EFFECT OF VARYING FOOTWEAR AND THROW PATTERN ON THE JOINT CONTACT FORCE OF THE KNEE IN FOOTBALL ATHLETES

An Undergraduate Research Scholars Thesis

by

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TABLE OF CONTENTS

ABSTRACT

Effect of Varying Footwear and Throw Pattern on the Joint Contact Force of the Knee in Football Athletes

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The most common site of running-related injury in athletes is the knee joint, or patellofemoral interface. Therefore, lower-extremity biomechanics is extensively studied in order to understand the factors that contribute to injury at this site. The project objective is to investigate the effect of footwear type and throw pattern on the patellofemoral contact force in football athletes. Footwear condition of an athlete while running has been shown to be a significant factor affecting biomechanical forces. Thus, it is of particular interest to identify how changing footwear will specifically affect football players and the internal knee forces they experience. Additionally, other factors such as football throw type will be analyzed to determine if certain throw patterns have the ability to increase or decrease the patellofemoral contact force in an athlete. Investigating how these factors contribute to the internal forces football athletes experience would provide a solid basis to relate specific practices to injury types. Cadaver studies focusing on the patellofemoral joint have led to the development of mathematical models that help estimate the internal contact force. This project will use these models in order to further explore how the knee contact force is affected by footwear and throw pattern. Body kinematics will be investigated using primarily motion capture technology.

DEDICATION

I would like to dedicate my work to my Grandmother, Mom and Dad who have led and shaped me into the person I am today. I would also like to thank Nicolaus Flug, who has been by my side in this process since the beginning. Thank you for your love and support.

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Finally, I would like to thank my parents, brothers and friends for always believing in me and offering their support and encouragement.

NOMENCLATURE

FFS	Forefoot Strike(r)
FSP	Foot Strike Pattern
GRF	Ground Reaction Forces
IRB	Institutional Review Board
MFS	Midfoot Strike(r)
PFPS	Patellofemoral Pain Syndrome
RFS	Rearfoot Strike(r)

CHAPTER I

INTRODUCTION

Background and motivation

One of the locations with the highest prevalence of sport-related injury is the patellofemoral joint [1]. Pain at the patellofemoral site accounts for about 25% of the knee injuries seen in sport-medicine clinics, and it has been suggested that patients experiencing this patellofemoral pain may be encountering greater joint contact forces at this site [2, 3]. Specifically, patellofemoral pain is common among athletes, regardless of any parameters that may affect their running gait (distance, sport type, footwear, gender, etc.). In fact, Patellofemoral Pain Syndrome (PFPS), or "Runner's Knee," is the most common overuse injury experienced by runners and athletes [1]. PFPS generally causes a large amount of pain and discomfort at the knee and can require medication, physical therapy, or in bad cases, surgery, to fix. As aforementioned, recent studies have proposed that injury and pain at the patellofemoral site is caused in part by the magnitude of the forces present at the knee joint [3]. The location of the patellofemoral joint is shown below in **Figure 1**.

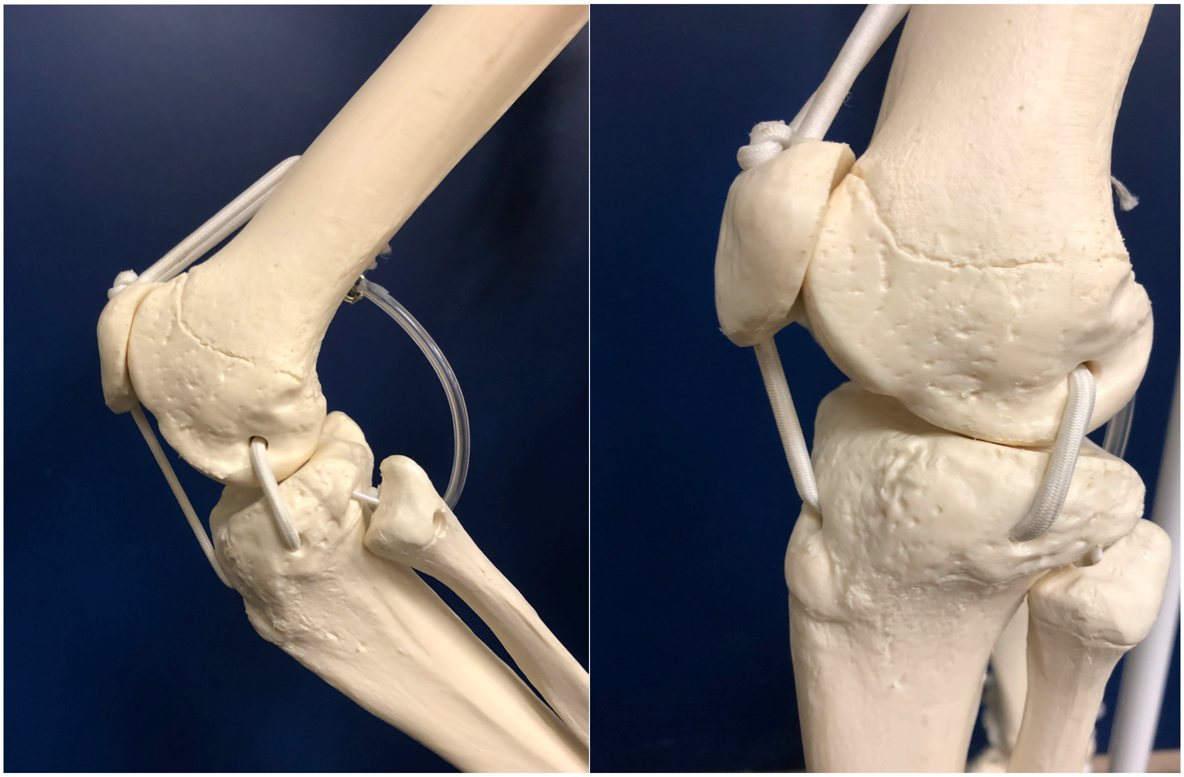

Figure 1. Patellofemoral site location. This image shows the location of the patellofemoral joint. The left image depicts a bent knee and the right pic depicts an unbent knee. This is intended to show the interface of the patella and femur.

Patellofemoral pain frequently occurs in running athletes that perform many sharp cutting, jumping, or pivoting movements [4]. Consequently, knee injury in football players is very common. It has been shown that the biomechanics of running can be manipulated by different factors that prove to increase or decrease sports-related injury [5]. Similar analyses on the effect of various running-related factors on injury in football players can also be performed to try and find methods of injury reduction. There are not many studies that specifically investigate the patellofemoral site in football athletes. There is, however, extensive previous literature that analyzes the patellofemoral interface and runners. Since knee injury is decently prevalent in football players, this current project aims to reduce the disparity between the patellofemoral joint research done on runners and football athletes.

At first it was thought that mainly ground reaction forces (GRF) were responsible for the injuries that commonly occurred at the patellofemoral site [6]. However, it has been demonstrated that both GRF and internal biomechanical forces are instrumental in the force experienced at the knee joint [7]. Since these biomechanical forces have been seen to contribute to running injury along with vertical GRF, identifying how these in vivo loading conditions are affected by various parameters is of extreme interest.

Analysis of GRF can easily be done through the use of force plate technology. Internal, biomechanical loading conditions at various joints are more difficult to measure, however, since these forces can only be estimated in live subjects. In fact, the forces found in intact human knees have not yet been measured in vivo in stationary conditions, let alone during human physical activity [8]. Human cadaver studies have led to the development of mathematical models that describe all the internal forces present at a specific site, such as the patellofemoral joint [9-10]. Although these mathematical models may not be completely accurate since the rigidity of a cadaver is very different from a live human being, they serve as very close approximations of various in vivo loading conditions [10]. A mathematical model for the patellofemoral joint will be employed in this research study in order to estimate the internal forces at the site for live athletic football subjects.

One parameter that has a considerable effect on the internal forces at the patellofemoral joint is footwear type [11]. It has been suggested that there are significant disparities between the running mechanics of shod, or with a shoe, and barefoot conditions [11]. Additionally, shod and barefoot running have been linked to distinct foot strike patterns (FSP), which also contribute to the internal forces present at the knee [11]. "FSP" is the way the foot contacts the running surface and can be grouped into three different categories. These categories include forefoot strikers (FFS), midfoot strikers (MFS), and rearfoot strikers (RFS). Generally, an FFS runner hits the ground with the ball of their foot, a MFS runner hits the ground with the middle arch of their foot, and an RFS runner hits the ground with the heel of their foot. However, specific classification of the FSP of an individual can be determined more precisely by the angle of the runner's foot or the force distribution of the foot when it comes in contact with the ground [12]. It has been thoroughly demonstrated that barefoot runners generally have an FFS pattern and shod runners have an RFS pattern. The combination of footwear condition and FSP can affect the biomechanics of running, so it is of great importance that the change in FSP is taken into consideration. In a recent study by Kulmala et al., it was demonstrated that there are distinct differences between FFS and RFS in the internal loading at the patellofemoral site [13]. In this current study, footwear condition, and therefore FSP, will be investigated in order to understand the best way for athletes to perform to reduce injury at the knee. This study will not manipulate footwear condition and FSP independently since they generally are very closely linked. It is understood that as the footwear type changes, so does the FSP. Therefore, only footwear condition will be directly manipulated to identify how the magnitude of the in vivo forces is different in shod and barefoot football athletes.

The two, distinct football throw types analyzed in this study are the Left Hitch and the Left 3-Step-Drop throws. A majority of the previous literature referencing football biomechanics has focused on the kinematics of the upper extremities and the mechanics of throwing. Therefore, there is not much past research or information on the mechanics of the lower extremities, including the knee joint, of football athletes. This study seeks to preliminarily determine how changing the throw pattern of a football player affects the magnitude of the patellofemoral contact force.

Problem statement

This research study aims to independently manipulate the parameters of footwear condition (shod or barefoot) and throw pattern type to determine how these factors affect the magnitude of the in vivo force at the patellofemoral joint. The resulting data will help to suggest the best way for football players to perform (in terms of footwear condition and throw type) in order to reduce pain, and therefore, injury, at the most common site of injury for athletes. Additionally, this study seeks to develop an experimental method that utilizes motion capture for the analysis of internal, biomechanical forces.

Research objectives

Objective 1

The first objective of this study is to utilize and build upon past relevant literature to develop a method for analysis of in vivo forces. The collected data, which were obtained and processed previously through motion capture technology, a set of reflective markers, force plate technology, and the NEXUS program, will be analyzed. These data will be used to identify knee flexion angle of the football athlete and knee extensor moment. Subsequent employment of previously developed mathematical models and computations will lead to the estimation of the specific internal contact force.

Objective 2

The second objective of this study is to estimate the in vivo loading conditions at the patellofemoral joint and formulate appropriate conclusions and suggestions for injury prevention in football athletes. Specifically, the patellofemoral joint contact force will be calculated. This estimated force will be compared across the subjects to determine if there are any differences. Footwear type and football throw type are the two variables that will be controlled and changed between subjects.

Objective 3

The third objective of this study is to design a custom Python program that can input the motion capture and force plate data and calculate the resulting in vivo patellofemoral force. This program must be able to import the large quantity of kinematic motion capture and force plate data and then subsequently output the knee flexion angle, patellofemoral contact force, and other relevant variable quantities for each subject.

Significance

This study will investigate and estimate the in vivo force at the patellofemoral joint. Information will be provided about the footwear type and throw type recommended to reduce the internal loading conditions at this common injury site. The knowledge of the biomechanical differences present when running with various parameters can lead to methods of injury prevention in running athletes of all types. The results of this study can be further explored with a larger sample size to define the significance in the disparities in force reported in this study. Additionally, the results will be able to be built upon in the future to identify significant differences in gender.

Limitations

There are various limitations that could have had an effect on acquired data. The subject sample size was very small, which prevents conclusions to be drawn for a wide range of the population. The subjects were all male football players, which also prevents data to be applied to a wide range of athletes or females. There was no predetermination of the order in which the subjects would perform their trials. Though it was encouraged that each subject run and perform as naturally as possible, it was hard to keep the environment of the trials the same as a normal environment for the subjects. In other words, the large camera system, set of reflective markers on clothing and extremities, and "research-like" setting could have impacted the way that each subject performed. The presence of the force plates could potentially alter the subjects' running stride, foot strike pattern, and in vivo loading conditions of the lower extremity joints. The reflective markers used for the motion capture technology were small and lightweight, but they had the potential to affect how each football player performed. The markers were also placed on top of the skin or spandex, which could have caused extra movement that was seen in the reconstructed data of the subjects. Finally, the calculated forces were only estimates, not actual measurements. The markers were sitting on the surface of the skin and the distance between the skin surface and the internal joints or bones was not taken into account for the analysis. All data was averaged and normalized, which further demonstrates that the findings were largely approximated.

CHAPTER II

METHODS

Subjects

Subjects were all comfortable with running and performing football throw patterns at a recreational or student-athlete level. There were two male subjects with ages ranging from 12-18 years old. One subject performed their respective throw patterns barefoot and the other subject performed their throws in a shod condition. Questionnaires on each subject's health were used to confirm that there were no recent injuries or conditions that would affect their performance. Any data belonging to a subject who demonstrated the presence of an adverse health condition were not considered for this study.

Experimental methodology

Since this study aims to investigate both footwear type and football throw pattern, the data for each subject was organized into groups in order to independently analyze each condition. The groups of data were first split up between throw patterns: the Left Hitch Throw versus the Left 3-Step-Drop. In this way, every trial of the same throw pattern for each subject was placed in the same group to compare the internal knee force across the two distinct throw types. Similarly, shod and barefoot conditions were considered within each individual throw group as well as between the entire subject group.

A marker set of 75 reflective markers was employed in this project to obtain kinematic data of the football athletes. This marker set had been previously developed for a quarterback study focusing on the kinematics of the upper extremities. The main goal of the marker set was to obtain clear trajectory data for each subject, so the markers extended to the head, arms, and lower extremities. For the data analysis and force calculations, however, only the markers from the lower limbs and feet were analyzed. The marker set that was previously developed is pictured below in **Figure 2**.

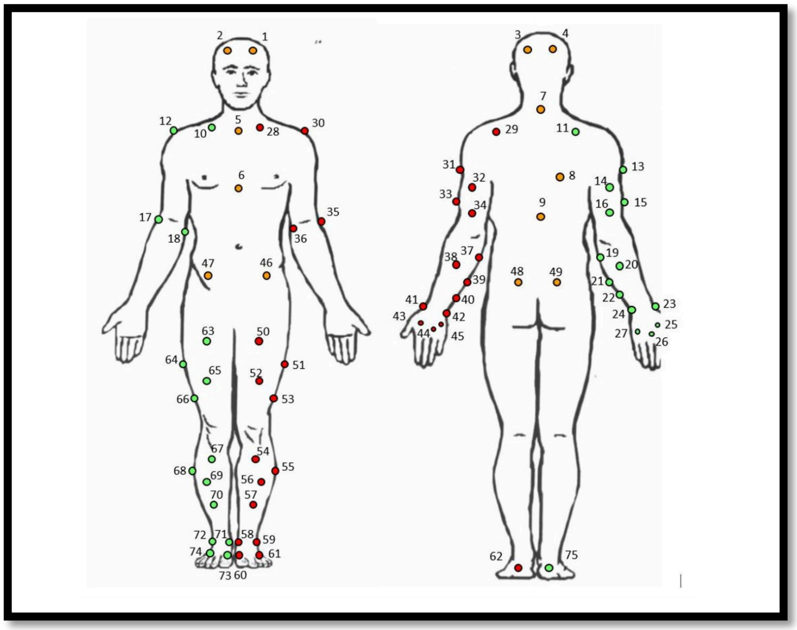

Figure 2. Marker set design. This image shows the placement of the markers on both sides of the subject's body for clarity. The only markers used for analysis were located on the lower extremities and feet (from the hips and down).

Each subject performed multiple trials for each football throw pattern. However, only five trials from each throw type were employed for the general analysis. The data from these five trials were averaged together and normalized. A twelve-camera motion capture system was employed along with four AMTI force plates. 3-dimensional lower body joint kinematics and ground reaction forces were obtained in each trial. The kinematic trajectory data was reconstructed using NEXUS. An image depicting a reconstructed trial is shown below in **Figure 3**.

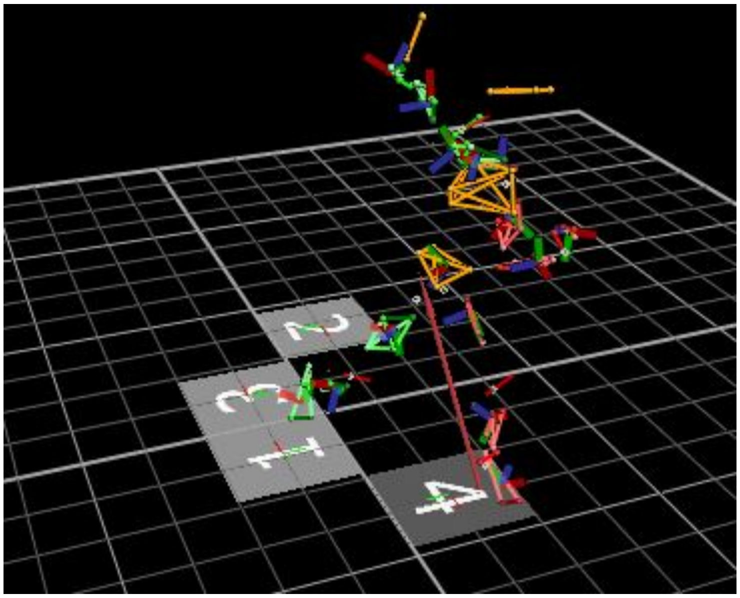

Figure 3. Reconstruction in NEXUS. This image displays a NEXUS reconstruction of the VICON trajectory data of a trial. In the reconstruction, the athlete is throwing the football.

The processed data were analyzed with a custom Python program that computed and compared the knee forces between subjects. The major parameters needed for the estimation of forces were knee extensor moment and knee flexion angle.

The knee flexion angle was found using the aforementioned custom Python program. The program computed and defined two vector segments: one from the hip to the midpoint of the knee and the other from the midpoint of the knee to the midpoint of the ankle. A function to determine the angle between the two vectors was implemented in order to obtain the knee flexion angle measurement.

The knee extensor moment was estimated using a mathematical model that displays the correlation between knee flexion angle and knee extensor moment [14]. The study that the mathematical model was reported in aimed to estimate and quantify the load at the knee joint during various activities, including walking and running [14]. This work, performed by Nisell, resulted in a simplistic biomechanical model that could be applied to movements in which the knee extended [14]. The work incorporated findings from 6 previous studies, including multiple studies that measured various angles of knee flexion and knee moments. The relationship between knee flexion angle and knee extensor moment was modeled by compiling all of the relevant literature together. Utilizing this model, the knee flexion angle data calculated in python was input to determine the corresponding knee extensor moment.

The previously mentioned method of finding the knee extensor moment was used in this study because the knee extensor moment was determined for a specific moment in time (peak force before throw) rather than over the trial as a whole. In the future, it would be ideal to use an online software, like the OpenSim program, to create a customized musculoskeletal model for each subject. OpenSim is a free software that aids in the generation of models and inverse mechanics using kinematic data. OpenSim was briefly used in this preliminary study to simply visualize a generic musculoskeletal model and understand the method of estimating forces and moments with inverse dynamics, but could not be extensively used due to time constraints.

Patellofemoral contact force during running was then determined as a function of these parameters using the mathematical model developed and implemented by Ho et al. and Kulmala et al. based on the cadaver study data obtained by van Eijden et al. [13, 15-16]. In order to find the quadriceps force (F_q), the knee extensor moment (M_k) was divided by the effective moment arm of the quadriceps muscle (L_q) (**1**) [13, 15-16].

$$F_q = M_k / L_q \quad (\mathbf{1})$$

The parameter (L_q) was calculated beforehand as a function of knee flexion angle (x) (**2**) [13].

$$L_q = 8.0E^{-5}x^3 - 0.013x^2 + 0.28x + 0.046 \qquad (\mathbf{2})$$

The patellofemoral contact force was then determined by multiplying the quadriceps force (F_q) by a constant (k) (**3**) [13, 15-16]. The constant, k, was estimated using the data from van Eijden et al. [16].

$$\text{Patellofemoral contact force} = F_q\,k \qquad (\mathbf{3})$$

As previously mentioned, all of the data was normalized and averaged before any analysis was performed. The patellofemoral contact force was not determined for the entire length of each trial, but rather, for a specific moment in time. The moment used was when the subject applied the maximum force to the ground surface during the last step before the football was released. This was determined through the force plate GRF and kept constant across all trials of each subject. Additionally, only the data for the left foot was analyzed for all of the trials across all subjects.

Expected results

It is highly predicted that the shod running condition will lead to the greatest internal patellofemoral force while the barefoot running condition will lead to the smallest force. This is consistent with the findings from previous literature. For football throw pattern type, it is expected that the Left 3-Step-Drop will lead to the greatest in vivo patellofemoral contact force and the Left Hitch will lead to the smallest internal forces. There is no previous literature suggesting this, however, the Left Hitch is the easiest, most natural throw to perform while the Left 3-Step-Drop is more complex. Therefore, the combination of the barefoot condition and the Left Hitch throw pattern is expected to produce the smallest internal loading conditions at the patellofemoral site. This would in theory be the best condition for the reduction of knee injury in football athletes.

Compliance

This study required the acquisition of research compliance granted by the Institutional Review Board (IRB) because of the analysis and use of human subjects for data. The granted IRB was IRB2016-0290D.

CHAPTER III

RESULTS

The first parameter determined and subsequently investigated was the knee flexion angle of each subject. This factor was critical for the calculation of the patellofemoral contact force, as seen explicitly in equation **(2)** from before. As previously mentioned, the knee flexion angle at the moment of maximum force was found for each trial. This was determined instead of a function of the knee flexion angle with respect to time. In future work, it would be best to find the knee flexion angle over the entire trial as a function of time. Each knee flexion angle at the moment of maximum force was averaged for 5 trials of the same throw type. The results are reported below in **Table 1**.

Table 1. Knee flexion at maximum force. This table displays the knee flexion angle (°) of the four conditions: Shod Left Hitch, Shod Left 3-Step-Drop, Barefoot Left Hitch, and Barefoot Left 3-Step-Drop.

	Subject 1: SHOD	**Subject 2: BAREFOOT**
Left Hitch	33.95° (+/- 2.58°)	36.58° (+/- 2.44°)
Left 3-Step-Drop	27.06° (+/- 3.22°)	40.45° (+/- 3.07°)

According to the data presented in **Table 1**, there does not seem to be any clear pattern or correlation between knee flexion angle and throw type. However, there does seem to be a difference in knee flexion angle between footwear conditions. The data obtained displays an overall increase in knee flexion angle for each throw type between the shod and barefoot conditions. This could be due to the disparity between shod and barefoot running biomechanics, or it could be simply due to the athlete's habitual throwing style. In other words, the difference in knee flexion angle between the subjects may not be because of the change in footwear, but rather because each player regularly throws with a certain knee flexion angle. This cannot be determined from the data in this study and should be expanded upon in future work with a much larger sample size and data set. However, in this preliminary study, it is important to note the initial differences in knee flexion angle since this parameter is very crucial in the calculation of the patellofemoral contact force. The results from **Table 1** are more clearly summarized in graphical form in **Figure 4**.

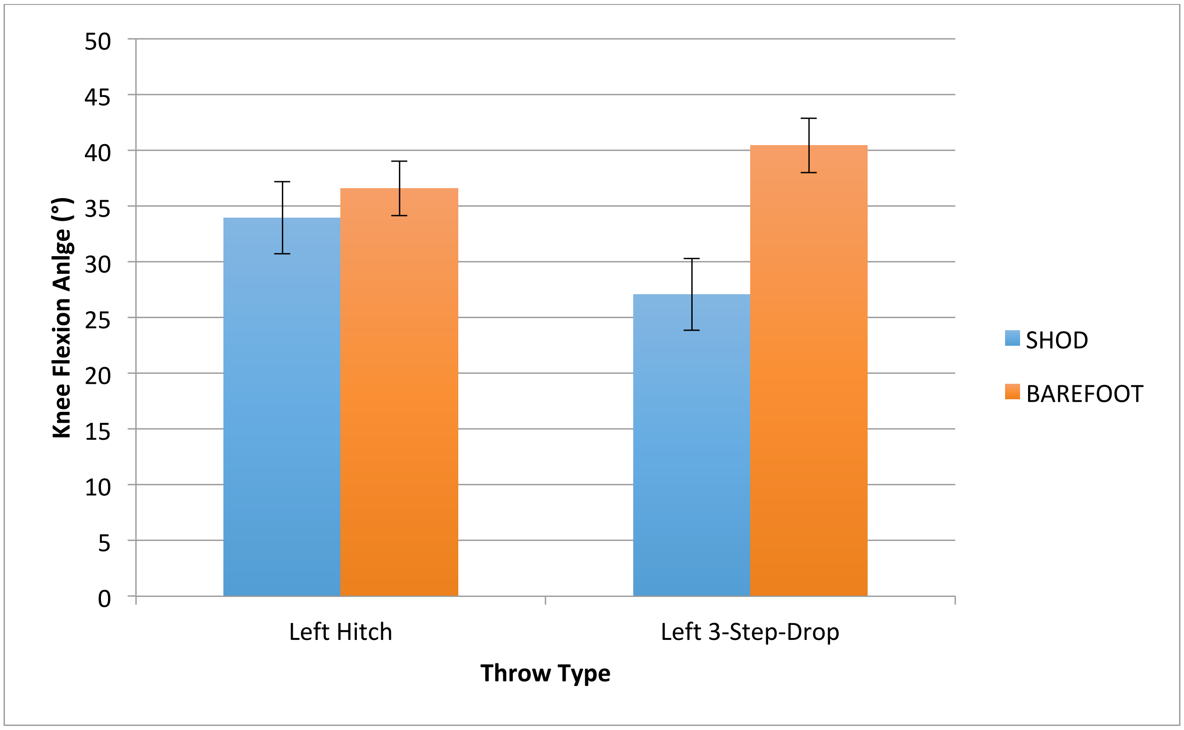

Figure 4. Knee Flexion Angle vs. Throw Type. The graphic displays the data obtained for the four conditions. The data was first split up by throw type and then by footwear type to more clearly show the disparities between the barefoot and shod conditions.

The second parameter that is very important in this study is the knee extensor moment. The knee extensor moment was estimated based on the knee flexion angle calculated at the time the subject applied the maximum force to the force plate. As stated before, the knee extensor moment was calculated using the model developed in the study by Nisell [14]. The calculations for knee extensor moment were all normalized by subject mass ($N \cdot m \cdot kg^{-1}$) and are reported in **Table 2** below.

Table 2. Knee extensor moment at maximum force. This table displays the knee extensor moment ($N \cdot m \cdot kg^{-1}$) of the four conditions: Shod Left Hitch, Shod Left 3-Step-Drop, Barefoot Left Hitch, and Barefoot Left 3-Step-Drop.

	Subject 1: SHOD ($N \cdot m \cdot kg^{-1}$)	**Subject 2: BAREFOOT ($N \cdot m \cdot kg^{-1}$)**
Left Hitch ($N \cdot m \cdot kg^{-1}$)	2.198 (+/- 0.18)	2.381 (+/- 0.16)
Left 3-Step-Drop ($N \cdot m \cdot kg^{-1}$)	2.123 (+/- 0.13)	2.644 (+/- 0.21)

As seen in the table above, the condition with generally the highest overall knee extensor moment was the barefoot 3-Step-Drop condition. It was seen that the barefoot conditions both had a higher average knee extensor moment.

Finally, the patellofemoral contact force was estimated for each subject at the time of peak force. This data was normalized (BW) by dividing the patellofemoral contact force by the subject's mass. The findings are displayed in **Table 3** below. It can be seen that the patellofemoral contact force is generally higher in the shod condition and lower in the barefoot condition. There are not any patterns that can be found between throw types for this internal force. The standard deviation is fairly high for this data, which prevents conclusions to be drawn between the variables.

Table 3. Patellofemoral Contact Force. This table displays the patellofemoral contact force (BW) of the four conditions: Shod Left Hitch, Shod Left 3-Step-Drop, Barefoot Left Hitch, and Barefoot Left 3-Step-Drop.

	Subject 1: SHOD	**Subject 2: BAREFOOT**
Left Hitch	3.50 BW (+/-0.45)	3.13 BW (+/- 0.27)
Left 3-Step-Drop	3.58 BW (+/- 0.36)	2.96 BW (+/- 0.43)

The data from **Table 3** is more clearly depicted in **Figure 5**.

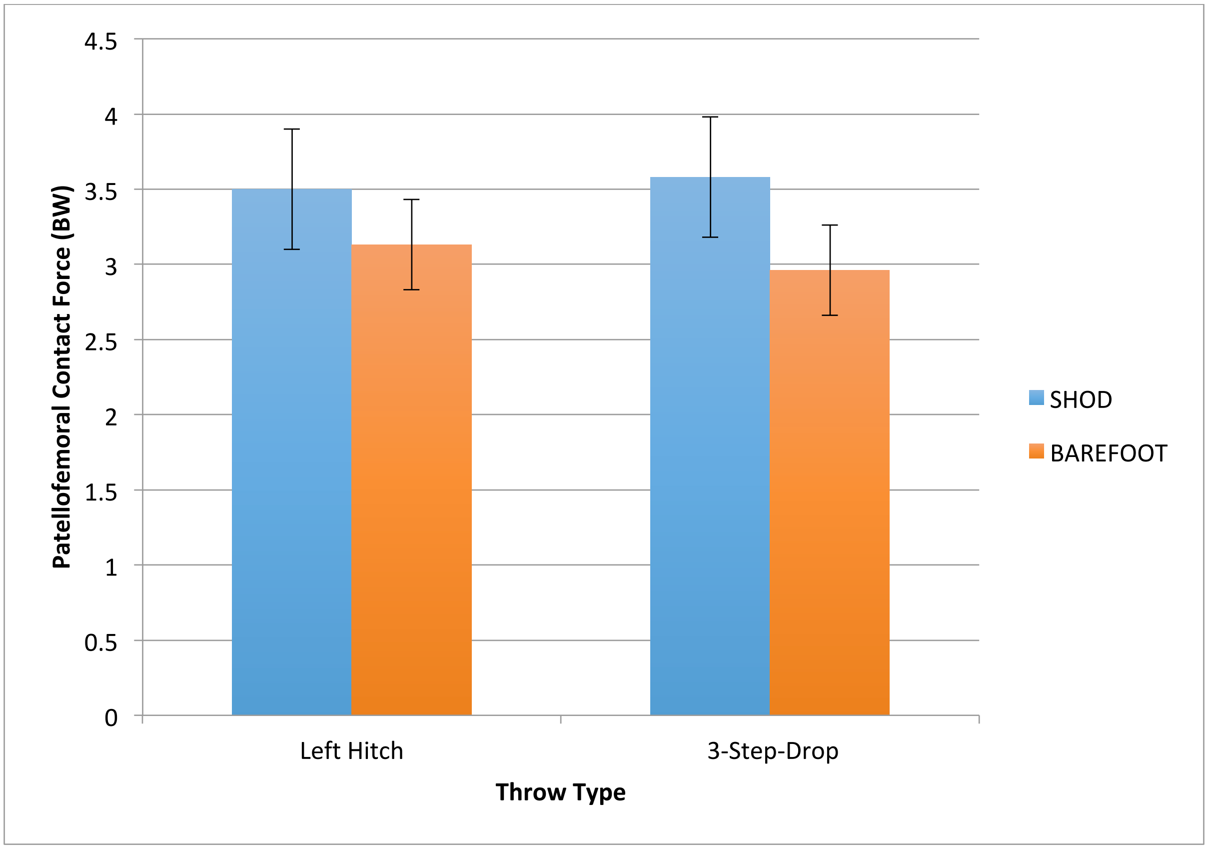

Figure 5. Patellofemoral Contact Force vs. Throw Type. The graphic depicts the data over the four different conditions. Like before, the data was first split up by throw type and then by footwear type.

CHAPTER IV

CONCLUSION

Discussion

This research was a small, preliminary study analyzing how specific factors affect the magnitude of the internal patellofemoral contact force in football athletes. The endeavor of this study was to determine what footwear and throw conditions lead to the greatest reduction in the joint contact force at the knee. With this information in mind, specific practices can be related to lower or higher in vivo forces and thus lower or higher potential injury occurrences. Additionally, another aim of this project was to develop an adequate experimental method to analyze and estimate internal forces. The design of this study can be adapted to other sports under investigation and can be repeated with a larger sample size to confirm its accuracy. Ultimately, the data analysis performed in this research study can help suggest methods of injury reduction in football athletes.

In this study, it was determined that there are important differences between the biomechanics of shod and barefoot conditions. In all three parameters investigated, there was an observable disparity between the two subjects. The main variable under analysis, the patellofemoral contact force, was seen to decrease in the barefoot condition and increase in the shod condition. This is consistent with the previous literature, especially the work done by Kulmala et al., which suggests that running barefoot causes a significant change in FSP that ultimately reduces the loading at the knee [13]. Therefore, it is important for an athlete to consider the biomechanical changes that occur when changing their footwear condition. Based on the results obtained in this study, athletes should try to mimic the barefoot condition during physical, dynamic activity. Barefoot running has the potential to reduce the patellofemoral contact force experienced by the athlete compared to running in shoes. The reduction of the internal knee joint contact force could ultimately lead to reduced pain and injury at that site.

Though it was found that there was a visible difference between barefoot and shod conditions, this may not have been because of the manipulation of variables in this study. Since there were only two subjects, the difference in knee flexion angle, knee extensor moment, and the patellofemoral contact force could have been because of the habitual difference in technique between the two football athletes. Therefore, no conclusions can be drawn from this study until it is repeated with a much larger group of athletes. However, though this study was small, the preliminary data can be taken under consideration and it is suggested that the differences found in this study be investigated further.

There was no observable difference in the patellofemoral contact force between the Left Hitch and Left 3-Step-Drop throw types. Further analysis will have to be done with a greater sample size and trial number to determine if there are any significant changes that occur in the forces internal to the knee when the throw type is altered.

The three objectives of this project, to develop an experimental method of analysis (1), actually estimate the in vivo patellofemoral contact force in different conditions (2), and create a python program to aid in my calculations (3), were all achieved successfully. Due to time constraints and such a small study size, it was difficult to confirm if my second objective was completed accurately. However, the basis of this project and the experimental methods developed over the course of this research compose a solid foundation for future work in this subject.

Future Work

The limitations of this study prevent the aforementioned conclusions to be extended to a wide range of the population. In the future, the study would be performed with a larger, more variable sample size. Additionally, the research would be performed with different subject groups to make sure the study has adequate repeatability. As previously stated, it was not clear whether the obtained results were due to the manipulation of the parameters being tested or due to the innate differences in the habits of the subjects themselves during athletic competition. Even though this study did not give any statistically significant information, the preliminary results demonstrate that there could potentially be important differences between the patellofemoral biomechanics of shod and barefoot conditions. Thus, it is worth investigating these results further with a similar, yet much larger, study.

Additionally, subjects of both genders should be investigated in the future to identify if there are significant differences between the internal forces at the patellofemoral site. Many studies have suggested and subsequently demonstrated that there are important disparities in the biomechanics between male and female athletes during dynamic physical activity [17]. Therefore, it is important to quantify and analyze the extent of the differences.

As stated before, it has been demonstrated that the parameters of FSP and footwear condition are closely linked. FSP was not individually investigated in this research study, but in the future it would be important to consider isolating FSP from footwear condition to identify the effects of each parameter by themselves. This could be done by recruiting habitual FFS athletes and habitual RFS athletes and analyzing the shod and barefoot conditions of each athlete.

Moreover, in future work, analyses can be done on the kinematic chain and the internal forces at different discrete throw events. In this study, the patellofemoral contact force was found for a distinct point in time, rather than for the whole trial. This can be expanded upon by determining the patellofemoral contact force as a function of time to develop an understanding of how the internal force changes through the dynamic movement of the athlete. Ultimately, this can lead to a full investigation of how the in vivo knee joint force differs at the important events characteristic of a typical football throw. Further investigation can be done with long-distance runners to identify how the patellofemoral contact force changes over the gait cycle (% gait).

Lastly, in the future, it would be ideal to analyze different types of athletes and their respective movements since the biomechanics of each sport can differ significantly. For example, the study could be adapted and repeated for long distance runners or soccer players. Many previous studies have investigated the patellofemoral joint in runners and have determined that shoe condition and FSP are important factors that can affect gait and biomechanics. Therefore, in the future, these studies can be built upon further with the type of analysis done in this research project. It would be insightful to understand how the methods developed in this study can be extended for the analysis of in vivo forces in other athletes and their respective sports.

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