IOWA STATE UNIVERSITY
Digital Repository

Graduate Theses and Dissertations

Iowa State University Capstones, Theses and Dissertations

2013

Biomechanical impact of lower-body PPE on the football athlete: An evaluation and redesign of the knee pad

Brandon F. Moeller
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/etd

Part of the Biomechanics Commons, Engineering Commons, and the Graphic Design Commons

Recommended Citation
Moeller, Brandon F., "Biomechanical impact of lower-body PPE on the football athlete: An evaluation and redesign of the knee pad" (2013). *Graduate Theses and Dissertations*. 13152.
https://lib.dr.iastate.edu/etd/13152

This Thesis is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

المنارة للاستشارات

www.manaraa.com

Biomechanical impact of lower-body PPE on the football athlete: An evaluation and redesign of the knee pad

by

Brandon F. Moeller

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Dr. Richard T. Stone, Major Professor
Timothy R. Derrick
Max D. Morris

Iowa State University
Ames, Iowa
2013

Copyright © Brandon F. Moeller, 2013. All rights reserved.

المنارة للاستشارات

www.manaraa.com

DEDICATION

I dedicate this research to my brothers and coaches at Wartburg College for their help in developing this topic and making it reality. HEP! Yeah Knights!

www.manaraa.com

TABLE OF CONTENTS

	Page
DEDICATION	ii
NOMENCLATURE	v
ACKNOWLEDGEMENTS	vi
ABSTRACT	vii
CHAPTER 1. INTRODUCTION	1
[Background]	1
[Seeking Functional Design]	2
[Development and History of PPE]	2
[Modification and Future of PPE]	5
[VAPPR pads]	7
CHAPTER 2. METHODS	9
[Player Surveys]	9
[Drop Test]	9
[VAPPR Pad Design]	10
[Data Collection]	11
[Performance Drill testing: Wartburg College]	11
[Gait Analysis testing: Iowa State University]	13
[Data Processing]	14
CHAPTER 3. RESULTS	15
[Design Theme Hierarchy]	15
[Performance Drill testing: ANOVA with repeated measures]	16
[Gait Analysis testing: Propulsive Impulse]	18

المنارة للاستشارات

www.manaraa.com

Page

CHAPTER 4. DISCUSSION 20

[Knee Pads brought up to speed] 20
[User-Centered Design Approach] 21
[VAPPR – Standard: safety] 22
[VAPPR – Standard: preference] 25
[VAPPR – Standard: performance] 27

CHAPTER 5. CONCLUSION 30

REFERENCES 31

APPENDIX A 36

APPENDIX B 38

APPENDIX C 39

APPENDIX D 40

APPENDIX E 41

APPENDIX F 42

APPENDIX G 43

APPENDIX H 44

APPENDIX I 45

المنارة للاستشارات

www.manaraa.com

NOMENCLATURE

Football	American Football (professional league – NFL)
PPE	Personal Protective Equipment
VAPPR	Vastus and Patella Protection with Range of motion (pad)
GRF	Ground Reaction Force (collected via force plate in Gait Analysis)
ML	Morel-Lavallée knee lesion
RoM	Joint Range of Motion (collected via markers in Gait Analysis)

المنارة للاستشارات
www.manaraa.com

ACKNOWLEDGEMENTS

I would like to thank my committee chair and advising professor, Dr. Richard T. Stone, for backing this research topic that was only a dream when I first visited the IMSE department. Also, I thank my committee members, Timothy R. Derrick and Max D. Morris, for their guidance and support throughout the course of this research. Finally, a thank you to my research partners Nate Moeller and Evan Day for their assistance and expertise during the data collection process.

In addition, I want to thank: my manufacturing colleagues/bosses, Dr. Matthew C. Frank, Dr. Frank Peters, and Kevin Brownsfield for making my working life in graduate school extremely enjoyable; and Lori, Devna, Donna, and Kristi for their help in keeping my head attached to my body when organizational and scheduling details seemed overwhelming.

A special thank you goes out to my family and friends for their encouragement and to my beautiful fiancé for supporting my ambition to obtain this degree.

Finally, I want to offer my personal appreciation to all those who were willing to donate their time and effort through participation in this study: Jason Shupp, Ryan Wurtz, Dan Myznik, Chad Crawford, Clayton Werkman, Curt Hruska, Alex Covington, Garret McGrane, Ross Naylor, Devon Reese, John Mallen, Logan Hanson, Kyle McKenna, Ryan Frahm, George Zacharakis-Jutz, Sam Berg, Cory Davis, Trent Klocke, Grant Riesberg, Zach Clarey, Morgan Hampel, Charles Heidrick, Vince Kaliwata, Matt Wickert, Mitch Blythe, and Charley Forey.

www.manaraa.com

ABSTRACT

Although football personal protective equipment (PPE) has developed considerably since the game's conception, knee pad design has lagged behind. Players at all levels of competition are dissatisfied with the device, claiming it impedes performance more than it protects from injury. To date, no published research has studied the football knee pad's effect on athletic performance, and no ergonomic evaluation of the design has been completed.

This research first created a new knee pad design based on survey feedback from 138 collegiate and high school football athletes. This new design, called the Vastus And Patella Protection with Range of motion (VAPPR) pad, was then tested for effectiveness. During testing, 10 collegiate athletes performed standardized football drills (Pro-Agility, L-Drill, Broad-Jump) under three padded conditions: unpadded, standard knee pad, VAPPR pad. Results were based on three padded comparisons. First, athletes performed at a higher level unpadded than wearing standard knee pads. Second, no difference in performance existed between testing unpadded and with VAPPR pads. Third, VAPPR pads resulted in superior performance, provided equal protection, and were preferred by athletes when compared to standard knee pads.

www.manaraa.com

CHAPTER 1. INTRODUCTION

Background

Football is the most popular game in the United States, and interest is growing. Player participation has increased over 16% at the collegiate level since the 2001-2002 season (58,090 in ’01-’02 : 69,643 in ’11-’12), and participation has been over 1 million at the high school level since documentation of participation began in 2006-2007 (NCAA *participation*, 2012; NFHS *participation*, 2012). Football is also the leading cause of sports-related injury, resulting in 8.61 injuries per 1000 athlete exposures at the collegiate level, and 4.36 at the high school level (Powell, 1999; Shankar et al., 2007). Given the physical nature of the game, these injury statistics are not surprising, and many pieces of personal protective equipment (PPE) have been introduced over the game’s history to guard against a variety of injuries (Figure 1). However, it is surprising that many football athletes are dissatisfied and prefer not to wear one customary piece of PPE – the standard knee pad.

Figure 1: standard football PPE

The principle investigator (BFM) has personal experience regarding this issue as a result of a four year career competing at the collegiate level. During this time at Wartburg College, many hours were spent modifying the standard knee pads issued to all players on the team at the start of each season. Applying basic human factors and ergonomics principles to this experience, it is clear that knee pad design is flawed and needs to be reevaluated.

www.manaraa.com

Seeking Functional Design

A common design cliché notes that form should follow function, and determining function was where an evaluation of the standard knee pad design would start. The question must be asked – what is the purpose of a knee pad? Statistically, the most injured part of the body in football athletes is the knee, but a large majority of those injuries consist of tendon and ligament damage (Pritchett, 1982; Culpepper & Niemann, 1983; Shankar et al., 2007; Feeley et al., 2008). In fact, no research exists that seeks to quantify the number of injuries avoided by use of lower-body PPE. Due to the lack of specific injury data and the fact that the knee pad is a required piece of equipment at the high school and collegiate level, a more primitive understanding of the intended purpose of the knee pad was sought. Therefore, a more basic form of the question became – what is the purpose of a piece of padding? Gerrard (1998) noted a concise definition of protective padding during his research into the use of PPE in professional rugby:

> "Padding is most commonly seen as the use of any material with impact absorption qualities that is applied to vulnerable body parts to minimize the effects of direct contact."

The most important component of this analysis is the mention of preventing direct contact injuries through use of padding. In short, the function of any piece of padding is to avoid injuries resulting from direct impacts to the body, and an ideally designed pad should be created with this function in mind.

Development and History of PPE

It is certain that the knee pads' purpose is to protect the athlete, but the question remains – why is the standard knee pad not accepted by players? The simple answer is that players believe the standard knee pad inhibits performance, but the source of this frustration is much more complex. Development and use of PPE for industrial and military applications accounts for

المنارة للاستشارات
www.manaraa.com

Figure 2: evolution of football equipment worn at the quarterback position (from left to right) – Harold "Red" Grange ('50s); Bart Starr ('70s); Troy Aikman ('90s); Robert Griffen III ('10s)

volumes of attention in the literature, but benefits of research could also be enjoyed in competitive athletics. Football athletes in particular use a number of standardized pieces of PPE and are required to do so by rule (NFL *rules*, 2012; NCAA *rules*, 2012; NFHS *rules*, 2012). However, use of this equipment is not standardized for all players, and modifications are made as athletes seek important competitive advantages. For some, an increased risk for injury in the future is a small cost for a mental or physical advantage on the field now. Perhaps this willingness to accept risk stems from the mindset that injuries are a part of the game. Today more than ever, a complete prevention of injury is not possible. This fact can mainly be attributed to new training and dietary techniques that are effectively used by players to increase both size and speed at all levels of the game (Kraemer et al., 2005).

With this increase in player physical potential, necessary improvements and additions have been made to PPE, and Figure 2 illustrates the evolution of equipment worn specifically by quarterbacks. A complete chronicling of each addition to the football uniform would extend well beyond the scope of this research, but certain points of emphasis are relevant. Note first that each of the four players in the figure play the quarterback position. Historically, the emphasis of the quarterback position is handling and throwing the ball. Currently in the game, more quarterbacks

المنارة للاستشارات
www.manaraa.com

contribute with their legs as well when throwing is not an option. Notice on the far right the difference in lower body PPE compared to the others. While there are still four main pads in play (tailbone, hip, thigh, and knee), most designs have adapted to the abilities of the player.

Advancements in helmet technology are visually evident in Figure 2, but lower-body PPE has undergone design changes as well. In a sport where the majority of game changing plays are made in open space, a player's ability to perform precise body movements and exert to their physical potential can be the difference between the sideline and a starting spot. These explosive movements are mainly generated by the legs, and any PPE used must not inhibit body mechanics. The most recent development in lower-body PPE was a device called a girdle, and its introduction moved past a technology patent that originated in 1941. McCoy's (1941) original design implemented the use of a fabric pocket to hold the pad against the player and allow for removal following competition opposed to pads permanently sewn into game pants. The purpose for this design change was to allow for, "cleaning, repairing, or changing" of player equipment (McCoy, 1941). This function is no longer necessary as materials used in PPE have evolved as well. Most foams used for padding are closed-cell and do not absorb moisture (Ashby & Mehl Medalist, 1983).

Girdle design incorporates the compressive assistance of fabric to aid in muscular function and secure PPE to the player body (Arensdort & Stromgren, 1992; Walde-Armstrong et al., 1996). The foundation of the design removed the pads from a player's game-uniform pants and placed them in a more compressive garment. In competition, lower-body PPE would remain in place within the tighter garment, allowing less restricted, natural movement of the lower limbs to occur. The girdle has been widely accepted as a standard piece of equipment at the collegiate

المنارة للاستشارات
www.manaraa.com

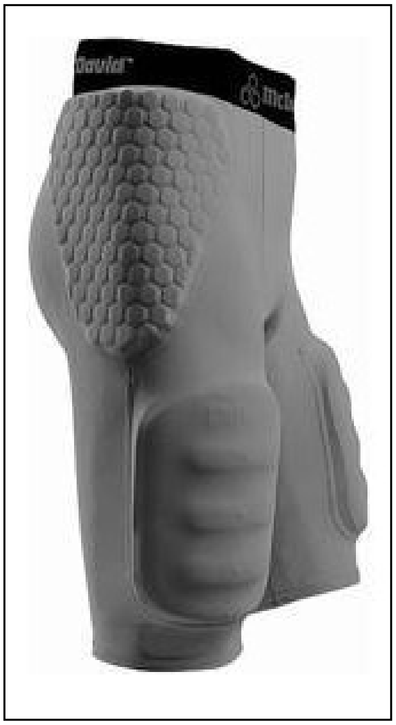


Figure 3: McDavid football girdle

and high school level, and a majority of college teams issue the garment to players as part of the uniform.

As noted earlier, all competitive levels of football require players to wear certain protective equipment. Collegiate and high school players are required to wear the full set of lower-body PPE (NCAA *rules*, 2012; NFHS *rules*, 2012). This set includes the aforementioned tailbone, hip, thigh, and knee pads, and the girdle is the preferred method of abiding by this rule. Having outlined the development, intended purpose, and effectiveness of the girdle, it is imperative to note that the girdle does not incorporate the full set of lower-body PPE (Figure 3). The knee pad is excluded from the girdle design and is still incorporated into the football uniform via fabric pocket as introduced by McCoy in 1941. Perhaps this exclusion has remained unaddressed because the NFL has not required players to wear these pieces of equipment. In fact, many skill position players (those positions which require speed, agility, and overall movement more than repeated physical collisions) choose not to wear any lower-body PPE. However, the choice to go without lower-body PPE will not be one players are allowed to make in the near future, and assessing the knee pad as part of the uniform is critical.

Modification and Future of PPE

In the summer offseason following the 2011-2012 NFL season, league owners met and passed a new rule requiring players to use both thigh and knee pads starting in the 2013 season. This ruling was made without much fanfare, but many agree that acceptance and enforcement of equipment requirements will not be easy (Fatsis, 2004; Battista, 2010; Gordon, 2012; Katzowitz,

www.manaraa.com

2012; Sando, 2012). The ruling is not the first of its kind, but player safety in the game and after retirement has been a very hot issue in mainstream media, giving the decision added controversy. Historically, the majority of NFL sponsored research has gone into learning about and preventing concussions. Elliot J. Pellman and David C. Viano are the primary investigators partnered with NFL management, and together they have completed vast amounts of research since 2003 aimed at improving helmet design and minimizing concussion occurrences (Pellman, 2003; Pellman & Viano, 2004; Viano & Pellman, 2005; Pellman et al., 2006; Viano et al., 2007). Based on this body of league sponsored research, it can be seen that general safety is an important component of the game. Players want to stay healthy and compete over a long career, and management wants to promote safe play and player well-being as the NFL is a role model for all levels of the sport. However, for most skill position players, performance now on the field trumps the concern for safety over the long term, and going without lower-body PPE has become the norm. Making the decision to go without lower-body PPE was the player's choice in the NFL until recently, but collegiate athletes did not have similar freedom. Instead, an adaptation to the equipment rule has led to the current state of the player uniform at this level. The complete rule listed in the NCAA Football Rules and Interpretations guidebook for 2011-2012 (NFHS *rules*) states:

> "Knee pads must be at least ½-inch thick and must be covered by pants. It is strongly recommended that they cover the knees. No pads or protective equipment may be worn outside the pants."

Due to the flexibility of the NCAA rule, players have the ability to wear their ½-inch thick knee pads in any manner they see fit, and common modifications include: 1) changing the size and/or shape of the pad; and 2) changing the location of the pad on the body. No research has gone into evaluating or understanding these PPE modifications, but Akbar-Khanzadeh et al.

المنارة للاستشارات

www.manaraa.com

Figure 4: NCAA skill position athletes wearing smaller PPE above the knee (left – Jai Eugene; right – A.J. Green)

(1995) note that when users encounter discomfort with their issued PPE devices, many will tamper with them to achieve higher satisfaction. However, sometimes these alterations may impair the effectiveness of the PPE device, and this is particularly important in a physical contact sport like football. Effective or not, a majority of collegiate players have modified their knee pads in accordance with the rule. As shown in Figure 4, the most common modification made by players is wearing the knee pad higher, above the knee. Whether this modification of equipment leads to a difference in injuries has gone unstudied, but it cannot be argued that a large number of players prefer to be outfitted in this way.

VAPPR Pads

It has been shown that the standard knee pad design has not progressed along with other pieces of PPE in the game of football, and players at multiple competition levels are dissatisfied. At the professional level, some players risk injury and compete without the knee pad in an effort to improve performance. Collegiate players have modified the use of their knee pads in an identical effort. In either case, the standard knee pad does not satisfy all user requirements, and therefore, a new design must be created. This new design must meet two basic criteria: 1) PPE must not inhibit player performance; 2) PPE must provide equal or greater protection than the standard knee pad. Meeting these two design criteria, the principle investigator (BFM) has

المنارة للاستشارات
www.manaraa.com

developed the Vastus And Patellar Protection with Range of motion (VAPPR) pad based on direct feedback from football athletes (patent pending).

The authors hypothesize:

- A player wearing no lower-body pads has a performance advantage over a player wearing standard lower-body pads.
- No difference in performance exists between players wearing VAPPR pads and those competing unpadded.
- VAPPR pads are superior to standard knee pads.

المنارة للاستشارات
www.manaraa.com

CHAPTER 2. METHODS

Player Surveys

In order to gain user perspective, a survey was constructed with the intent of generating a research hypothesis focused on standard knee pad design. Accordingly, this survey consisted of a series of YES/NO questions followed by an open section in which to elaborate and describe the reasoning behind the initial response. The survey also collected information about player age, height, weight, and position in order to link potential response trends to certain positions. A total of 138 participants completed the survey (Figure 5), of which 65 competed at the collegiate level and 73 at the high school level. The complete player survey can be found in Appendix A.

6. Have you ever made alterations to your knee pads? Yes □ No □
<u>6.a)</u> If yes, describe the alteration made and the intended purpose…

Figure 5: player survey sample section - yes/no response and open-ended component

Drop Test

A common method for evaluating the effectiveness of a protective pad is by executing a material drop test (Hrysomallis, 2009). Although the VAPPR pad design was created by simply altering the shape of the existing pad, the drop test was performed to ensure no material property changes had occurred. An 8.5 kg striker 4.5 cm in diameter was dropped from a height of 5 cm on both the standard knee pad and VAPPR design. Both drops were performed without warming up the material as high frequency impacts to the knee pad do not commonly occur during competition. Peak impact acceleration from the striker was measured, and a lesser acceleration indicates more energy absorbed by the pad. For the standard knee pad, peak acceleration was 24.14 g; and for the VAPPR design, peak acceleration was 23.92 g. The similarities in impact demonstrate that the absorption properties of both pads are effectively identical.

المنارة للاستشارات
www.manaraa.com

VAPPR Pad Design

Figure 6 displays the standard knee pad and VAPPR design. Shown in (A) are pads only, standard above and VAPPR below. (B) and (C) show both knee PPE incorporated into the uniform, standard left and VAPPR right. The prototype garment is illustrated in (D) with black fabric representing additions made to the common girdle (patent pending). This single compression garment can secure all lower-body PPE to the football athlete.

Figure 6: knee PPE for the football athlete – a comparison of the standard knee pad and VAPPR design

المنارة للاستشارات
www.manaraa.com

Data Collection

Testing was performed in two phases. For Performance Drill testing, participants performed a series of standardized football performance drills under three different padded conditions (unpadded, standard, VAPPR). Following the drills, participants completed a survey regarding their experience during the testing. During Gait Analysis testing, participants performed a series of 5 yard bursts under identical padded conditions.

Performance Drill testing: Wartburg College

10 men (age: 21 ± 1 years, height: 72 ± 3 in, mass: 200 ± 26 lb), free from injury for at least 12 months prior to testing, served as participants. All were collegiate football players and experienced in completing the three performance drills. Informed consent was obtained prior to any testing procedures. During testing, each participant was outfitted with a full set of lower-body football performance apparel including: girdle with hip and tailbone pads, thigh boards for insert, knee pads for insert, and game pants. After going through a dynamic warm-up, the participants performed a series of football performance drills while outfitted with three padded conditions: 1) Girdle Only; 2) Girdle, Thigh Boards, and Standard Knee Pads; 3) Girdle, Thigh Boards, and VAPPR Pads. Participants were allowed to recover between exertions. Performance drills completed during the experiment included: Broad Jump, L-Drill, and Pro-Agility (Figure 7). Listed below are descriptions of the three drills taken from the NFL Combine *"Workouts and Drills"* (2013) website:

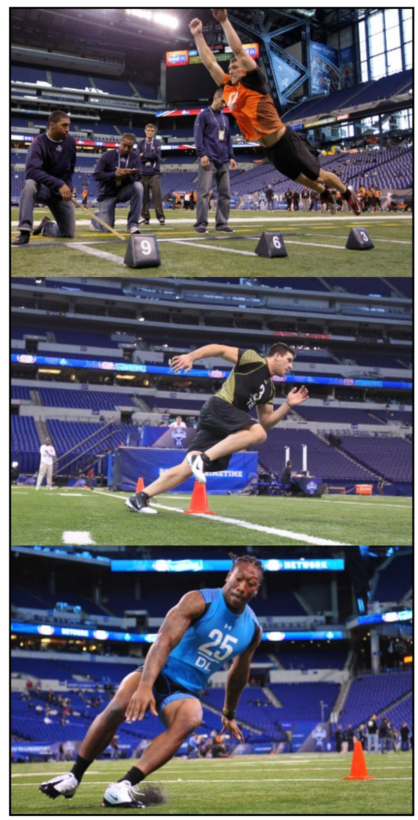


Figure 7: Broad-Jump (top), L-Drill (middle), Pro-Agility (bottom)

www.manaraa.com

Broad-Jump
The Broad-Jump is used to test an athlete's lower-body explosion and lower-body strength. The athlete starts out with a balanced stance, and then he explodes out as far as he can. The drill tests explosion and balance because the landing must be made without motion.
L-Drill
The L-Drill tests an athlete's ability to change directions at a high speed. Three cones in an L-shape are used in this drill. The athlete begins in a three-point stance at the starting line, goes 5 yards to the first cone and back. Then he pivots, runs around the second cone, runs a weave around the third cone (which is the high point of the L), changes directions, and returns around the second cone through the finish.
Pro-Agility
The Pro-Agility tests an athlete's lateral quickness and explosion in short areas. The athlete starts in the three-point stance, explodes out 5 yards to his right, touches the line, goes back 10 yards to his left, left hand touches the line, pivot, and he turns 5 more yards and finishes.

Running drills (L-Drill, Pro-Agility) were timed via stopwatch by two judges in order to limit variability associated with hand-timing. The Broad-Jump was measured to the nearest quarter inch as is customary for the drill. For all performance drills, participants completed two trials under each padded condition. During the experiment, a participant's padded conditions and performance drill order followed a counterbalanced design. In doing so, variability due to fatigue or insufficient warm-up could be mitigated. After performing the drills, participants completed a follow-up survey regarding their testing experience (portion Figure 8). The survey incorporated design criteria collected from the initial player survey mentioned earlier in the section. Questions were constructed to gather quantitative and qualitative feedback from participants concerning their satisfaction with the knee pads worn during testing. The complete follow-up survey can be found in Appendix B.

2. Indicate your level of satisfaction with the following criteria for both the standard knee pad and VAPPR design; 1 being completely dissatisfied 10 being completely satisfied.

a. **FIT** (defined as size of the pad, thickness, and ability to be worn on the knee)

(standard)	1	2	3	4	5	6	7	8	9	10
(VAPPR)	1	2	3	4	5	6	7	8	9	10

***comments ____

Figure 8: follow-up survey sample section – quantitative and qualitative design criteria component

المنارة للاستشارات
www.manaraa.com

Gait Analysis testing: Iowa State University

15 men (age: 23 ± 3 years, height: 71 ± 2 in, mass: 186 ± 28 lb), free from injury for at least 12 months prior to testing, served as participants. All were collegiate (or previously high school) football players experienced in starting from a three-point stance. Informed consent was obtained prior to any testing procedures. Each participant was outfitted with a full set of lower-body football performance apparel as listed in the Performance Drill testing section, and identical padded conditions were used. A series of anthropometric measurements were taken from each subject, 17 retro-reflective markers were placed on anatomical landmarks of a participant's right leg and pelvis (Figure 9). Anthropometrics were used to build a rigid-body model of each participant that would allow for the estimation of joint torques. Following anthropometry and marker placement, a dynamic warm-up was completed before testing began.

Figure 9: Gait Analysis marker positions on right leg and pelvis

During the Gait Analysis, participants performed a 5 yard maximum speed burst through a force platform, starting from a three-point sprinting stance. Participants were allowed to recover between exertions. Five bursts were performed for each of the four padded conditions. The order of padded conditions used for the bursts followed a counterbalanced condition design. During each burst, marker position was collected at 200 Hz using a Vicon motion system, and ground reaction force (GRF) data were collected at 1000 Hz by the AMTI force platform.

www.manaraa.com

Data Processing

Times and distances collected from Performance Drill testing were entered into a JMP table for statistical analysis. For each participant, an average score (time or distance) was used for each drill under all three padded conditions. To achieve this, the stopwatch times were averaged, and the two trials of each drill were averaged. The result was an average score for each padded condition during the three performance drills.

Marker positions and force platform data collected during Gait Analysis testing were processed using MatLab. Both marker positions and force platform data were smoothed using a zero-lag, low pass (20 Hz) Butterworth filter. All kinematic and kinetic variables were analyzed during the right leg stance phase for movement in the sagittal plane. Ideally, all 17 markers would be present during the stance phase, but redundancy is built into the marker set to accommodate for any that are missing. Only three markers are required to perform calculations for each segment: pelvis, thigh, leg, foot. Anthropometric measurements were used to estimate segment masses, moments of inertia, and center of mass locations for the four segments (which are assumed to be constant). All calculations followed principles of inverse dynamics with rigid body assumptions (Vaughan et al., 1992; Ko & Badler, 1995). Resulting variables associated with effective sprint start acceleration were entered into a JMP table for statistical analysis.

For both phases of research (Performance Drill and Gait Analysis testing) an ANOVA with repeated measures was chosen to determine if any significant differences existed between padded conditions. Counterbalanced experimental design ensured independence, resulting data followed a normal distribution, and sphericity assumptions were met. If significance existed from the ANOVA testing, Tukey's HSD test was used to investigate paired differences between padded conditions.

المنارة للاستشارات
www.manaraa.com

CHAPTER 3. RESULTS

Design Theme Hierarchy

Questions on the player survey provided insight into two general questions:

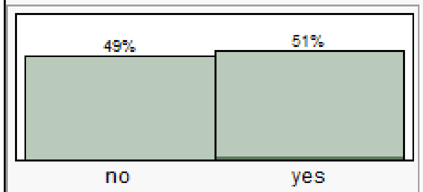
1) *Do players believe the standard knee pad impacts performance on the field?*
2) *What criteria are most important for knee pad design?*

The first question was addressed by asking players to describe the impact wearing standard knee pads has on three components of performance: straight-line speed, agility or lateral quickness, and flexibility (Figure 10). The second was addressed specifically by the following two questions:

- *If you have made alterations to your knee pads, describe these alterations.*
- *If knee pads were to be improved, they would need to be ______________.*

Of all respondents, 40% indicated they had made alterations to their standard knee pads, and all went on to describe the alterations made. The level of detail in the responses to the two questions allowed for a comprehensive design hierarchy to be created. 11 knee pad design traits were then categorized into three low-order design themes: *Fit*, defined as size of the pad, thickness, and ability to be worn on the knee; *Shape*, defined as area of the pad, type of padding, and position of the pad on the body; and *Performance*,

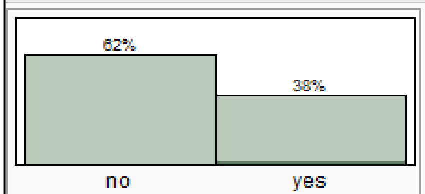
Impact Straight-Line



Frequencies

Level	Count	Prob
no	67	0.48551
yes	71	0.51449
Total	138	1.00000

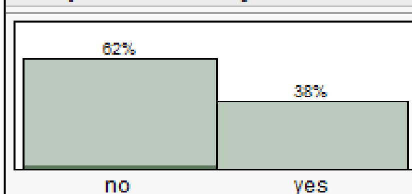
Impact Agility-Lateral



Frequencies

Level	Count	Prob
no	85	0.61594
yes	53	0.38406
Total	138	1.00000

Impact Flexibility



Frequencies

Level	Count	Prob
no	86	0.62319
yes	52	0.37681
Total	138	1.00000

Figure 10: survey questions – does the standard knee pad inhibit performance?

المنارة للاستشارات
www.manaraa.com

defined as flexibility of the pad and ability to function normally while wearing the pad. A portion of the hierarchy is shown in Figure 11, and the entire design theme hierarchy is displayed in Appendix C.

When I have my knee pads in my pants, they just seem to agitate me. But I have to wear them...		
I don't really see anything wrong design wise with my knee pads, they're just uncomfortable is all.	User Comfort	
It would be nice if the knee pad had a form fit to it. They're too stiff now.		*Fit*
...it may be more due to the pants than the pad, they just don't fit in the pants well.		
One thing I do is roll my pants up to hold the pad up higher on my knee. This works for me.	How the Pad Sits on the Player	
I continuously have to pull the pads up on my knee during games/practices.		
Maybe knee pads should be made of gel so that they form better to a player's body.		
My knee pads iritate me because they don't breathe. Maybe it's just the material they use.	Type/Amount of Padding	
I don't know how thick the pad should be, but if it could be strong but lighter that would be good.		
They seem to limit my flexibility and range of motion.		
It's a battle to get them in my pants pockets. They should be more flexible and easier to place.	Flexibility of the Pad	
I even cut slits into my knee pads to make them bend more around my knee.		
Possibly add some elastic to the pad to keep it covering the lower thigh, and prevent sliding.		*Performance*
I don't want a huge knee pad, but the smaller ones have a tendency to move around. It's no win.	Pad Movement	
All my pads move (thigh, hip, knee) but the girdle helps, and the knee pad is the worst.		
If the pad was thinner it would conform to my body more.		
I'd like the pad to be smaller, thinner, and lighter overall.	Thinner/Lighter Pads	
I could get the same protection from a thinner/lighter pad. They don't do much to protect I'd say.		

Figure 11: portion of design theme hierarchy generated from survey responses

Performance Drill testing: ANOVA with repeated measures

Participants that completed the Performance Drills phase of the experiment were going through standardized assessments used at the highest level of competition in the game of football. All were trained in performance of the drills and practiced them on a regular basis. Times and distances achieved were organized by drill and corresponding padded condition. An ANOVA with repeated measures was then used to determine if any of the three padded conditions (unpadded, standard knee pad, and VAPPR pad) led to different results during the same performance drill.

For the Pro-Agility times (seconds), an ANOVA showed significant differences existed among the three padded conditions (F-Ratio = 7.9199; Prob > F = .0034*). Comparing means indicated that trials performed unpadded (Mean = 4.407, Std. Dev. = 0.210) and with the VAPPR

المنارة للاستشارات
www.manaraa.com

pad (Mean = 4.400, Std. Dev. = 0.202) were significantly faster than those completed wearing the standard set of pads (Mean = 4.463, Std. Dev. = 0.226) given a confidence interval of 95%. A comparison of times achieved unpadded and while wearing the VAPPR pad in place of a standard knee pad did not show any significant difference.

Table 1: Pro-Agility performance comparison

	Padded Condition Comparison	p-Value
Pro-Agility	standard – unpadded	.0128*
	standard – VAPPR	.0050*
	VAPPR – unpadded	.9021

For the L-Drill times (seconds), an ANOVA showed significant differences existed among the three padded conditions (F-Ratio = 6.1661; Prob > F = .0091*). Comparing means indicated that trials performed unpadded (Mean = 7.093, Std. Dev. = 0.321) and with the VAPPR pad (Mean = 7.118, Std. Dev. = 0.328) were significantly faster than those completed wearing the standard set of pads (Mean = 7.204, Std. Dev. = 0.314) given a confidence interval of 95%. A comparison of times achieved unpadded and while wearing the VAPPR pad in place of a standard knee pad did not show any significant difference.

Table 2: L-Drill performance comparison

	Padded Condition Comparison	p-Value
L-Drill	standard – unpadded	.0096*
	standard – VAPPR	.0453*
	VAPPR – unpadded	.7426

المنارة للاستشارات
www.manaraa.com

For the Broad-Jump distances (inches), an ANOVA showed significant differences existed among the three padded conditions (F-Ratio = 7.1022; Prob > F = .0053*). Comparing means indicated trials performed unpadded (Mean = 102.650, Std. Dev. = 5.758) and with the VAPPR pad (Mean = 102.625, Std. Dev. = 5.360) were significantly farther than those completed wearing the standard set of pads (Mean = 100.925, Std. Dev. = 5.814) given a confidence interval of 95%. A comparison of distances achieved unpadded and while wearing the VAPPR pad in place of a standard knee pad did not show any significant difference.

Table 3: Broad-Jump performance comparison

	Padded Condition Comparison	p-Value
Broad-Jump	standard – unpadded	.0109*
	standard – VAPPR	.0120*
	VAPPR – unpadded	.9987

Gait Analysis testing: Propulsive Impulse

Multiple variables associated with effective sprint starting were processed during the Gait Analysis, and all displayed identical trends to the Performance Drills when comparing padded conditions (Table 4). During the analysis, all selected measures showed improved performance unpadded and with the VAPPR pad compared to the standard knee pad. Although the same padded conditions patterns existed between the two phases of research, only one variable in the Gait Analysis was found to be significant (Table 5). However, this variable has been noted by many researchers (Baumann, 1976; Mero et al., 1983; Mero, 1988; Harland & Steele, 1997; Weyand et al., 2000; Hunter et al., 2005; Čoh et al., 2006; Slawinski et al., 2010) to be one of the most significant contributors in effective sprint starting.

www.manaraa.com

Table 4: Gait Analysis measured variables

Variable (units)	Padded Condition (mean score)			F-Ratio	Prob > F
	unpadded	VAPPR	standard		
GRF (N)	614.4079	616.1286	603.9113	2.2065	0.1289
Propulsive Impulse (N-s)	0.0827	0.0841	0.0824	3.7746	0.0354*
Velocity (m/s)	5.4636	5.4846	5.4635	1.7774	0.1876
Hip Moment (N-m)	0.3436	0.3531	0.3358	1.7775	0.1876
Hip RoM (°)	68.9231	69.1489	67.9466	1.4457	0.2526

Propulsive impulse is a combination of measured GRF and contact time of the striking foot. In terms of measuring explosiveness (the aim of the Gait Analysis), this variable informs a great deal. Mathematically, propulsive impulse is an integral of GRF in the horizontal direction over time. Simply stated, it is a measure of the magnitude and quickness of the force used by an athlete to accelerate forward.

Table 5: Gait Analysis significant variable – propulsive impulse

	Padded Condition Comparison	p-Value
Propulsive Impulse	standard – unpadded	.1025
	standard – VAPPR	.0406*
	VAPPR – unpadded	.8981

المنارة للاستشارات
www.manaraa.com

CHAPTER 4. DISCUSSION

Knee Pads brought up to speed

The results of this research have shown that the standard knee pad inhibits player performance, but why has this design flaw gone unresolved in such a popular sport? A potential answer to this question comes from past equipment rules at the highest level of competition in the game, the NFL. Before May 2012, professionals could choose what lower-body padding to adopt in competition, and many skill position players preferred to go without thigh and knee pads. Logic behind these decisions has gone unstudied (until now), but perceived physical and psychological advantages have been voiced by NFL athletes. Ron Bartell (8-year career), cornerback for the Detroit Lions, made the following comment regarding his decision to compete without lower-body padding, "(Lower-body pads) take away from the speed of the game. They're not going to stop you from tearing an ACL" (Katzowitz, 2012). Bartell is not alone in his thinking; even after owners passed a new equipment rule set to take effect fall 2013, multiple athletes publically voiced displeasure with the decision. Steve Smith (12-year career), wide receiver for the Carolina Panthers notes, "Unless they (owners) say we're going to get fined, nobody is going to (comply)" (Battista, 2010). Furthermore, the dialogue has not been limited to a physical or monetary nature as some athletes believe the choice is personal. Quentin Jammer (11-year career), cornerback for the San Diego Chargers argues, "You play this game because you want to play this game, and the risks you take are the risks you take. If you don't want to wear (lower-body) pads, you shouldn't have to. It should be a choice" (Katzowitz, 2012).

Figure 12: Steve Smith (#89); Ron Bartell (#21)

المنارة للاستشارات

www.manaraa.com

Regardless of the reasons, it is clear that some NFL professionals believe they are at an advantage competing without lower-body pads, and their beliefs have been confirmed through this research. Still, the fact remains that players are seeking competitive advantages at the cost of safety. The quote from Jammer is not unusual among NFL athletes, and recent rule changes by owners have been made to meet the issue of safety head-on. To briefly summarize the dilemma facing both sides (players and owners): the common player will do whatever it takes, within the rules, to gain an advantage over his competitor regardless of long-term health consequences; owners accept this warrior mentality and are attempting to change the game to protect players from themselves. The task for owners is a difficult one, as everyday impacts in NFL competition regularly top forces of 50G (Gay, 2004; Viano & Pellman, 2005; Viano et al., 2007; Halkon et al., 2012). However, rule changes requiring PPE already standardized at other levels of the game should not be met with such resistance. With improved designs, players will not be forced to sacrifice safety in an effort to gain performance advantages. For the knee pad in particular, development of the VAPPR pad provides an alternative choice of PPE that allows athletes to perform at the same level as they would unpadded.

User-Centered Design Approach

Incorporating user-centered or iterative design processes is becoming more common in the sports equipment industry today as users have access to a wide variety of products. With interest and participation in the game of football growing (NCAA *participation*, 2012; NFHS *participation*, 2012), manufacturers of equipment are experiencing increased demand and competition. Some of this competition stems from perceived performance improvements attributed to the use of one type of PPE over another, and Roberts et al. (2001) believe this may be the consumer’s deciding criteria. Although these perceived benefits can only be measured

المنارة للاستشارات

www.manaraa.com

through subjective assessment, a player's comfort and confidence in their PPE can be critical. Velani et al. (2012) claim that athletes will choose a particular PPE device based on compromise between three criteria: personal safety, comfort, and performance. Webster and Roberts (2009) would agree, as they identified perceived comfort in particular as one of the most underutilized design criteria in their study of cricket leg guards. This preference for comfort and performance at the cost of safety has been the basis of decisions made at both the collegiate and professional level of football regarding knee pad PPE. However, results of this research have shown that this sacrifice of safety is a choice players will no longer need to make as the VAPPR pad is as effective as competing unpadded.

Advantages in terms of safety are obvious when comparing the unpadded player to one wearing PPE, but designing to protect and enable performance is a major focus in the literature (Roberts et al., 2001; McIntosh, 2005; McInosh, 2012; Velani et al., 2012). The VAPPR pad has been designed to enable a high level of performance, and results of the Performance Drills have shown no effective difference between performance unpadded and performance with the VAPPR pad. However, the main focus of this research was to improve the standard knee pad, and it is certain that the VAPPR pad is a superior design.

VAPPR – Standard: safety

It is clear that the standard knee pad is an effective guard against injury, but effectiveness is not in question. What is clear from this research is that the functionality of the standard knee pad is poor, and the VAPPR pad provides greater or equal protection against injuries that occur from common impacts in the game of football.

المنارة للاستشارات

www.manaraa.com

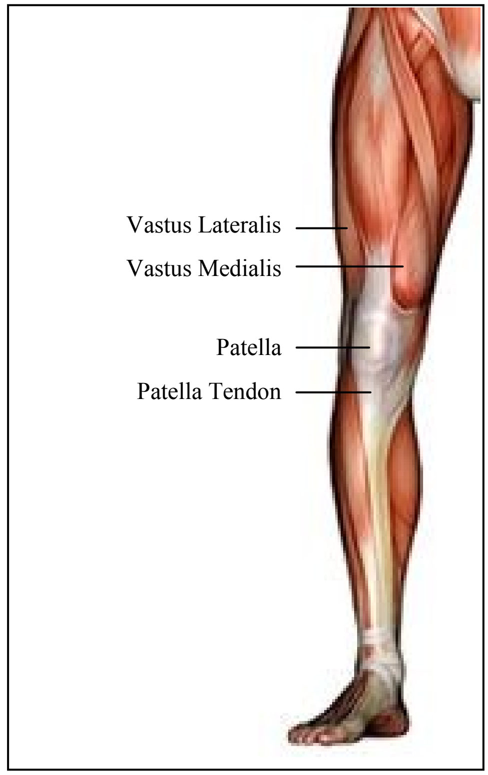


Figure 13: anatomical areas protected by the knee pad

The most common impact injury in all sports is the muscle contusion, and it is the second leading cause of injury in football (Pritchett, 1982; Culpepper & Niemann, 1983; Crisco et al., 1994; Shankar et al., 2007; Feeley et al., 2008; Hrysomallis, 2009). Contusion injuries are also influenced by the energy and shape of the impacting object, and football can be categorized as high energies and large areas. According to Viano et al. (1989), PPE devices designed to prevent contusions will absorb energy of the impacting object and prevent biological deformation beyond a recoverable limit. The function of the knee pad is to reduce impact energy; therefore it can be an effective guard against contusion injuries to the distal portion of the medial and lateral vastus. Both the standard knee pad and VAPPR pad provide coverage to this region (Figure 13), but the VAPPR pad has been shaped to better fit the asymmetric development of this portion of the quadriceps.

A much less common impact injury can occur when the impacting object creates direct force on the patella or patella tendon. The patellar rupture specifically was studied by Boublik et al. (2011), and the authors describe the injury as 'relatively rare'. Tracking injuries over ten years in the NFL, Boublik et al. (2011) noted twenty-four patellar tendon ruptures and also identified the most common method of injury – a deviation from the normal contraction of an extensor mechanism. Other researchers documenting limited incidences of patellar rupture are: Feeley et al. (2008), zero occurrences during NFL training camp (roughly 45 days per year) from 1998-

www.manaraa.com

2007; Pritchett (1982), 58 out of 5077 reported injuries (1.14%) in a six-state study from 1975-1977. The other patella injury that can occur from an impact is a patellar fracture. Most research on patellar fractures exists in literature dedicated to automobile-pedestrian collisions, but similar impact situations have been inferred to fit the game of football. Cooke and Nagel (1996) and Atkinson and Haut (2001) both studied knee impacts and corresponding injuries to the patella. Both found that 2-6 kN forces (relatively small in football) can cause patellar fracture when the impacting object strikes directly on a knee flexed to 90°. Furthermore, both groups of researchers note that any deviation from a direct blow of the same force will likely result in instability or avulsion of knee ligaments or tendons (Cooke & Nagel, 1996; Atkinson & Haut, 2001).

For both patellar injuries, normal player movement limits the instances in which a direct blow to the front of a flexed knee could occur. Collisions generally occur above the waist or at an angle from the striking to the struck player. Based on the patella injury statistics, a reduction in area was made for the VAPPR pad compared to the standard. The standard knee pad covers both the patella cap and tendon, and the VAPPR pad protects the patella cap only. While the VAPPR pad design will help guard against a patellar fracture, the true purpose for this component of the design is to address a Morel-Lavallée (ML) knee lesion.

Lesions are a degloving injury caused by shearing forces on the lower extremities, and this research has determined that the ML knee lesion is the main injury which a knee pad can guard against. The ML knee lesion has been studied by multiple researchers in a variety of areas. Most of the research documents injury cases, corresponding treatment, and recovery, but all describe the injury event as painful and requiring a week or more of recovery (Diaz et al., 2003; Scott et al., 2003; Pitrez et al., 2010; van Gennip et al., 2012). Research performed by Tejwani et al. (2007) from 1993-2006 within one NFL team provides the best documentation of this injury

المنارة للاستشارات
www.manaraa.com

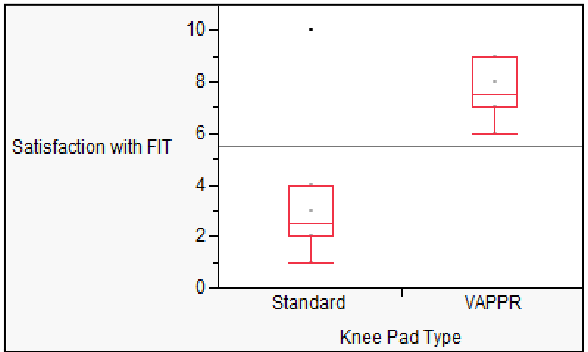
occurring in the game of football. The researchers (2007) report 24 players incurring the ML knee lesion, with the majority (81%) of instances occurring from an impact to the playing surface resulting in shearing force (Figure 14). Of primary importance to this research is the fact that no players were wearing knee pads when the injury occurred (Tejwani et al., 2007). Without a knee pad, the lower extremity would be the first contact with the playing surface, resulting in high shear force. However, both the standard and VAPPR pad would be effective in guarding against this particular injury.

VAPPR – Standard: preference

With minimal differences in safety established between the standard knee pad and VAPPR design, Velani et al. (2010) would argue that performance and comfort are the factors that will determine which PPE is selected by the user. For the player, perceived performance and comfort are both subjective measures of satisfaction, and results of the follow-up survey clearly establish that the VAPPR pad is preferred to the standard. Isolating the three low-order design themes generated through the player survey, participants were asked to rate their satisfaction with *Fit*, *Shape*, and *Performance* for both the standard knee pad and VAPPR design. Responses highlighted in Figure 15 show a very significant preference for the VAPPR pad over the standard.

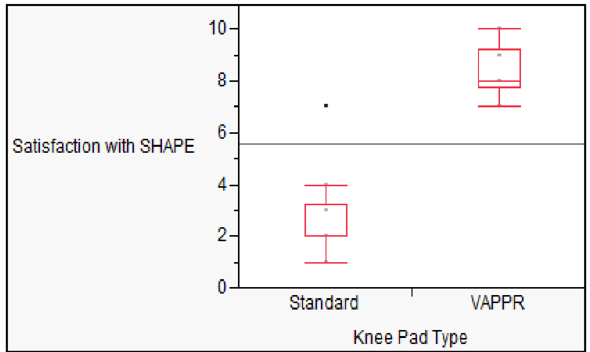
Figure 14: diving player with now lower-body PPE (Lance Moore)

المنارة للاستشارات
www.manaraa.com



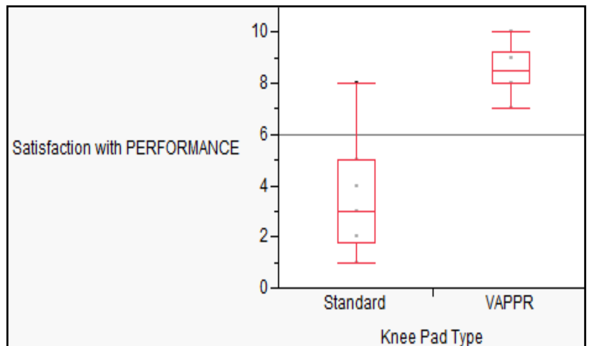
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Knee Pad Type	1	96.80000	96.8000	25.5484	<.0001*
Error	18	68.20000	3.7889		
C. Total	19	165.00000			



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Knee Pad Type	1	151.25000	151.250	76.2605	<.0001*
Error	18	35.70000	1.983		
C. Total	19	186.95000			



Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Knee Pad Type	1	135.20000	135.200	47.9055	<.0001*
Error	18	50.80000	2.822		
C. Total	19	186.00000			

Figure 15: player satisfaction comparison of standard knee pad to VAPPR design

In order to understand why the standard knee pad is perceived as unacceptable by the football athlete, it is necessary to uncover the origins of the design. Before the game of football was being played, manual laborers were utilizing knee PPE to guard against injury. In (1896), W.P. Fekgusson developed a protective device for the workers' knee (Figure 16). The design is intended to be worn over the knee, providing coverage for the entire knee, patella tendon, and proximal shin area. It is a very effective design for a user that spends a large amount of time in a kneeling position. In (1904), W.T. Stall invented a protective garment to be worn by competitors in a new sporting event, foot ball. Stall's Foot Ball Trousers also incorporated knee pads, and they were shaped very much like the worker's knee pads introduced by Fekgusson almost a decade earlier.

المنارة للاستشارات
www.manaraa.com

The purpose of this historical review is to demonstrate that the standard knee pad design is outdated. In fact, the design may be obsolete in today's game, which is so dependent on speed. Perhaps the single most valued attribute in football is a player's speed, and any PPE that negates this component of performance will be rejected by athletes. Results from the Performance Drills have shown that wearing the VAPPR pad leads to significant performance improvements compared to the standard design, but further investigating is needed for a complete understanding of the biomechanics involved.

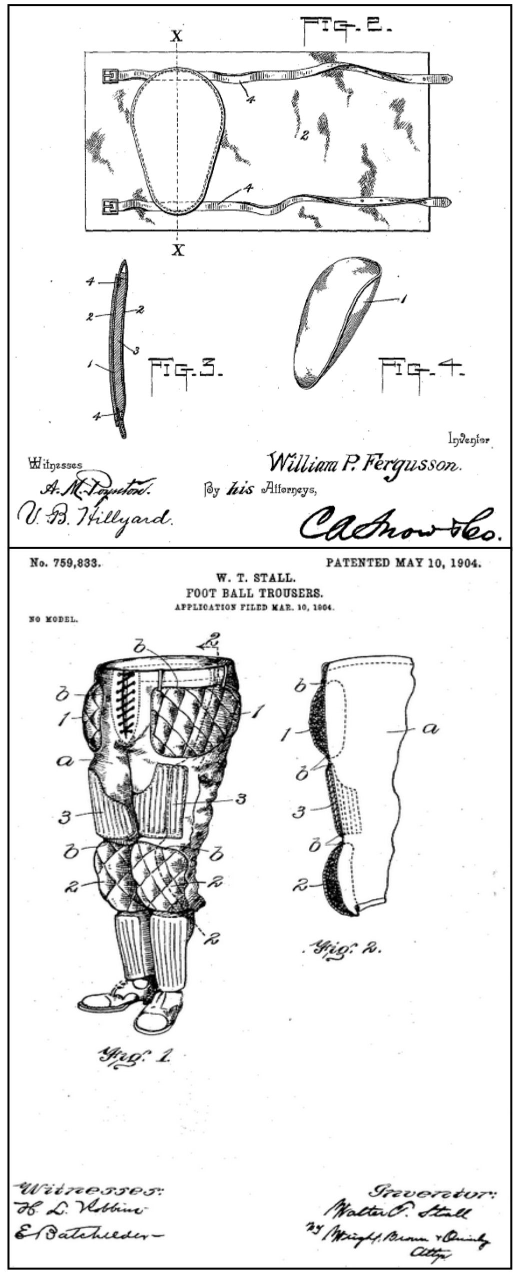


Figure 16: worker's knee pad– 1896 (top) foot ball trousers – 1904 (bottom)

VAPPR – Standard: performance

One of the newest goals of sports equipment design is to improve an athlete's mechanical efficiency during competition. A common method of achieving this goal is utilizing compressive garments most notable in swimming, but the design principles can be applied elsewhere. Millet et al. (2006) claim that an athlete's overall performance can be improved by introducing equipment that allows for better mechanical efficiency, and the VAPPR pad was created with biomechanics in mind. In order to gain a more complete understanding of an athlete's biomechanics while wearing football pads, a gait analysis was performed.

www.manaraa.com

During the Gait Analysis phase of this research, a sprint start was used as the measure of an athletes' explosiveness. The start was selected over a maximal speed portion of a sprint due to the importance of acceleration or quickness in the game of football. Cronin and Hansen (2005) reiterate the importance of acceleration in their study of predictors of sports speed.

> "For many sporting activities, initial speed rather than maximal speed would be considered of greater importance to successful performance."

Hunter et al. (2005) also studied the acceleration portion of a sprint, and define three external forces that impact the runner: Ground Reaction Force (GRF), gravitational force, and wind resistance. Of the three, GRF is the only factor athletes can functionally control, and measuring this variable became the foundation of the Gait Analysis results.

Table 6: prior research into sprint start mechanics – significant variables by study

Study	GRF	Propulsive Impulse	Velocity	Hip Moment	Hip RoM
Baumann (1976)		X	X		
Mann & Hagy (1980)				X	X
Mero et al. (1983)	X	X	X		
Mero (1988)	X	X	X		
Guskiewicz et al. (1993)				X	X
Harland & Steele (1997)	X	X			
Weyand et al. (2000)	X	X			
Cronin & Hansen (2005)			X		
Hunter et al. (2005)	X	X	X		
Čoh et al. (2006)	X	X	X		
Mero et al. (2006)	X			X	X
Slawinski et al. (2010)	X	X			

Many authors have found GRF to be a significant contributor to the acceleration phase of a sprint start, and Table 6 outlines specific studies and resulting impactful variables. Results of

www.manaraa.com

the gait analysis indicate that propulsive impulse was the only significantly different variable between padded conditions, and this finding correlates well to the performance drills. As suggested by Cronin and Hansen (2005), initial speed is imperative to successful performance in the game of football, and the Performance Drills are a strong indicator of in-game performance. During the drills, participants repeatedly accelerate and change directions, and increasing impulse would translate to more effective performance.

Although all variables followed a similar pattern to that found in the Performance Drills (unpadded and VAPPR performance superior to standard), not all differences were significant. Propulsive impulse was significantly different between padded conditions of the gait analysis, but the lack of significance in the other variables must be contemplated. Mechanically, the forces exerted by the athlete will far exceed those differences in ground reaction force, range of motion, or moment caused by a different pad set. However, in a game of inches, minor difference may become more evident during competition. Further biomechanical analysis is needed to fully understand why performance differences occur while competing under different padded conditions, but perhaps the answer is not entirely mechanical. Perceived differences will obviously exist for athletes under the different padded conditions and may lead to physical or psychological changes in gait or mentality that impact performance. Attempting to understand these physical or psychological changes should be the focus of future research.

المنارة للاستشارات
www.manaraa.com

CHAPTER 5. CONCLUSION

Prior to this study, no investigation existed regarding the impact that lower-body pads have on the football athlete. Personal experiences of the Principle Investigator (BFM) identified the standard knee pad as the most ineffective PPE in the football uniform, and further inquiry confirmed this belief. Player feedback indicated that a design flaw existed and also became the foundation for the creation of the VAPPR pad. With a new design achieved, performance and usability testing were necessary to confirm an improvement over the standard knee pad. Performance Drill testing (1) proved the unpadded player performs at a higher level than the padded; (2) established no difference in performance exists between an unpadded player and one wearing VAPPR pads; and (3) validated the VAPPR pad's superiority to the standard knee pad.

In an attempt to further analyze these differences in performance, or lack thereof, a full gait analysis was undertaken. However, results from the small scale experiment indicated that no significant biomechanical differences existed as a result of the different padded conditions. Future research should be directed towards understanding biomechanical differences while competing under different padded conditions as well as considering potential psychological impacts that wearing different PPE have on athletic performance. Other effort could be focused on identifying injury occurrences that are prevented through the use of PPE or quantifying the effectiveness of PPE devices.

www.manaraa.com

REFERENCES

1. Akbar-Khanzadeh, F., Bisesi, M. S., & Rivas, R. D. (1995). Comfort of personal protective equipment. Applied Ergonomics, 26(3), 195-198.

2. Arensdorft, S.C., Stromgren, L.T. (1992). U.S. Patent No. 5,161,257. Washington, DC: U.S. Patent and Trademark Office.

3. Ashby, M. F., & Medalist, R. M. (1983). The mechanical properties of cellular solids. Metallurgical Transactions A, 14(9), 1755-1769.

4. Atkinson, P. J., & Haut, R. C. (2001). Injuries produced by blunt trauma to the human patellofemoral joint vary with flexion angle of the knee. Journal of Orthopaedic Research, 19(5), 827-833.

5. Battista, J. (2010, August 5). NFL give lower-body padding a tryout. The New York Times.

6. Baumann, W. (1976). Kinematic and dynamic characteristics of the sprint start.Biomechanics V Vol. B, 194-199.

7. Boublik, M., Schlegel, T., Koonce, R., Genuario, J., Lind, C., & Hamming, D. (2011). Patellar tendon ruptures in national football league players. The American Journal of Sports Medicine, 39(11), 2436-2440.

8. Čoh, M., Tomažin, K., & Štuhec, S. (2006). The biomechanical model of the sprint start and block acceleration. Facta universitatis-series: Physical Education and Sport, 4(2), 103-114.

9. Cooke, F., & Nagel, D. (1996). Biomechanical Analysis of Knee Impact. Progress in Technology, 56, 163-172.

10. Crisco, J. J., Jokl, P., Heinen, G. T., Connell, M. D., & Panjabi, M. M. (1994). A Muscle Contusion Injury Model Biomechanics, Physiology, and Histology. The American Journal of Sports Medicine, 22(5), 702-710.

11. Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. The Journal of Strength & Conditioning Research, 19(2), 349-357.

12. Culpepper, M. I. & Niemann, K. M. (1983). High School Football Injuries in Birmingham, Alabama. Southern Medical Journal, 76(7), 873-875.

13. Diaz, J. A., Fischer, D. A., Rettig, A. C., Davis, T. J., & Shelbourne, K. D. (2003). Severe Quadriceps Muscle Contusions in Athletes A Report of Three Cases. The American Journal of Sports Medicine, 31(2), 289-293.

14. Fatsis, S. (2004, December 23). In the NFL, playing safety doesn't mean a lot of padding. The Wall Street Journal.

المنارة للاستشارات
www.manaraa.com

15. Feeley, B. T., Kennelly, S., Barnes, R. P., Muller, M. S., Kelly, B. T., Rodeo, S. A., & Warren, R. F. (2008). Epidemiology of National Football League training camp injuries from 1998 to 2007. The American Journal of Sports Medicine, 36(8), 1597-1603.

16. Fekgusson, W. P. (1896). U.S. Patent No. 563,468. Washington, DC: U.S. Patent and Trademark Office.

17. Gay, T. (2004). Football Physics: The Science of the Game. Rodale Books.

18. Gordon, J. (2012, May 23). Will thigh pads save NFL players? The Wall Street Journal.

19. Guskiewicz, K., Lephart, S., & Burkholder, R. (1993). The relationship between sprint speed and hip flexion/extension strength in collegiate athletes. Isokinet Exerc Sci, 3(2), 111-116.

20. Halkon, B., Webster, J., Mitchell, S., & Mientjes, M. (2012). Development of a test methodology for the assessment of human impacts in sport. Procedia Engineering, 34, 813-818.

21. Harland, M. J., & Steele, J. R. (1997). Biomechanics of the sprint start. Sports Medicine, 23(1), 11-20.

22. Hrysomallis, C. (2009). Surrogate thigh model for assessing impact force attenuation of protective pads. Journal of Science and Medicine in Sport, 12(1), 35-41.

23. Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. Journal of Applied Biomechanics, 21(1), 31-43.

24. Katzowitz, J. (2012, May 23). Players threaten not to wear newly mandated leg pads. CBS Sports.

25. Ko, H., & Badler, N. I. (1996). Animating human locomotion with inverse dynamics. Animating Gait and Locomotion, 50-59.

26. Kraemer, W. J., Torine, J. C., Silvestre, R., French, D.N., Ratamess, N.A., Spiering, B.A., Hatfield, D.L., Vingren, J.L., & Volek, J.S. (2005). Body size and composition of national football league players. Journal of Strength and Conditioning Research, 19(3), 485-489.

27. Mann, R. A., & Hagy, J. (1980). Biomechanics of walking, running, and sprinting. The American Journal of Sports Medicine, 8(5), 345-350.

28. Mccoy, A. M. (1941). U.S. Patent No. 2,266,886. Washington, DC: U.S. Patent and Trademark Office.

29. McIntosh, A. S. (2005). Risk compensation, motivation, injuries, and biomechanics in competitive sport. British Journal of Sports Medicine, 39(1), 2-3.

www.manaraa.com

30. McIntosh, A. S. (2012). Biomechanical considerations in the design of equipment to prevent sports injury. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 226(3-4), 193-199.

31. Mero, A. (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. Research Quarterly for Exercise and Sport, 59(2), 94-98.

32. Mero, A., Kuitunen, S., Harland, M., Kyröläinen, H., & Komi, P. V. (2006). Effects of muscle–tendon length on joint moment and power during sprint starts. Journal of Sports Sciences, 24(2), 165-173.

33. Mero, A., Luhtanen, P., & Komi, P. V. (1983). A biomechanical study of the sprint start. Scandinavian Journal of Sports Science, 5(1), 20-28.

34. Millet, G., Perrey, S., Divert, C., & Foissac, M. (2006). The role of engineering in fatigue reduction during human locomotion—a review. Sports Engineering, 9(4), 209-220.

35. National Collegiate Athletic Association. (2012). 2012 and 2013 NCAA football rules and interpretations. United States of America: Redding, R.

36. National Collegiate Athletic Association. (2012). NCAA sports sponsorship and participation rates report. Indianapolis, IN: Irick, E.

37. National Federation of State High School Associations. (2012). 2011-2012 high school athletics participation summary. Indianapolis, IN. Colgate, B.

38. National Federation of State High School Associations. (2012). 2012 NFHS football rules book. Indianapolis, IN: Colgate, B.

39. National Football League. (2012). Official playing rules and casebook of the national football league. United States of America: Goodell, R.

40. Pellman, E. J. (2003). Background on the National Football League's research on concussion in professional football. Neurosurgery, 53(4), 797-798.

41. Pellman, E. J., Powell, J. W., Viano, D. C., Casson, I. R., Tucker, A. M., Feuer, H., ... & Robertson, D. W. (2004). Concussion in professional football: Epidemiological features of game injuries and review of the literature-Part 3. Neurosurgery, 54(1), 81-96.

42. Pellman, E. J., Viano, D. C., Withnall, C., Shewchenko, N., Bir, C. A., & Halstead, P. D. (2006). Concussion in professional football: Helmet testing to assess impact performance-Part 11. Neurosurgery, 58(1), 78-96.

43. Pitrez, E. H., Pellanda, R. C., Silva, M. E., Holz, G. G., Hertz, F. T., & Hoefel Filho, J. R. (2010). Morel-Lavallée lesion in the knee: a case report. Radiologia Brasileira, 43(5), 336-338.

المنارة للاستشارات
www.manaraa.com

44. Powell, J. W., & Barber-Foss, K. D. (1999). Injury patterns in selected high school sports: a review of the 1995-1997 seasons. Journal of Athletic Training, 34(3), 277.

45. Pritchett, J. W. (1982). A statistical study of knee injuries due to football in high-school athletes. J Bone Joint Surg Am, 64(2), 240-242.

46. Roberts, J., Jones, R., Harwood, C., Mitchell, S., & Rothberg, S. (2001). Human perceptions of sports equipment under playing conditions. Journal of Sports Sciences, 19(7), 485-497.

47. Sando, M. (2012, May 23). NFL: thigh, knee pads mandatory. ESPN.com News.

48. Shankar, P. R., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Epidemiology of high school and collegiate football injuries in the United States, 2005–2006. The American Journal of Sports Medicine, 35(8), 1295-1303.

49. Slawinski, J., Bonnefoy, A., Levêque, J. M., Ontanon, G., Riquet, A., Dumas, R., & Chèze, L. (2010). Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. The Journal of Strength & Conditioning Research, 24(4), 896-905.

50. Stall, W. T. (1904). U.S. Patent No. 759,833. Washington, DC: U.S. Patent and Trademark Office.

51. Tejwani, S. G., Cohen, S. B., & Bradley, J. P. (2007). Management of Morel-Lavallee Lesion of the Knee Twenty-Seven Cases in the National Football League. The American Journal of Sports Medicine, 35(7), 1162-1167.

52. van Gennip, S., van Bokhoven, S. C., & van den Eede, E. (2012). Pain at the Knee: The Morel-Lavallée Lesion, a Case Series. Clinical Journal of Sport Medicine, 22(2), 163-166.

53. Vaughan, C. L., Davis, B. L., & O'Connor, J. C. (1992). Dynamics of Human Gait. (2nd ed.). Western Cape, South Africa: Kiboho Publishers.

54. Velani, N., Wilson, O., Halkon, B. J., & Harland, A. R. (2012). Measuring the risk of sustaining injury in sport a novel approach to aid the re-design of personal protective equipment. Applied Ergonomics, 43(5), 883-890.

55. Viano, D. C., & Pellman, E. J. (2005). Concussion in professional football: Biomechanics of the striking player-Part 8. Neurosurgery, 56(2), 266-280.

56. Viano, D. C., Casson, I. R., & Pellman, E. J. (2007). Concussion in professional football: biomechanics of the struck player—part 14. Neurosurgery, 61(2), 313-328.

57. Viano, D. C., King, A. I., Melvin, J. W., & Weber, K. (1989). Injury biomechanics research: an essential element in the prevention of trauma. Journal of Biomechanics, 22(5), 403-417.

المنارة للاستشارات
www.manaraa.com

58. Walde-Armstrong, K. M., Branson, D. H., & Fair, J. (1996). Development and evaluation of a prototype athletic girdle. Clothing and Textiles Research Journal, 14(1), 73-80.

59. Webster, J. M., & Roberts, J. (2009). Incorporating subjective end-user perceptions in the design process: A study of leg guard comfort in cricket. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 223(2), 49-62.

60. Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. Journal of Applied Physiology, 89(5), 1991-1999.

61. "Workouts & Drills." NFL Combine Workouts Information. Web. 13 Feb. 2013. http://www.nfl.com/combine/workouts

المنارة للاستشارات

www.manaraa.com

APPENDIX A – Player Survey

Prologue:

Advances in football protective equipment have been occurring since before the facemask was added to the helmet. Understanding the elements of safety within the game provide numerous benefits: longer careers, more competition, bigger and faster players. To date, one of the only non-standardized pieces of protective equipment in the game is protective leg padding. The purpose of this questionnaire is to investigate the functionality of football knee pads from the perspective of the player.

Questionnaire:

1. While playing in competitive games, do you wear knee pads? Yes □ No □

2. What is the *purpose* of a knee pad?

2.a) Does the knee pad *serve its purpose*? Yes □ No □

3. Do knee pads have an effect on your *straight-line speed*? Yes □ No □

3.a) **If yes**, describe the effect…

4. Do knee pads have an effect on your *lateral quickness*? Yes □ No □

4.a) **If yes**, describe the effect…

www.manaraa.com

APPENDIX A – Player Survey (continued)

5. Do knee pads have an effect on your *flexibility or range of motion*? Yes ☐ No ☐

5.a) **If yes**, describe the effect…

6. Have you ever made alterations to your knee pads? Yes ☐ No ☐

6.a) If yes, describe the alteration made and the intended purpose…

7. If knee pads were to be improved, they would need to be…

(Indicate your level of agreement with the following sentences – mark only one answer)

8. *Knee padding is an important piece of protective equipment in the game of football.*

Strongly Disagree Moderately Disagree Neutral Moderately Agree Strongly Agree

9. *If knee pads were NOT mandatory, I would choose not to wear them.*

Strongly Disagree Moderately Disagree Neutral Moderately Agree Strongly Agree

Classification:

What is your age? ______________ *What is your height?* ______________

What position(s) do you play? ______________ *What is your weight?* ______________

المنارة للاستشارات
www.manaraa.com

APPENDIX B – Performance Drill testing Follow-Up Survey

1. Rank the following design criteria based on your opinion of importance; 1 being the most important component of knee pad design and 9 being the least important consideration in design.

☐ Size	☐ Thickness	☐ Shape
☐ Customizable Fit	☐ Type of Padding	☐ Flexibility
☐ Stays in Place	☐ Weight	☐ Comfortable to Wear

2. Indicate your level of satisfaction with the following criteria for both the standard knee pad and VAPPR design; 0 being completely dissatisfied 9 being completely satisfied.

a. **FIT**
(defined as size of the pad, thickness, and ability to be worn on the knee)

(standard)	1	2	3	4	5	6	7	8	9	10
(VAPPR)	1	2	3	4	5	6	7	8	9	10

***comments ____

b. **SHAPE**
(defined as area of the pad, type of padding, and position of the pad on the body)

(standard)	1	2	3	4	5	6	7	8	9	10
(VAPPR)	1	2	3	4	5	6	7	8	9	10

***comments ____

c. **PERFORMANCE**
(defined as flexibility of the pad and ability to function normally while wearing the pad)

(standard)	1	2	3	4	5	6	7	8	9	10
(VAPPR)	1	2	3	4	5	6	7	8	9	10

***comments ____

المنارة للاستشارات
www.manaraa.com

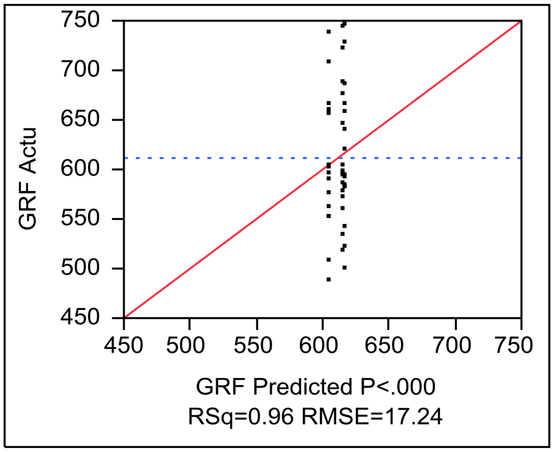
APPENDIX C – Design Theme Hierarchy

EXAMPLE QUOTES	BASE DESIGN TRAITS	LOW-ORDER THEMES	HIGH-ORDER THEMES	GENERAL GOAL
Normal pads are too big for me; I usually use an elbow slip-on pad instead.				
I cut my knee pads every year; I've never played with a full knee pad since graduating High School.	Modified Smaller Pads			
Cutting my pads into circle shapes seems to work well for me - feel more mobile and less restricted.				
Knee pads in general just get in the way; they're too big.				
Big knee pads have the tendency to ride up my knee as I play, then I have to adjust them.	Large Pads			
If the pad is too big, it affects the bending of my knees. I have to be able to move freely.		*Shape*		
Feels like the pad is holding back my movement.				
If the pad is too bulky, it makes my pants fit way too tight. Then I feel like I lose range of motion.	Thick/Bulky Pads			
My movement feels restricted when I wear my knee pads. I feel faster without them.				
First thing I do with new pads is cut them in half.				
A shorter pad is a more comfortable pad for me because of my height.	Long Pads			
The knee pad should be small/short enough to just cover a player's knee cap.			***Knee Pad Feel***	
Knee pads would be better if they were easier to adjust; how they sit and the fit in my pants.				
I like the way a girdle feels, it feels like it forms to my body. The knee pad should do that.	Customizable Fit			
If the pad could fit my pants pocket more naturally, maybe they would be more comfortable.				
When I have my knee pads in my pants, they just seem to agitate me. But I have to wear them...				
I don't really see anything wrong design wise with my knee pads, they're just uncomfortable is all.	User Comfort			
It would be nice if the knee pad had a form fit to it. They're too stiff now.		*Fit*		
...it may be more due to the pants than the pad, they just don't fit in the pants well.				
One thing I do is roll my pants up to hold the pad up higher on my knee. This works for me.	How the Pad Sits on the Player			***Knee Pad Design***
I continuously have to pull the pads up on my knee during games/practices.				
Maybe knee pads should be made of gel so that they form better to a player's body.				
My knee pads irritate me because they don't breathe. Maybe it's just the material they use.	Type/Amount of Padding			
I don't know how thick the pad should be, but if it could be strong but lighter that would be good.				
They seem to limit my flexibility and range of motion.				
It's a battle to get them in my pants pockets. They should be more flexible and easier to place.	Flexibility of the Pad			
I even cut slits into my knee pads to make them bend more around my knee.				
Possibly add some elastic to the pad to keep it covering the lower thigh, and prevent sliding.		*Performance*	***Knee Pad Function***	
I don't want a huge knee pad, but the smaller ones have a tendency to move around. It's no win	Pad Movement			
All my pads move (thigh, hip, knee) but the girdle helps, and the knee pad is the worst				
If the pad was thinner it would conform to my body more				
I'd like the pad to be smaller, thinner, and lighter overall.	Thinner/Lighter Pads			
I could get the same protection from a thinner/lighter pad. They don't do much to protect I'd say.				

www.manaraa.com

APPENDIX D – ANOVA: Gait Analysis (GRF)

Variable: GRF
Actual by Predicted Plot



Summary of Fit

RSquare	0.95887
RSquare Adj	0.956912
Root Mean Square Error	17.24249
Mean of Response	611.4826
Observations (or Sum Wgts)	45

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error
Participant	15.276894	4541.8723	1754.323
Residual		297.30338	79.457672
Total		4839.1757	1754.9227

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Padded Condition	2	2	28	2.2065	0.1289

Least Squares Means Table

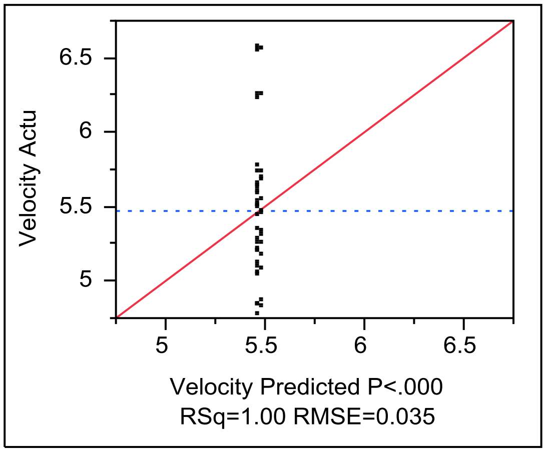
Level	Least Sq Mean	Std Error
standard	603.91130	17.961395
unpadded	614.40791	17.961395
VAPPR	616.12863	17.961395

www.manaraa.com

APPENDIX E – ANOVA: Gait Analysis (Velocity)

Variable: Velocity

Actual by Predicted Plot



Summary of Fit

RSquare	0.996348
RSquare Adj	0.996174
Root Mean Square Error	0.035282
Mean of Response	5.470582
Observations (or Sum Wgts)	45

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error
Participant	181.64588	0.2261167	0.085621
Residual		0.0012448	0.0003327
Total		0.2273615	0.0856212

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Padded Condition	2	2	28	1.7774	0.1876

Least Squares Means Table

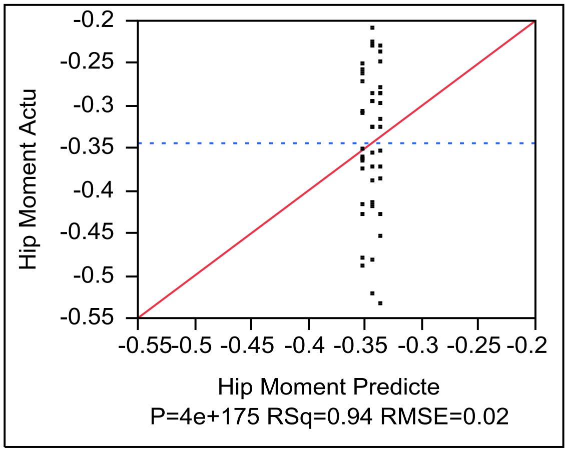
Level	Least Sq Mean	Std Error
standard	5.4635011	0.12311554
unpadded	5.4636391	0.12311554
VAPPR	5.4846055	0.12311554

www.manaraa.com

APPENDIX F – ANOVA: Gait Analysis (Hip Moment)

Variable: Hip Moment

Actual by Predicted Plot



Summary of Fit

RSquare	0.942482
RSquare Adj	0.939743
Root Mean Square Error	0.025029
Mean of Response	-0.34416
Observations (or Sum Wgts)	45

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error
Participant	10.681309	0.0066911	0.0026085
Residual		0.0006264	0.0001674
Total		0.0073175	0.0026103

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Padded Condition	2	2	28	1.7775	0.1876

Least Squares Means Table

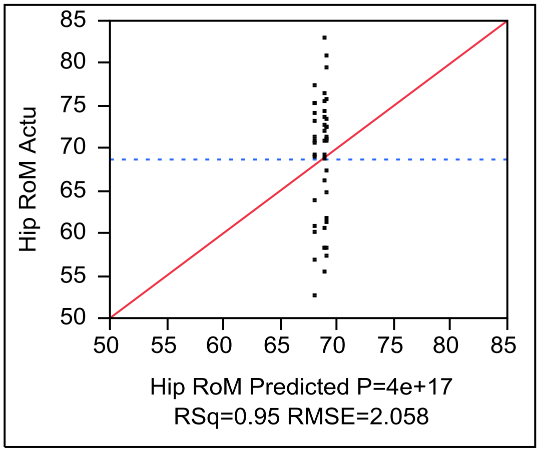
Level	Least Sq Mean	Std Error
standard	-0.3358478	0.02208702
unpadded	-0.3435758	0.02208702
VAPPR	-0.3530500	0.02208702

www.manaraa.com

APPENDIX G – ANOVA: Gait Analysis (Hip RoM)

Variable: Hip RoM

Actual by Predicted Plot



Summary of Fit

RSquare	0.949838
RSquare Adj	0.947449
Root Mean Square Error	2.058195
Mean of Response	68.67286
Observations (or Sum Wgts)	45

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error
Participant	12.395434	52.509101	20.383775
Residual		4.2361647	1.1321626
Total		56.745266	20.394253

Fixed Effect Tests

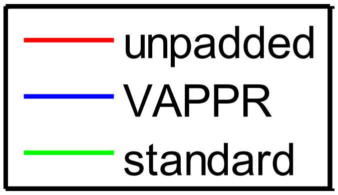
Source	Nparm	DF	DFDen	F Ratio	Prob > F
Padded Condition	2	2	28	1.4457	0.2526

Least Squares Means Table

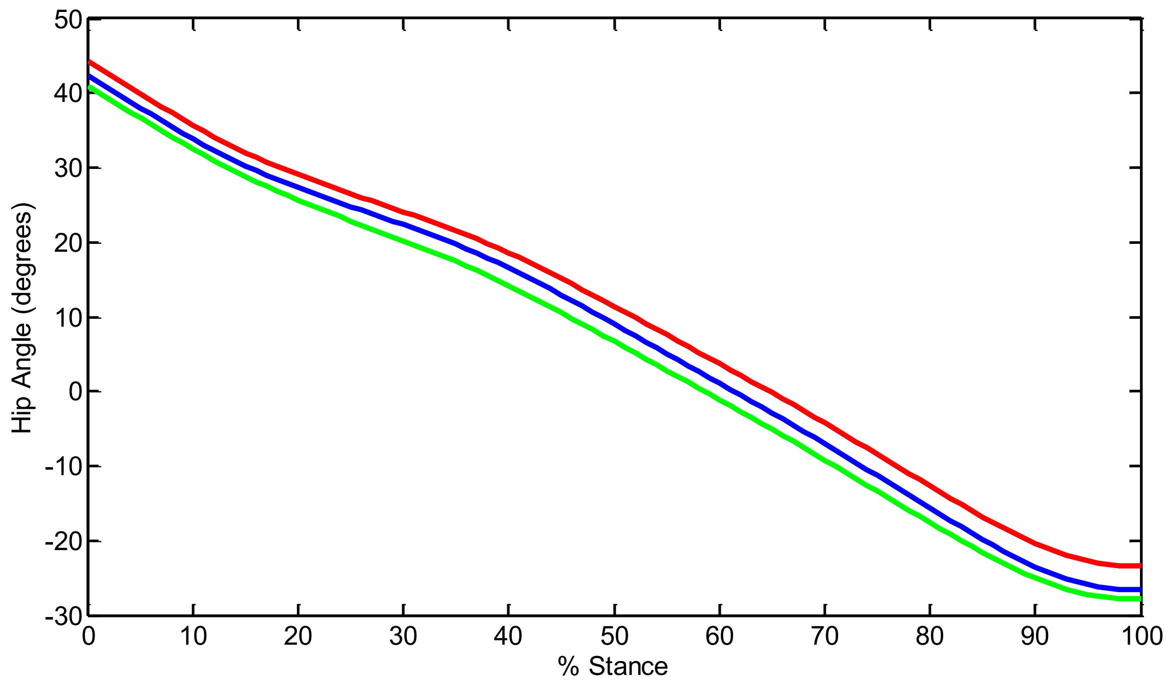
Level	Least Sq Mean	Std Error
standard	68.923070	1.9449981
unpadded	67.946639	1.9449981
VAPPR	69.148868	1.9449981

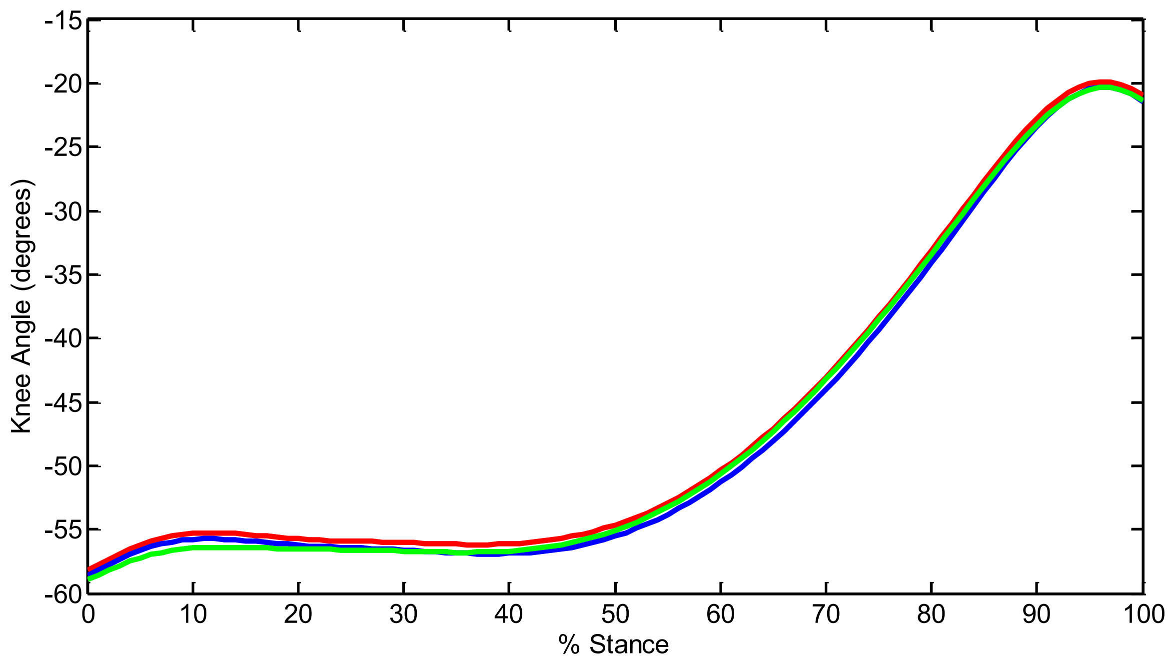
www.manaraa.com

APPENDIX H – Hip and Knee RoM: graphical display of all-subject average



Differences between padded conditions in terms of Range of Motion were mostly seen in hip flexion and extension (top). Unpadded trials led to most flexion while standard knee pad trials led to most extension of the hip. No noticeable difference exists between padded conditions for knee range of motion.





www.manaraa.com

APPENDIX I – Image Citations

Figure 1

- Helmet
  - http://www.triple-s-sports.com/images/products/detail/RAW_MOMENTUMY_black2.jpg
- Shoulder Pads
  - http://www.shoprawlings.com/products/A4_lg.jpg
- Leg Pads
  - http://www.ondecksports.com/Schutt-deluxe-7pc-pad-set-blkicon.jpg

Figure 2

- Red Grange
  - http://prosportsextra.com/fourth-and-inches/wp-content/uploads/2012/08/Red-Grange.jpg
- Bart Starr
  - http://www.footballspeakers.com/i/starr_bart.jpg
- Troy Aikman
  - http://www.celebritiesfans.com/media/pictures/troy_aikman.jpg
- Robert Griffin III
  - http://i0.mail.com/314/1630314,h=425,pd=1,w=620/robert-griffin-iii-jamarca-sanford.jpg

Figure 3

- McDavid Girdle
  - http://www.gobros.com/images/thumbnails/3/450/450/755TGirdleGREY_xl.jpg

Figure 4

- AJ Green and Jai Eugene
  - http://farm4.staticflickr.com/3019/2976740399_43d28c4487_z.jpg?zz=1

Figure 7

- Broad- Jump
  - http://graphics8.nytimes.com/images/2013/02/21/sports/JP-PRYCE/JP-PRYCE-blog480.jpg
- L-Drill
  - http://nfldotcom.files.wordpress.com/2012/02/bl011737.jpg
- Pro-Agility
  - http://nfldotcom.files.wordpress.com/2012/02/gv1_9914.jpg

Figure 12

- Steve Smith
  - http://www1.pictures.zimbio.com/gi/Steve+Smith+Carolina+Panthers+v+Detroit+Lions+uY2k259j PZfl.jpg

Figure 13

- Knee Muscle Anatomy
  - http://www.moogee.com/images/blank-muscle-anatomy.jpg

Figure 14

- Lance Moore
  - http://mediacenter.smugmug.com/002-SPORTS/NFL/122312Saints-vs-Cowboys/i-qpJDbQc/1/L/122312kw_CowboyS_23-L.jpg

المنارة للاستشارات
www.manaraa.com