al., Effect of firefighters' personal protective equipment on gait. Applied ergonomics, 2015. 48: p. 42-48.

6. Blanchette, M.G. and C.M. Powers, The influence of footwear tread groove parameters on available friction. Applied Ergonomics, 2015. 50: p. 237-241 DOI: https://doi.org/10.1016/j.apergo.2015.03.018.

7. Chander, H., et al., Impact of military type footwear and workload on heel contact dynamics during slip events. International Journal of Industrial Ergonomics, 2018. 66: p. 18-25 DOI: https://doi.org/10.1016/j.ergon.2018.02.008.

8. Irzmańska, E., Evaluating the comfort of use of protective footwear: Validation of a method based on microclimate parameters and peripheral blood flow. Measurement, 2016. 77: p. 34-39 DOI: https://doi.org/10.1016/j.measurement.2015.08.012.

9. Lam, W.K., T. Sterzing, and J.T.-M. Cheung, Reliability of a basketball specific testing protocol for footwear fit and comfort perception. Footwear Science, 2011. 3(3): p. 151-158.

10. Mündermann, A., et al., Development of a reliable method to assess footwear comfort during running. Gait & Posture, 2002. 16(1): p. 38-45 DOI: https://doi.org/10.1016/S0966-6362(01)00197-7.

11. Sevier, T.L., J.K. Wilson, and B. Helfst, The industrial athlete? Work, 2000. 15(3): p. 203-207.

12. Garvin, D.A., What Does "Product Quality" Really Mean. Sloan management review, 1984. 25 DOI: https://doi.org/10.1080/09544129100000001.

13. Brauner, T., M. Zwinzscher, and T. Sterzing, Basketball footwear requirements are dependent on playing position. Footwear Science, 2012. 4(3): p. 191-198 DOI: https://doi.org/10.1080/19424280.2012.674980.

14. Brizuela, G., et al., The influence of basketball shoes with increased ankle support on shock attenuation and performance in running and jumping. Journal of Sports Sciences, 1997. 15(5): p. 505-515.

15. Fu, W., et al., The effect of high-top and low-top shoes on ankle inversion kinematics and muscle activation in landing on a tilted surface. Journal of foot and ankle research, 2014. 7(1): p. 14.

16. Cámara Tobalina, J., et al., The effect of basketball footwear on the vertical ground reaction force during the landing phase of drop jumps. Revista de psicología del deporte, 2013. 22(1).

17. Blache, Y., A. Beguin, and K. Monteil, Effects of various parameters of basketball shoes on vertical jumping performance: A case study. Science & Sports, 2011. 26(1): p. 48-50.

18. Barisch-Fritz, B., et al., Foot deformation during walking: differences between static and dynamic 3D foot morphology in developing feet. Ergonomics, 2014. 57(6): p. 921-933 DOI: https://doi.org/10.1080/00140139.2014.899629.

19. Hong, W.-H., et al., Influence of heel height and shoe insert on comfort perception and biomechanical performance of young female adults during walking. Foot & ankle international, 2005. 26(12): p. 1042-1048.

20. Hennig, E.M., G.A. Valiant, and Q. Liu, Biomechanical variables and the perception of cushioning for running in various types of footwear. Journal of Applied Biomechanics, 1996. 12(2): p. 143-150.

21. Che, H., B. Nigg, and J. De Koning, Relationship between plantar pressure distribution under the foot and insole comfort. Clinical Biomechanics, 1994. 9(6): p. 335-341.

22. Goonetilleke, R.S., Footwear cushioning: relating objective and subjective measurements. Human Factors, 1999. 41(2): p. 241-256 DOI: https://doi.org/10.1518/001872099779591231.

23. Chen, H., B. Nigg, and J. De Koning, Relationship between plantar pressure distribution under the foot and insole comfort. Clinical Biomechanics, 1994. 9(6): p. 335-341.

24. Mündermann, A., et al., Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. Med Sci Sports Exerc, 2003. 195(9131/03): p. 3510-1710.

25. Nigg, B.M., The role of impact forces and foot pronation: a new paradigm. Clinical journal of sport medicine, 2001. 11(1): p. 2-9.

26. Nigg, B.M., M.A. Nurse, and D.J. Stefanyshyn, Shoe inserts and orthotics for sport and physical activities. Medicine and science in sports and exercise, 1999. 31: p. S421-S428.

27. Zhang, S., et al., Effects of various midsole densities of basketball shoes on impact attenuation during landing activities. Journal of applied biomechanics, 2005. 21(1): p. 3-17.

28. Hildebrandt, S., et al., Quality culture and TQM. Total Quality Management, 1991. 2(1): p. 1-16 DOI: 10.1080/09544129100000001.

29. Edwards, C.D., The meaning of quality. Quality progress, 1968. 1(10): p. 36-39.

30. Kuehn, A.A. and R.L. Day, Strategy of product quality. Harvard Business Review, 1962.

31. Juran, J.M., F.M. Gryna, and R.S. Bingham, Quality control handbook. Vol. 3. 1951: McGraw-Hill New York.

32. Evans, J.R., Quality & performance excellence. 2013: Cengage Learning.

33. Gruner, K.E. and C. Homburg, Does Customer Interaction Enhance New Product Success? Journal of Business Research, 2000. 49(1): p. 1-14 DOI: https://doi.org/10.1016/S0148-2963(99)00013-2.

34. Kumar, N., L.K. Scheer, and J.-B.E. Steenkamp, The effects of supplier fairness on vulnerable resellers. Journal of marketing research, 1995. 32(1): p. 54-65 DOI: https://doi.org/10.1177/002224379503200107

35. Mohr, J. and J.R. Nevin, Communication strategies in marketing channels: A theoretical perspective. Journal of marketing, 1990. 54(4): p. 36-51 DOI: https://doi.org/10.2307/1251758

36. Curtis, C.K., et al., The role of shoe design in ankle sprain rates among collegiate basketball players. Journal of athletic training, 2008. 43(3): p. 230-233 DOI: https://doi.org/10.4085/1062-6050-43.3.230

37. Hartson, R. and P.S. Pyla, The UX Book: Process and guidelines for ensuring a quality user experience. 2012: Elsevier.

38. Cancian, D. NIKE SHOE BLOWOUT: $1.12 BILLION WIPED OFF SWOOSH BRAND'S STOCK AFTER ZION WILLIAMSON'S INJURY. 2019 [cited 2019 4/5/2019].

39. Jones, R. Zion Williamson Comments on His New Nike Sneakers. [Digital] 2019 [cited 2019 March 19].

40. Luczak, T., Burch, R. F., Lewis, E., Chander, H., & Ball, J. , Athletics Wearable Technology State of the Art Review: What 113 strength and conditioning coaches and athletic trainers from the USA said about technology in sports. International Journal of Sports Science and Coaching., 2019 DOI: https://doi.org/10.1177/1747954119885244.

41. Brizuela, G., et al. INFLUENCE OF FOOTWEAR ON THE ANKL SPRAIN PRODUCTION MECHANISM IN BASKETBALL. in ISBS-Conference Proceedings Archive. 1996.

42. Cole, C.L., Nike's America/America's Michael Jordan. Michael Jordan, Inc.: Corporate sport, media culture, and late modern America, 2001: p. 65-103.

43. Rovell, D. NBA signs deal with Nike; logo to appear on uniforms. 2015.

44. Riley Jones, B.R., Zac Dubasik, Matt Welty. The 15 Best NBA Signature Sneakers in Basketball Right Now. 2019.

45. Cong, Y., et al., In-shoe plantar tri-axial stress profiles during maximum-effort cutting maneuvers. Journal of Biomechanics, 2014. 47(16): p. 3799-3806 DOI: https://doi.org/10.1016/j.jbiomech.2014.10.028.

46. Beckham, G., T. Suchomel, and S. Mizuguchi, Force plate use in performance monitoring and sport science testing. New Studies in Athletics, 2014. 3: p. 25-37.

47. McPoil, T.G., Athletic footwear: Design, performance and selection issues. Journal of Science and Medicine in Sport, 2000. 3(3): p. 260-267 DOI: https://doi.org/10.1016/S1440-2440(00)80035-3.

48. Griffin, L.Y., et al., Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. The American journal of sports medicine, 2006. 34(9): p. 1512-1532 DOI: https://doi.org/10.1177/0363546506286866.

49. Chumanov, E.S., et al., Hamstrings are most susceptible to injury during the late swing phase of sprinting. 2012, BMJ Publishing Group Ltd and British Association of Sport and Exercise Medicine.

50. McClay, I.S., et al., A profile of ground reaction forces in professional basketball. Journal of Applied Biomechanics, 1994. 10(3): p. 222-236 DOI: https://doi.org/10.1123/jab.10.3.222

51. Lafortune, M.A., New approach to assess in vivo rearfoot control of court footwear during side-stepping moves. Journal of Applied Biomechanics, 1997. 13(2): p. 197-204 DOI: https://doi.org/10.1123/jab.13.2.197.

52. Lake, M.J., Determining the protective function of sports footwear. Ergonomics, 2000. 43(10): p. 1610-1621 DOI: https://doi.org/10.1080/001401300750004032.

53. Nigg, B. and B. Segesser, Biomechanical and orthopedic concepts in sport shoe construction. Medicine and science in sports and exercise, 1992. 24(5): p. 595-602 DOI: https://doi.org/10.1249/00005768-199205000-00014.

54. Lamberth, J.D., J. Martin, and A. Sanguinetti, Antomical Kinesiology. Vol. 1. 2016, Digital: Kendall Hunt. 247.

55. Oh, Y.K., et al., What strains the anterior cruciate ligament during a pivot landing? The American journal of sports medicine, 2012. 40(3): p. 574-583 DOI: https://doi.org/10.1177/0363546511432544.

56. Cavanagh, P.R. and M.A. Lafortune, Ground reaction forces in distance running. Journal of biomechanics, 1980. 13(5): p. 397-406 DOI: https://doi.org/10.1016/0021-9290(80)90033-0.

57. Snel, J., et al., Shock-absorbing characteristics of running shoes during actual running. Biomechanics IX-B, 1985: p. 133-138.

58. Steindler, A., Kinesiology of the human body under normal and pathological conditions. 1955: Thomas Springfield.

59. Nike, I. Nike PG 3 NASA Basketball Shoe. 2019.

60. Werd, M.B., Athletic Shoe Lacing in Sports Medicine, in Athletic Footwear and Orthoses in Sports Medicine. 2017, Springer. p. 107-114.

61. Caselli, M.A., Selecting the proper athletic shoe. Podiatry Management, 2006. 25(8): p. 147.

62. Füller, J., G. Jawecki, and H. Mühlbacher, Innovation creation by online basketball communities. Journal of Business Research, 2007. 60(1): p. 60-71 DOI: https://doi.org/10.1016/j.jbusres.2006.09.019.

63. Second Spectrum Data. NBAstuffer 2018.

64. Sozzi, B. Why Adidas is taking a radically different approach to sneaker technology. [Web Site] 2019.

65. Chan, M., et al., Smart wearable systems: Current status and future challenges. Artificial Intelligence in Medicine, 2012. 56(3): p. 137-156 DOI: https://doi.org/10.1016/j.artmed.2012.09.003.

66. Chen, M., et al., Wearable 2.0: Enabling Human-Cloud Integration in Next Generation Healthcare Systems. IEEE Communications Magazine, 2017. 55(1): p. 54-61 DOI: 10.1109/MCOM.2017.1600410CM.

67. Hertel, J., Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. Journal of athletic training, 2002. 37(4): p. 364.

68. Kovács, I., et al., Foot placement modifies kinematics and kinetics during drop jumping. Medicine and Science in Sports and Exercise, 1999. 31: p. 708-716.

69. Harry, J.R., et al., Effects of footwear condition on maximal jumping performance. The Journal of Strength & Conditioning Research, 2015. 29(6): p. 1657-1665.

70. Baker, D., Improving vertical jump performance through general, special, and specific strength training. Journal of strength and Conditioning Research, 1996. 10: p. 131-136.

71. Komi, P.V. and C. Bosco, Muscles by men and women. Med Sci Sport, 1978. 10: p. 261-5.

72. Harman, E.A., et al., The effects of arms and countermovement on vertical jumping. Med Sci Sports Exerc, 1990. 22(6): p. 825-833.

73. Boden, B.P., et al., Mechanisms of anterior cruciate ligament injury. Orthopedics, 2000. 23(6): p. 573-578.

74. Bates, N.A., et al., Impact differences in ground reaction force and center of mass between the first and second landing phases of a drop vertical jump and their implications for injury risk assessment. Journal of Biomechanics, 2013. 46(7): p. 1237-1241 DOI: https://doi.org/10.1016/j.jbiomech.2013.02.024.

75. Woodard, C.M., M.K. James, and S.P. Messier, Computational methods used in the determination of loading rate: Experimental and clinical implications. Journal of Applied Biomechanics, 1999. 15(4): p. 404-417.

76. Leong, H.F., et al., Center of Pressure and Perceived Stability in Basketball Shoes With Soft and Hard Midsoles. Journal of applied biomechanics, 2018. 34(4): p. 284-290 DOI: 10.1123/jab.2017-0120.

77. Lam, G.W.K., et al., Shoe collar height effect on athletic performance, ankle joint kinematics and kinetics during unanticipated maximum-effort side-cutting performance. Journal of sports sciences, 2015. 33(16): p. 1738-1749.

78. Faiss, R., et al., Influence of initial foot dorsal flexion on vertical jump and running performance. The Journal of Strength & Conditioning Research, 2010. 24(9): p. 2352-2357.

79. Thomas, S., J. Reading, and R.J. Shephard, Revision of the physical activity readiness questionnaire (PAR-Q). Canadian journal of sport sciences, 1992.

80. Mohr, M., et al., Increased athletic performance in lighter basketball shoes: shoe or psychology effect? International journal of sports physiology and performance, 2016. 11(1): p. 74-79.

81. Worobets, J. and J.W. Wannop, Influence of basketball shoe mass, outsole traction, and forefoot bending stiffness on three athletic movements. Sports Biomechanics, 2015. 14(3): p. 351-360.

82. McNeal, J.R., W.A. Sands, and M.H. Stone, Effects of fatigue on kinetic and kinematic variables during a 60-second repeated jumps test. International Journal of Sports Physiology and Performance, 2010. 5(2): p. 218-229.

83. Mullineaux, D.R., et al., Normalization of ground reaction forces. Journal of applied biomechanics, 2006. 22(3): p. 230-233.

84. Kong, P.W. and M. Bagdon, Shoe preference based on subjective comfort for walking and running. Journal of the American Podiatric Medical Association, 2010. 100(6): p. 456-462.

85. Card, S., T.P. Moran, and A. Newell, The model human processor- An engineering model of human performance. Handbook of perception and human performance., 1986. 2: p. 45-1.

86. Hertzberg, H.T.E., The human buttocks in sitting: pressures, patterns, and palliatives. 1972, SAE Technical Paper.

87. Zhang, L., M.G. Helander, and C.G. Drury, Identifying factors of comfort and discomfort in sitting. Human factors, 1996. 38(3): p. 377-389.

88. Helander, M.G. and L. Zhang, Field studies of comfort and discomfort in sitting. Ergonomics, 1997. 40(9): p. 895-915 DOI: https://doi.org/10.1080/001401397187739.

89. Llana, S., et al., A study of the discomfort associated with tennis shoes. Journal of Sports Sciences, 2002. 20(9): p. 671-679.

90. Borg, G.A., Psychophysical bases of perceived exertion. Med sci sports exerc, 1982. 14(5): p. 377-381.

91. Pontrelli, G., Partial analysis of comfort's gestalt. Clothing comfort: Interaction of thermal, ventilation, construction, and assessment factors, 1977: p. 71-80.

92. Knight, J.F., et al. Assessing the wearability of wearable computers. in 2006 10th IEEE International Symposium on Wearable Computers. 2006. IEEE.

93. Cheng, Y.L. and Y. Hong, Using size and pressure measurement to quantify fit of running shoes. Footwear Science, 2010. 2(3): p. 149-158 DOI: https://doi.org/10.1080/19424280.2010.520678.

94. Herbaut, A., et al., A reliable measure of footwear upper comfort enabled by an innovative sock equipped with textile pressure sensors. Ergonomics, 2016. 59(10): p. 1327-1334 DOI: 10.1080/00140139.2016.1142122.

95. Coudert, T., et al. A method to obtain 3D foot shape deformation during the gait cycle. in Proceedings of the 9th international symposium on the 3D analysis of human movement. 2006.

96. Ito, K., et al., Dynamic measurement of surface strain distribution on the foot during walking. Journal of the Mechanical Behavior of Biomedical Materials, 2017. 69: p. 249-256 DOI: https://doi.org/10.1016/j.jmbbm.2016.12.009.

97. Chen, L.-H., et al., Comparison of foot shape between recreational sprinters and non-habitual exercisers using 3D scanning data. International Journal of Industrial Ergonomics, 2018. 68: p. 337-343 DOI: https://doi.org/10.1016/j.ergon.2018.08.006.

98. Riley, P.O., et al., Foot kinematics and loading of professional athletes in American football-specific tasks. Gait & Posture, 2013. 38(4): p. 563-569 DOI: https://doi.org/10.1016/j.gaitpost.2012.03.034.

99. Shorten, M. Biomechanically driven developments in sports shoe technology: the example of tuned air. in Proceedings of the 4th Symposium on Footwear Biomechanics. 1999.

100. Robbins, S.E. and G.J. Gouw, Athletic footwear: unsafe due to perceptual illusions. Medicine & Science in Sports & Exercise., 1991.

101. Robbins, S.E., & Gouw, G. J. , Athletic footwear and chronic overloading. Sports Medicine, 1990. 9(2): p. 76-85.

102. Milani, T.L., E.M. Hennig, and M.A. Lafortune, Perceptual and biomechanical variables for running in identical shoe constructions with varying midsole hardness. Clinical biomechanics, 1997. 12(5): p. 294-300.

103. Milgrom, C., et al., Prevention of overuse injuries of the foot by improved shoe shock attenuation. Clin Orthop, 1992. 281(281): p. 189-92.

104. Stefanyshyn, D. and B. Nigg, Energy aspects associated with sport shoes. Sportverletzung· Sportschaden, 2000. 14(03): p. 82-89.

105. Page, A., et al., Furniture design based on subjective tests. Application of discriminant analysis methods. . In IEA’94, Proceddings of the 12 th Congress of the International Ergonomics Association., 1994.

106. Page, A., et al. Furniture design based on subjective tests. Application of discriminant analysis methods. in IEA’94, Proceddings of the 12 th Congress of the International Ergonomics Association. 1994.

107. Luczak, T., et al., Closing the wearable gap: mobile systems for kinematic signal monitoring of the foot and ankle. Electronics, 2018. 7(7): p. 117 DOI: https://doi.org/10.3390/electronics7070117.

108. Luczak, T., et al., State-of-the-art review of athletic wearable technology: What 113 strength and conditioning coaches and athletic trainers from the USA said about technology in sports. International Journal of Sports Science & Coaching, 2019: p. 1747954119885244.

109. Saucier, D., et al., Closing the Wearable Gap—Part II: Sensor Orientation and Placement for Foot and Ankle Joint Kinematic Measurements. Sensors, 2019. 19(16): p. 3509 DOI: https://doi.org/10.3390/s19163509.

110. Chander, H., et al., Closing the Wearable Gap—Part III: Use of Stretch Sensors in Detecting Ankle Joint Kinematics During Unexpected and Expected Slip and Trip Perturbations. Electronics, 2019. 8(10): p. 1083 DOI: https://doi.org/10.3390/electronics8101083.

111. Saucier D, D.S., Turner A, Luczak T, Nguyen P, Carroll W, F. Burch V. R, Ball JE, Smith BK, Chander H, Knight A, Prabhu RK., Closing the Wearable Gap—Part IV: 3D Motion Capture Cameras Versus Soft Robotic Sensors Comparison of Gait Movement Assessment. Electronics. Electronics, 2019;. 8(12) DOI: https://doi.org/10.3390/electronics8121382.

112. Bunton, E.E., et al., The role of limb torque, muscle action and proprioception during closed kinetic chain rehabilitation of the lower extremity. Journal of Athletic Training, 1993. 28(1): p. 10.

113. Mengüç, Y., et al. Soft wearable motion sensing suit for lower limb biomechanics measurements. in Robotics and Automation (ICRA), 2013 IEEE International Conference on. 2013. IEEE DOI: https://doi.org/10.1109/icra.2013.6631337.

114. Trung, T.Q. and N.E. Lee, Flexible and Stretchable Physical Sensor Integrated Platforms for Wearable Human-Activity Monitoringand Personal Healthcare. Advanced materials, 2016. 28(22): p. 4338-4372 DOI: https://doi.org/10.1002/adma.201504244.

115. Yeo, J.C. and C.T. Lim, Emerging flexible and wearable physical sensing platforms for healthcare and biomedical applications. Microsystems & Nanoengineering, 2016. 2 DOI: https://doi.org/10.1038/micronano.2016.43.

116. Atalay, A., et al., Batch Fabrication of Customizable Silicone-Textile Composite Capacitive Strain Sensors for Human Motion Tracking. Advanced Materials Technologies, 2017 DOI: https://doi.org/10.1002/admt.201700136.

117. Yin, J., et al., Measuring Dynamic Shear Force and Vibration With a Bioinspired Tactile Sensor Skin. IEEE Sensors Journal, 2018. 18(9): p. 3544-3553 DOI: https://doi.org/10.1109/JSEN.2018.2811407.

118. Miodownik, M., et al., A deep learning approach to non-linearity in wearable stretch sensors. Frontiers in Robotics and AI, 2019. 6: p. 27 DOI: https://doi.org/10.3389/frobt.2019.00027.

119. Cai, L., et al., Super-stretchable, transparent carbon nanotube-based capacitive strain sensors for human motion detection. Scientific reports, 2013. 3: p. 3048 DOI: https://doi.org/10.1038/srep03048.

120. Yao, S. and Y. Zhu, Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires. Nanoscale, 2014. 6(4): p. 2345-2352 DOI: https://doi.org/10.1039/c3nr05496a.

121. Amjadi, M., et al., Stretchable, skin-mountable, and wearable strain sensors and their potential applications: a review. Advanced Functional Materials, 2016. 26(11): p. 1678-1698 DOI: https://doi.org/10.1002/adfm.201504755.

122. Martinelli, L., C. Hurschler, and D. Rosenbaum, Comparison of capacitive versus resistive joint contact stress sensors. Clinical Orthopaedics and Related Research®, 2006. 447: p. 214-220 DOI: https://doi.org/10.1097/01.blo.0000218730.59838.6a.

123. Urry, S., Plantar pressure-measurement sensors. Measurement science and technology, 1999. 10(1): p. R16 DOI: https://doi.org/10.1088/0957-0233/10/1/017.

124. Chesnin, K.J., L. Selby-Silverstein, and M.P. Besser, Comparison of an in-shoe pressure measurement device to a force plate: concurrent validity of center of pressure measurements. Gait & posture, 2000. 12(2): p. 128-133 DOI: https://doi.org/10.1016/S0966-6362(00)00071-0.

125. Saito, M., et al., An in-shoe device to measure plantar pressure during daily human activity. Medical Engineering & Physics, 2011. 33(5): p. 638-645 DOI: https://doi.org/10.1016/j.medengphy.2011.01.001.

126. Renner, K.E., D. Williams, and R.M. Queen, The reliability and validity of the Loadsol® under various walking and running conditions. Sensors, 2019. 19(2): p. 265 DOI: https://doi.org/10.3390/s19020265.

127. Ravi, D., et al., A deep learning approach to on-node sensor data analytics for mobile or wearable devices. IEEE journal of biomedical and health informatics, 2016. 21(1): p. 56-64 DOI: https://doi.org/10.1109/JBHI.2016.2633287.

128. Li, G. and Y. Wang, Automatic ARIMA modeling-based data aggregation scheme in wireless sensor networks. EURASIP Journal on Wireless Communications and Networking, 2013. 2013(1): p. 85 DOI: https://doi.org/10.1186/1687-1499-2013-85.

129. Connor, J.T., R.D. Martin, and L.E. Atlas, Recurrent neural networks and robust time series prediction. IEEE transactions on neural networks, 1994. 5(2): p. 240-254 DOI: https://doi.org/10.1109/72.279188.

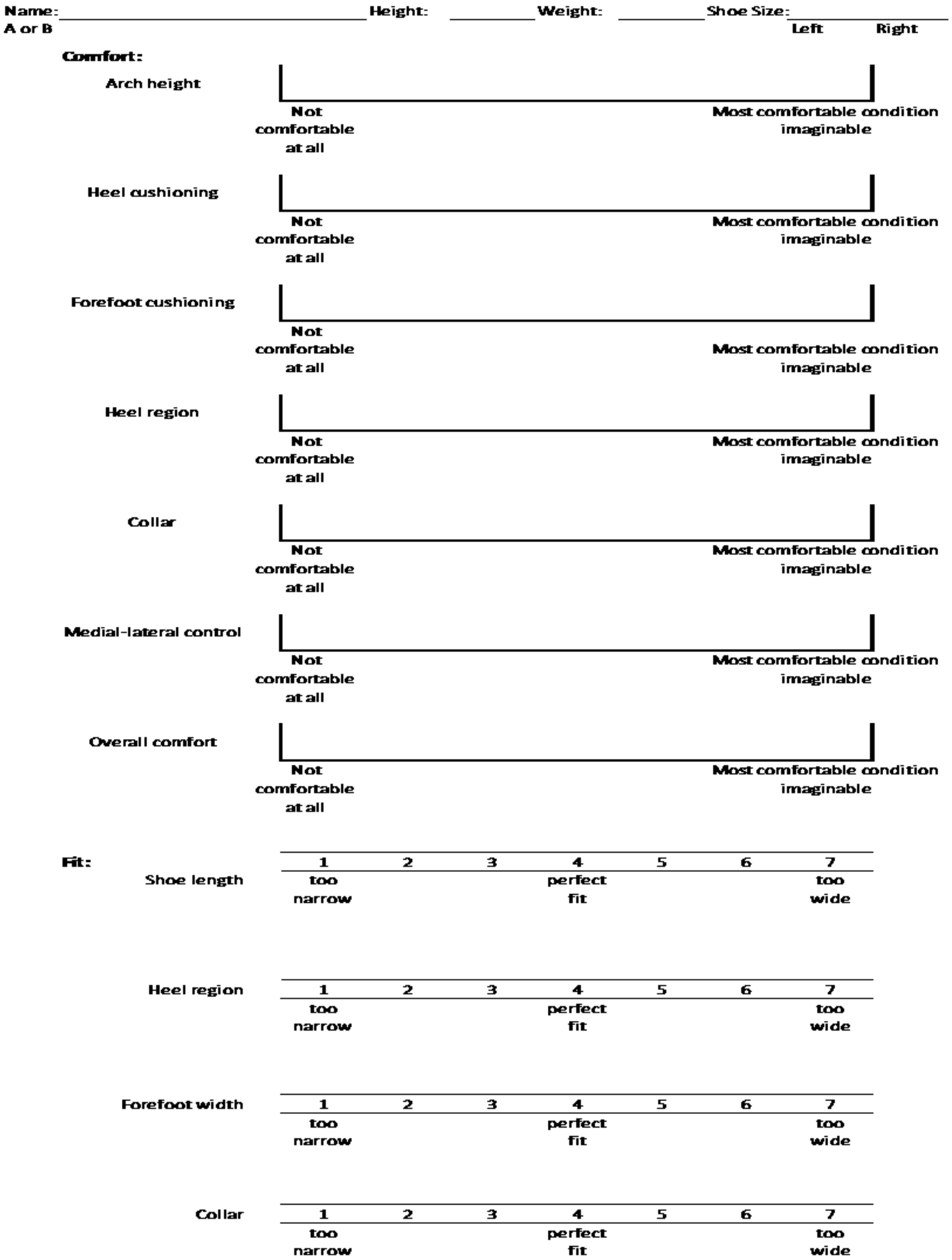
130. Ma, Z., B.C. Li, and Z. Yan. Wearable driver drowsiness detection using electrooculography signal. in 2016 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet). 2016. IEEE DOI: https://doi.org/10.1109/WISNET.2016.7444317.

131. Doherty, S.T. and S.P. Greaves, Time-series analysis of continuously monitored blood glucose: the impacts of geographic and daily lifestyle factors. Journal of diabetes research, 2015. 2015: p. 804341-804341 DOI: https://doi.org/10.1155/2015/804341.

132. Ridenour, T.A., et al., Toward rigorous idiographic research in prevention science: Comparison between three analytic strategies for testing preventive intervention in very small samples. Prevention Science, 2013. 14(3): p. 267-278 DOI: https://doi.org/10.1007/s11121-012-0311-4.

APPENDIX A

BASKETBALL COMFORT AND FIT SURVEY WITH DESCRIPTIONS



Name:____________________________ **Height:** ________ **Weight:** ________ **Shoe Size:**______________

A or B **Left** **Right**

Comfort:

Arch height
Not comfortable at all — Most comfortable condition imaginable

Heel cushioning
Not comfortable at all — Most comfortable condition imaginable

Forefoot cushioning
Not comfortable at all — Most comfortable condition imaginable

Heel region
Not comfortable at all — Most comfortable condition imaginable

Collar
Not comfortable at all — Most comfortable condition imaginable

Medial-lateral control
Not comfortable at all — Most comfortable condition imaginable

Overall comfort
Not comfortable at all — Most comfortable condition imaginable

Fit:

	1	2	3	4	5	6	7
Shoe length	too narrow			perfect fit			too wide
Heel region	too narrow			perfect fit			too wide
Forefoot width	too narrow			perfect fit			too wide
Collar	too narrow			perfect fit			too wide

Figure A.1 – VAS basketball shoe comfort and fit assessment tool [9].

Figure A.2 – VAS basketball shoe comfort and fit assessment tool definitions