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### Kinematic and Kinetic Analyses of E-TPU Material in Bowling Footwear

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Kinematic and Kinetic Analyses of E-TPU Material in Bowling Footwear

Tsung-Lin Lu

Submitted to the Graduate School of Bridgewater State University

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN PHYSICAL EDUCATION

May 2019

Kinematic and Kinetic Analyses of E-TPU Material in Bowling Footwear

A Thesis Presented

By

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May 2019

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## Abstract

The purpose of this study was to examine the effects of midsole construction (barefoot, traditional bowling shoes with minimalist midsole design, and the modified bowling shoes with E-TPU midsole design) on the amount of shock absorption and the mechanics of bowling delivery. All shoes underwent static testing on top of a force platform. The static test involved dropping a 0.5 kg dumbbell inside a PVC pipe from a height of 0.61 meters onto the heel cup region in each type of shoe. Twelve healthy, college, right-handed recreational males participated in dynamic testing of bowling delivery. Data collection took place at the Biomechanics Laboratory. Participants stood five meters away from cushioning mat and performed a four-step approach to roll the bowling ball on top of a mat. A Casio high speed camera was set up to capture the right sagittal view of bowling ball delivery at 120 Hz in conjunction with a 650 watts spotlight. Every participant was asked to bowl five balls in each type of footwear, so a total of 15 bowls were collected for each participant. A total of 180 trials were collected in this study. Force plate data were recorded at 1000 Hz with Vicon Nexus software to evaluate the amount of shock and force absorption. Ariel Performance Analysis System (APAS) software was used to measure the 2D body kinematic joint angles and velocities of hip, knee, and ankle, stride length, and linear ball velocity. For the static testing, a t-test was conducted to compare the amount of vertical ground reaction force between the traditional bowling footwear with minimalist midsole design and the modified bowling footwear with E-TPU midsole design. For the dynamic testing, a one-way repeated measure ANOVA for the initial peak vertical force ( $F_z$ ), the rate of loading, and peak vertical ground reaction force to body weight ratio were compared between three different footwear conditions. A one-way repeated ANOVA ( $\alpha = 0.05$ ) for the joint angles and velocities of hip, knee, and ankle, stride length, and linear ball velocity were compared between three different footwear conditions. Post hoc pairwise comparisons were conducted using t-test with Bonferroni adjustment if a statistical significance was found. The kinetic results indicate that the bowling footwear with the E-TPU material provided lower amount of initial peak vertical ground reaction force and rate of loading, which may potentially be beneficial to bowlers to minimize lower

extremity injury. However, there was no significant difference found in the peak vertical ground reaction force with respect to each participant's body weight. The findings of this study provide a preliminary understanding on the effects of the E-TPU material on shock absorption in bowling footwear. The kinematic results indicate that no significant difference was found in the lower extremity for the joint angles and velocities of hip, knee, and ankle, stride length, and linear ball velocity. The findings of this study could help practitioners understand that bowling footwear does not alter mechanics of bowling delivery and also provide further understanding on the effect of footwear cushioning on athletic performance. Sports footwear developers may use this information to construct appropriate footwear to minimize injury. Future studies are warranted to evaluate 3D motion analysis with experienced bowlers at the bowling alley and the internal joint forces and torques of bowling delivery mechanics with the E-TPU material footwear.

**KEYWORDS:** bowling, e-tpu, kinematic, kinetic, midsole.



Bowling is one of the most popular indoor sports in the world and can be divided into several different categories that include five-pin, nine-pin, ten-pin, candlepin and duckpin. In all categories proper footwear (i.e. bowling shoes) is required to play the game. Bowling footwear consists of four components: upper, insole, midsole, and outsole. First, the upper portion is typically above the sole and is usually made of leather, suede, or synthetic material. This portion of shoe helps fit the shoe onto the foot and is often embellished or given different styles to make the shoe attractive. Secondly, the insole is the interior bottom of shoe and is removable and replaceable. The intent of the insole is to provide foot arch support and control moisture inside the shoe. Thirdly, the midsole lies between the insole and the outsole for shock absorption. The design of midsole can be beneath the heel, toe, or even entire foot in order to absorb the greatest amount of ground reaction force. Finally, the outsole is the exterior bottom of the shoe that is in direct contact with the ground. The design of outsole has a particular purpose as for sliding and braking in bowling delivery because bowlers need to take a stride, and slide and brake simultaneously to release the bowling balls. Therefore, the slick area of the outsole, usually made of microfiber, helps with the slide, while the traction pad, made of higher friction material like rubber, helps the bowlers to brake (DeMello, 2009).

Bowling is a popular and sophisticated sport that requires precise motion and timing, and the most common bowling delivery are the four-step and five-step which involve three different phases, preparation, movement, and follow through. The preparation phase takes place when the bowler carries out the stance position. The movement phase initiates with the first step of the approach and ends with the last step approach, and the follow through phase begins immediately after releasing the bowling ball. In the mechanics of bowling delivery, the lower extremity is crucial because the ability to slide the front foot consistently will affect bowler's ability to deliver the bowling ball more accurately (Razman et al., 2010). Improper gait, mechanics, or footwear can possibly increase the risk of lower extremity injuries such as adductor muscle strains, ankle sprains, and knee ligament injuries (Hsiao et al., 1996). Kerr et al. (2011) conducted an investigation to examine bowling-related injuries presenting to US emergency departments. The report showed there were 8,754 injuries in bowling

from 1990 to 2008, and the rate of occurrence on lower extremity injuries was approximately 14.9%. In addition, according to the National Electronic Injury Surveillance System in the United States, there was an average of 11,295 injuries each year between 2002 to 2014 in bowling. The incident rate of knee injury was approximately 12%. Additionally, a recent research study was conducted to evaluate the injury rate of bowling during an intercollegiate bowling championship, and the results showed that the thigh and knee regions had an injury rate of 25.9% and 22.2%, respectively (Liu, Chung, Lin & Lee, 2011).

These findings suggest that it is crucial to understand the mechanism of these bowling injuries. One of the causes may be due to improper footwear. The bowling footwear can be classified into three different categories; rental, athletic, and performance. Bowling shoes are similar to other athletic footwear that are constructed with three key principles: performance, injury protection and comfort. The current design of bowling shoes has the midsole portion made of minimalist leather for rental bowling footwear, and rubber, Ethylene Vinyl Acetate (EVA) or Polyurethane (PU) for athletic and performance bowling footwear, which may potentially influence mechanics of bowling delivery with various types of midsole design footwear. In addition, the high incident rate of bowling may be attributed to unique bowling competitive rules and regulations. For example, a typical bowling competition consists of six games, and a standard bowling championship consists of five events including single, double, trios, group, and master. If a participant uses a five-step approach in his/her bowling delivery, he or she needs to deliver between 72 to 126 balls per event and also has to perform between 360 to 630 steps per event. On average each event takes between three to four hours to complete. Due to the repetitive of foot contact with the ground and long duration of the usage as in running, serious injury may occur in the lower extremity if proper bowling footwear is not worn. Hence, it is critical to investigate different footwear material for the midsole section of the bowling shoe in order to minimize lower extremity injury.

Badische Anilin- und Soda-Fabrik (BASF), the largest chemical company in the world, recently developed a material called Expanded Thermoplastic Polyurethane (E-TPU) which combines

the properties of TPU with the advantages of foams, making shoes more comfortable to wear and providing greater shock absorption. The E-TPU can be molded into different shapes and forms which makes it flexible in design. The properties of E-TPU include lightweight, shock impact absorption, elastic, re-bounce effect, softness, resilience, and durability (BASF, 2017). A major athletic footwear corporation, Adidas, successfully applied and adopted E-TPU material in the midsoles section of their athletic footwear in several sports including running, basketball, tennis, baseball, and golf. The main usage of E-TPU in the midsole section of these shoes is to reduce shock and force absorption. However, the E-TPU material has yet been used in the bowling footwear. Therefore, the purpose of this study was to design the midsole section of bowling footwear using E-TPU material and to evaluate the amount of shock and force absorption that the bowling shoe with E-TPU material can sustain during bowling delivery, and to examine the effects of midsole construction on the mechanics of bowling delivery. The results of the study would enable practitioners to have a better understanding the effects of shock absorption on footwear with E-TPU material and the effects of footwear cushioning on athletic performance, so proper footwear can be worn by bowlers to increase athletic performance and to minimize lower extremity injury.

## Literature Review

### Ancient and Modern Bowling

Modern bowling is an indoor sport in which a participant scores by striking down as many pins as possible with a bowling ball rolled along a wooden or polyurethane lane; however, the origin of bowling could be dated back several millennia. The earliest history of bowling can be traced back to ancient Egyptian time because a British anthropologist named Sir Flinders Petrie discovered a collection of objects in a child's grave in Egypt in the 1930's that appeared to be a crude form of bowling, Figure 1. These artifacts have been dated back to 3,200 BC, effectively making bowling over 5,000 years old (Fuss, Kong, & Tan, 2006). The next historical bowling related discovery was found around 300 A.D. by a German historian named William Pehle. He asserted that most Germans carried Kegels, a wooden and pin-shaped rod, and it was believed that knocking down these Kegels with a rock would pardon their sins - a most popular religious ceremony at that time (Help with Bowling, 2017), Figure 2.



**Figure 1 Evidence of Bowling in Egypt in the 1930's**  
(from International Bowling Museum & Hall of Fame, 2019)



**Figure 2 Evidence of Bowling in Germany around 300 A.D.**  
(from PC Archaeology, 2019)

Around 1366, bowling was banned by King Henry III because British soldiers were distracted and could not concentrate on archery practice (Fuss, Kong, & Tan, 2006), Figure 3. By the 1400s, bowling was allowed in England again and British built the roof on the top of bowling lanes and turned bowling into a sport that could be played in severe weather (The Bowling Universe, 2017). Bowling was brought by European settlers to America in the 19<sup>th</sup> century, Figure 4. At that time, the ancient game of ninepin bowling was a very popular sport. Unfortunately, bowling became a favorite activity for gamblers. The government of the state of Connecticut passed an 1841 law that forbade playing and owning a ninepin bowling alley. In order to keep bowling, people simply modified the rules of the game by adding an extra pin to the bowling setup to create tenpin bowling which has shown to be more popular than ninepin bowling.



**Figure 3 The 14th Century Bowling in England**  
(from Help with Bowling, 2019)



**Figure 4 Evidence of Bowling in North America in the 19th Century**  
(from The Bowling Universe, 2019)

Presently, bowling has been developed into several different categories that include five-pin, nine-pin, ten-pin, candlepin and duckpin, Figure 5. The purpose of the game is to approach and roll a bowling ball from the foul line down to the lane in attempt to knock down pins. For example, one tenpin bowling game consists of ten frames in which a bowler scores by striking down as many pins as possible and each individual is allowed two attempts per frame to knock down the pins. Knocking down all ten pins on the first ball is considered as a strike, whereas knocking down all ten pins on the second ball is termed a spare. Once a game is completed, the registered score will range from 0 to 300 points and the maximum points can be scored in a single game is 300 with 12 consecutive strikes which is also called a perfect game. Tenpin bowling is played by more than 95 million people worldwide in over 90 countries and governed by the World Bowling and United States Bowling Congress (The Bowling Universe, 2017).



**Figure 5 Different Categories of Bowling**  
(from Hans Sommer, 2019)

World Bowling first began in 1926 as the International Bowling Association (IBA). In 1952, the IBA developed into to Fédération Internationale des Quilleurs (FIQ – International federation of Bowlers) to advocate worldwide interest in tenpin and ninepin bowling, as well as international friendship by hosting world and zone tournaments, and other competitions between bowlers from different countries. FIQ has been recognized by the International Olympic Committee since 1979 as

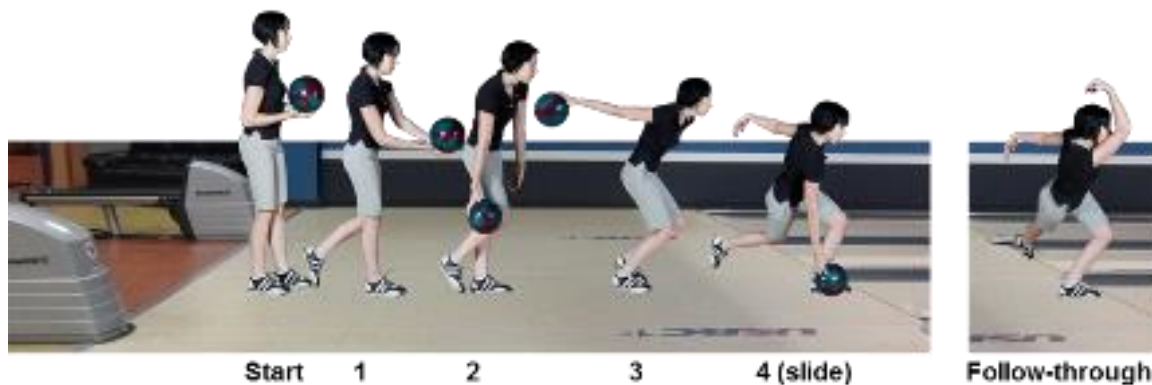
the world governing body for the sport of bowling. In 2014, the international bowling organizations of the FIQ united under the new brand name of World Bowling to expand the reach and relevance of bowling worldwide. World Bowling is an autonomous administration and is responsible for promoting the development of bowling throughout the world. World Bowling has strived to make bowling an Olympic sport, established the rules for bowling, and ensured that all official bowling activities meet the requirements of the Olympic Charter (World Bowling, 2017).

The United States Bowling Congress (USBC) officially launched in 2005, as the organization to serve almost every level of bowlers in America. Today, USBC serves nearly two million members. USBC is the national governing body of bowling as recognized by the United States Olympic Committee (USOC). USBC provides standardized rules, regulations and benefits to make bowling fair for everyone and stands for values that include commitment, innovation, integrity, inclusiveness and fun. USBC supports various programs that include USBC Youth, High School, Collegiate, Coaching, Team USA and Junior Team USA, Tournaments, Playing Rules, Equipment Specification and Certification. The mission of USBC is to offer services, resources and the standards for the sport, and the vision is to continue to be the leading authority to the sport, servicing the needs of bowling (United State Bowling Congress, 2017).

### **Bowling Mechanics, Footwear and Common Injuries**

Bowling is a sophisticated sport that requires precise motion and timing, and the most common bowling deliveries are the four-step and five-step which involve three different phases: preparation, movement, and follow through, Figure 6. The preparation phase takes place when the bowler carries out the stance position. The movement phase initiates with the first step of the approach and ends with the last step approach, and the follow through phase begins immediately after releasing the bowling ball. Fuss (2008) has categorized the kinematics of bowling ball which can be divided into three different types of shots. First, a “straight ball” is used commonly by beginners and is also a useful release for picking up spares. The straight ball is executed by rolling the bowling ball in a

straight route from the foul line down to the lane. Second, a “hook ball” is utilized mostly by professional bowlers and is released in a smooth arching route down to the lane. The hook ball will help the bowlers get more strikes, as the bowling ball rotates as it hits the pins creating pin action. Third, a “spin ball” was invented by Taiwanese bowlers and common used by bowlers in Asia. The spin ball is performed by rotating the bowling ball counterclockwise and delivered in an unconventional path through the pins creating a domino effect to knock down pins.



**Figure 6 Four-Step Bowling Delivery**  
**(from United State Bowling Congress, 2019)**

In order to bowl, bowlers are required to wear specific footwear because most street shoes could harm the wooden or polyurethane surface of the lane. Each pair of bowling footwear is designed for a particular purpose such as sliding and braking. Bowling footwear are classified as rental, athletic, and performance, Figure 7. The rental bowling footwear have the sliding outsoles on both toes as well as tractions on both heels and can be worn by both right or left-handed bowlers. Similarly, the athletic bowling footwear are designed with the slick area on the toe region for sliding and the traction pad on the heel region for braking and can be used by both right or left handers. The performance bowling footwear are geared to helping bowlers improve their performance. The design of outsole on sliding foot is usually made of microfiber or similar material that will permit bowlers to take a stride easily at the last step of bowling delivery, while the design of outsole on non-sliding foot is usually



made of rubber or higher friction material that will provide traction and braking during bowling delivery. The sliding outsole and traction pad on performance bowling footwear are interchangeable so bowlers can adjust the sliding outsole and traction pad on both feet while playing on different types of floor surface (DeMello, 2009).



**Figure 7 Different Categories of Bowling Footwear  
(from USBC High School Coaching Guide, 2019)**

In order to generate greater momentum in bowling, bowlers choose a heavier ball (Strickland, 1996). In turn, bowlers are susceptible to upper extremity injuries, which normally occur in the hand and fingers since holding the heavy bowling ball requires the bowler to place the thumb, middle finger and ring finger into three holes drilled into the bowling ball. Such injuries can potentially hurt tendons and ligaments (Barton, 1997). Hence, most recent research and studies in bowling have been concentrated on the investigation of upper extremities (Tan, Aziz & Chuan, 2000; Tan, Aziz, Teh & Lee, 2001; Fuss, 2009). However, bowlers should also focus on their lower extremities because the ability to slide the front foot consistently will affect bowler's ability to deliver the bowling ball more accurately (Razman, Abas, & Othman, 2010). Lower extremity injuries in bowling are related to the bowler's gait, mechanics, and footwear while delivering the bowling ball. Improper gait, mechanics, or footwear can possibly increase the risk of lower extremity injury such as adductor muscle strains, ankle sprains, knee ligament injuries and femoral shaft fractures (Hsiao, Chen & Tu, 1996). In addition, the high incident rates of bowling may be attributed to unique bowling competitive rules and

regulations. For instance, a general bowling competition consists of six games. If a bowler uses a four-step bowling delivery, he or she needs to bowl between 72 to 126 balls and perform between 288 to 504 steps in six games. Due to the repetitive of sliding and breaking on the feet and twisting torque on the hip for the bowling delivery, bowlers tend to be overuse and are prone to acute or chronic injuries on the lower extremity. Hence, some recent investigations in bowling-related injuries have been reported with high-frequency rates on lower extremities of thigh, knee, ankle, foot, and toe (Kerr et al., 2011; Liu et al., 2011; National Electronic Injury Surveillance System in the United States, 2017). Thus, it is critical to investigate the gait cycle of bowling approach, mechanics of bowling delivery, different footwear material for the midsole section of the bowling shoe in order to provide an important understanding for bowling practitioners and footwear developers to prescribe appropriate bowling training programs and construct appropriate bowling footwear to minimize bowling-related injuries.

### **Cushioning Characteristics of Athletic Footwear**

In sports biomechanics, the investigation of athletic footwear has become one of the most important and popular issues for several decades because the results can have profound impact on optimizing athletic footwear construction for comfort, protection, performance, support and shock absorption (Nebo, 2005; Lloyd & Wu, 2013). Since Nigg & Segesser (1992) evaluated the characteristics of cushioning and stability in athletic footwear, the design of cushioning on athletic footwear has received much attention on the balance and shock absorption in biomechanics research (Robbins & Waked, 1997). Athletic footwear can be separated upper and lower parts. The upper part can be made of fabric, leather, suede, mesh or synthetic material, and a lower part, a flexible sole that consists of insole, midsole, and outsole that are made of rubber, or other materials, especially the midsole section provides stability and cushioning at the interface between the ground and the plantar surface of the foot (Hilgers et al., 2009).

Brückner et al. (2010) has reported that most athletic footwear midsoles are made of Ethylene Vinyl Acetate (EVA) and polyurethane (PU). EVA is the standard material for midsole on athletic

footwear because it provides durability and flexibility at low density. PU is currently used in manufacturing as sole material of casual footwear since it is known to display excellent mechanical long-term property. Hence, research studies in athletic footwear have been focused on the ability of shock absorption during running with regard to durability in the design of midsole section (Brückner et al., 2010; Hennig, 2011; Liang & Chiu, 2010; Schwanitz & Odenwald, 2008; Verdejo & Mills, 2004; Wang et al., 2012). Some investigations have indicated that the deterioration of shock absorption occurred due to structural damage in the foam of midsole when the usage increased after long-distance running, range from 300 km to 750 km (Liang & Chiu, 2010; Schwanitz & Odenwald, 2008; Verdejo & Mills, 2004; Wang et al., 2012). Nonetheless, Hennig (2011) has completed an 18 years of running footwear testing in Germany and suggested that high quality running footwear should be able to maintain good functional stability and cushioning properties after long-term usage. Thus, the durability for a high-quality running footwear is expected to be much longer than 1,000 km.

The hardness of midsole is one of the most crucial characteristics for athletic footwear during running (Baltich et al., 2015; Clarke, Frederick & Cooper, 1983; De Wit et al., 1995; Kersting & Brüggemann, 2006; Nigg et al., 1987). Some research studies have reported that running with hard midsoles resulted in the similar magnitude of vertical ground reaction force as running with soft midsoles (Clarke, Frederick & Cooper, 1983; Kersting & Brüggemann, 2006; Nigg et al., 1987) although running with hard midsoles would reach the first peak faster than running with soft midsoles (Clarke, Frederick & Cooper, 1983). Interestingly, De Wit et al. (1995) demonstrated that hard midsoles showed smaller impact force on initial phase of foot contact during running, and Baltich et al. (2015) also illustrated that the vertical impact was significantly greater for the soft midsole than for the medium midsole and hard midsole during running. Apart from kinetic effects, most kinematic changes occurred on the lower extremities due to the different hardness of midsole (Baltich et al., 2015; De Wit et al., 1995; Hardin et al., 2004). De Wit et al. (1995) discovered that running with harder midsole would have obvious initial eversion in the heel angle and the Achilles tendon angle. Additionally, Hardin et al. (2004) also found that harder midsoles would cause an increase in knee flexion velocity

during running. However, Baltich et al. (2015) observed the contrary finding that apparent ankle joint stiffness increased as shoe midsole hardness decreased.

During landing, the thickness and density of midsoles for athletic footwear have been used to evaluate the attenuation of impact force (Bowser et al., 2017; Fu et al., 2013; Nolan et al., 2005; Oliver et al., 2011; Soares et al., 2018; Zhang et al., 2005). Nolan et al. (2005) proposed that the variation of midsole densities on athletic footwear had no significant influence on peak vertical ground reaction force after landing from a volleyball spike approach jump, whereas Zhang et al. (2005) claimed that the vertical ground reaction force was significantly greater for the hard midsole than for the soft midsole and normal midsole during basketball landing activities. In addition, Bowser et al. (2017) indicated that the peak vertical force was significantly lower in the barefoot conditions compared to minimalist cushioning conditions and standard athletic footwear conditions during single-leg landing. However, Soares et al. (2018) showed that thicker midsoles provided more cushioning, decreasing vertical ground reaction force and rate of loading compared to barefoot and minimalist footwear on single-leg drop landing. Furthermore, other research studies have also confirmed that the thickness of cushioning can significantly affect impact attenuation during drop landing (Oliver et al., 2011), and during unanticipated drop landings. (Fu et al., 2013). Additional to kinetic analyses, research studies in athletic footwear have been focused on the kinematic changes of lower limb joints during landing (Hong et al., 2014; Oliver et al., 2011; Yeow et al., 2010; Zhang et al., 2005). Some research studies have shown that no significant differences in knee displacement on both legs between three different drop landing conditions (Oliver et al., 2011), and the range of motion and maximum velocity of ankle, hip, and knee showed no significant differences between these conditions (Zhang et al., 2005). On the contrary, some studies have suggested that shoed conditions displayed greater knee flexion angles than barefoot conditions during double-leg landing (Yeow et al., 2010), and both knee and ankle movements increased during single-leg landing in shoed conditions compared to barefoot conditions (Hong et al., 2014).

The athletic footwear industry is focused on researching, discovering, and developing an innovative material for cushioning in the midsole section. Badische Anilin- und Soda-Fabrik (BASF), the largest chemical company in the world, recently introduced a newest material called Infinergy<sup>®</sup> that is the world's first Expanded Thermoplastic Polyurethane (E-TPU). The closed-cell, elastic particle foam combines the properties of TPU with the advantages of foams and the key features are low density, high elasticity, outstanding resilience, high abrasion resistance, high tensile strength, good chemical resistance, and good long-term durability in a wide temperature range. The E-TPU can be applied in several areas such as footwear industry, sports equipment, vehicle construction, and mechanical engineering (BASF, 2017). Adidas and Puma, two prestigious sporting goods companies, successfully applied and adopted E-TPU material in the midsoles section of their athletic footwear. The main usage of E-TPU in the midsole section of these shoes is to absorb shock impact on the foot during jogging or running and provide rebound effect to improve sports performance during exercise. However, the E-TPU material has yet been used in the bowling footwear. Thus, it is crucial to design the midsole section of bowling footwear using E-TPU material and to examine the kinetic and kinematic parameters that the bowling shoe with E-TPU material can absorb shock impact on single-leg landing and reduce movements on lower extremity joints at the last step of bowling delivery.

## **Summary**

Bowling is not only suitable for competition but also appropriate for leisure activity. Children, adults, and elders of almost all age groups can participate, and it can be enjoyed as a leisure, recreational, and social activity. Bowling footwear is required to play the game and can be classified in three different categories, including rental, athletic, and performance. Generally, competitive or senior bowlers have their own personal athletic or performance bowling footwear. Most recreational participants rent bowling footwear at the front counter of bowling alley. Athletic and performance bowling footwear are usually made of EVA or PU midsoles. Therefore, these types of bowling footwear may provide the attenuation of shock absorption to a certain degree. However, rental bowling

footwear provide minimal amount of cushion. Bowling is one of the sports that has features of walking, running and landing movements. The characteristics of gait cycle in bowling approach is similar to walking and running that contains the rear-foot contact, fore-foot contact, heel-off, and toe-off. In addition, the last step of bowling delivery is unique because the front foot acts as a slide and brake to absorb the impact force from the ground during landing; no toe off or push off is involved as in walking and running. Since impact forces and shock waves have been identified as one of the key factors in the preventive of sports injuries due to the repetitive of foot contact with the ground, serious injury may occur in the lower extremity if proper athletic footwear is not worn. Moreover, Lloyd & Wu (2013) have also indicated that dynamic shock waves are generated through repeated ground impacts, and athletic footwear with adequate cushioning may attenuate the skeletal shock waves produced by such impacts. Research studies are published on athletic footwear, where various abilities involve shock absorption, cushioning, stability, and energy return are being researched, discovered, and developed, bowling footwear is a field that is unexploited. Additionally, the E-TPU material has been used in variety of athletic footwear. Therefore, the purpose of this study was to examine the amount of shock and force absorption that the bowling footwear with the E-TPU material could sustain during bowling delivery in both kinematic and kinetic analyses and the effects of midsole construction on the mechanics of bowling delivery. This study hypothesized that the bowling footwear with the E-TPU material could lower the vertical ground reaction force and reduce the movements on lower extremity joints during bowling delivery. The results of this study could enable practitioners to have a better understanding on the effects of shock absorption on footwear with E-TPU material and the effects of footwear cushioning on bowling performance, so bowlers can increase athletic performance and minimize lower extremity injury.

## **Methods**

### **Participants**

Twelve healthy, college, right-handed recreational male participants (height  $1.76 \pm 0.06$  m; weight  $76.5 \pm 10.8$  kg; age  $25 \pm 4$  years old) volunteered for dynamic bowling testing. Approval from the Institutional Review Board (IRB) at Bridgewater State University was obtained prior to the study, and all participants were volunteers. All volunteers signed a consent form prior to their participation in the study. No participants had any lower extremity injury within the last six months.

### **Experimental Setup**

Data collection took place at the Biomechanics Laboratory. Five meters (16 ft.) approach was marked with tape from starting line to the force plate. This distance was chosen because it is equal to the length of the lane approach in a bowling alley. AMTI force plate recorded at 1,000 Hz with Vicon Nexus software (v. 1.8) to evaluate the amount of shock and force absorption. Additionally, a Casio high speed camera (Model: EX-FH 25) was set up to capture the right sagittal view of motion of bowling ball delivery at 120 Hz in conjunction with a 650 watts spotlight, so the effects of footwear on lower body mechanics could be examined, particularly at the thigh and knee regions. Twenty meters cushioning mat (64 ft.) was placed on the ground behind the force plate in order to provide protection to the floor, Figure 8.

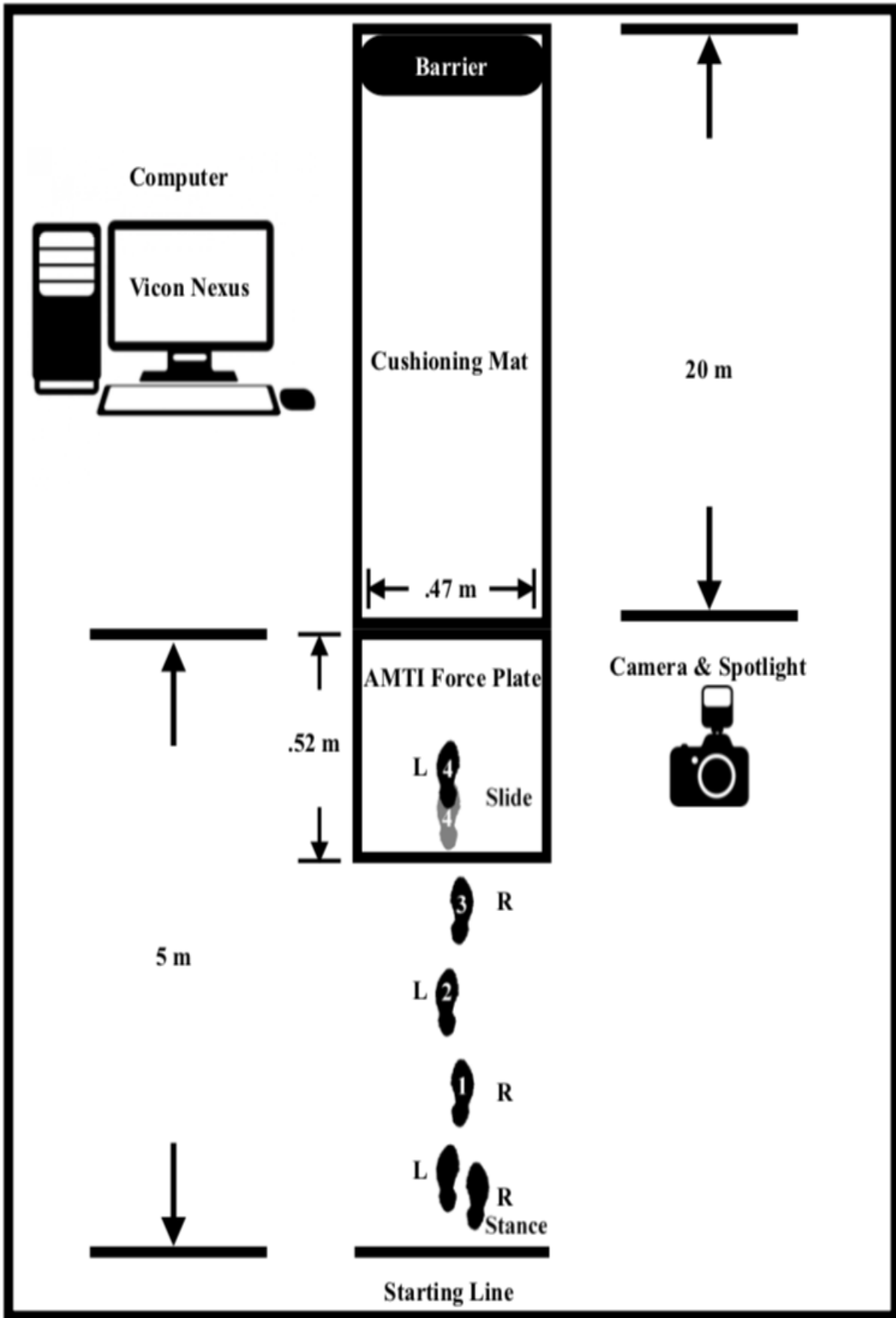


Figure 8 Experimental Setup



## Participant Preparation

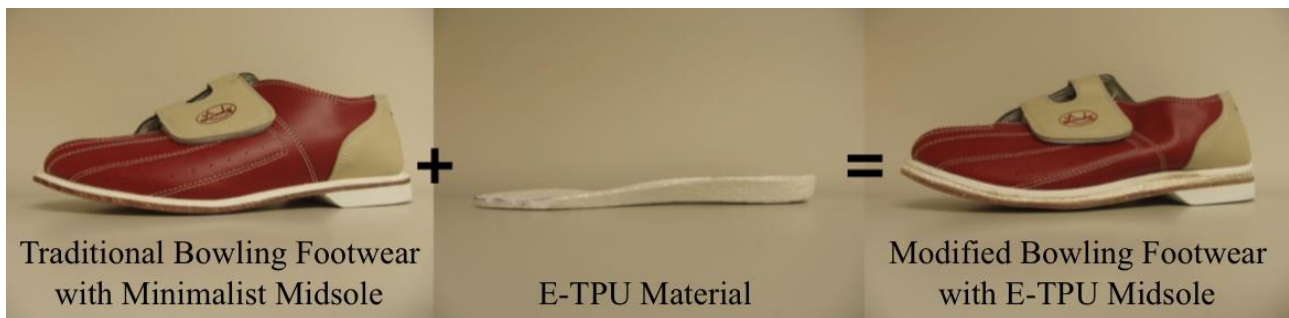
Each participant wore black tight-fitting clothes and was asked to bowl barefoot, with the traditional bowling shoes with minimalist midsole design, and with the modified bowling shoes with E-TPU midsole design. Five to ten minutes were given to the participant to warm up and become accustomed to the footwear. Three joint reflective markers were fixed to the right side of participant's upper body at the acromioclavicular joint, lateral epicondyle of humerus, styloid process of radius. Four joint reflective markers were fixed to the right side of the participant's lower body at the greater trochanter of femur, lateral malleolus, lateral epicondyle of femur, the base of the fifth metatarsal. Three markers were fixed at the left side of the participant's lower body at the medial malleolus, medial epicondyle of femur, and the base of the first metatarsal, Figure 9.



**Figure 9 Reflective Markers**

## Footwear Development

A pair of traditional bowling footwear was purchased from bowling sporting goods company and a pair of E-TPU insole was purchased from the factory in Asia, and then the modified bowling footwear with E-TPU midsole was made by a shoemaker and eventually could be used in this study, Figure 10.



**Figure 10 The Development of Bowling Footwear with E-TPU Midsole**

### Procedures

One traditional bowling shoe with minimalist midsole design, Figure 11 and one modified bowling shoe with E-TPU midsole design, Figure 12 underwent the static performance testing. The static testing consisted of dropping a 0.5 kg dumbbell inside a PVC pipe from a height of 0.61 meters at the heel cup region in each type of shoe on the AMTI force plate. Three trials in each condition for static tests were conducted with the same researcher to ensure the reliability of the test. The peak vertical ground reaction force ( $F_z$ ) was recorded at 1,000 Hz, and the Butterworth filter function was applied.



**Figure 11 Traditional Bowling Footwear with Minimalist Midsole Design &**

**Figure 12 Modified Bowling Footwear with E-TPU Midsole Design**

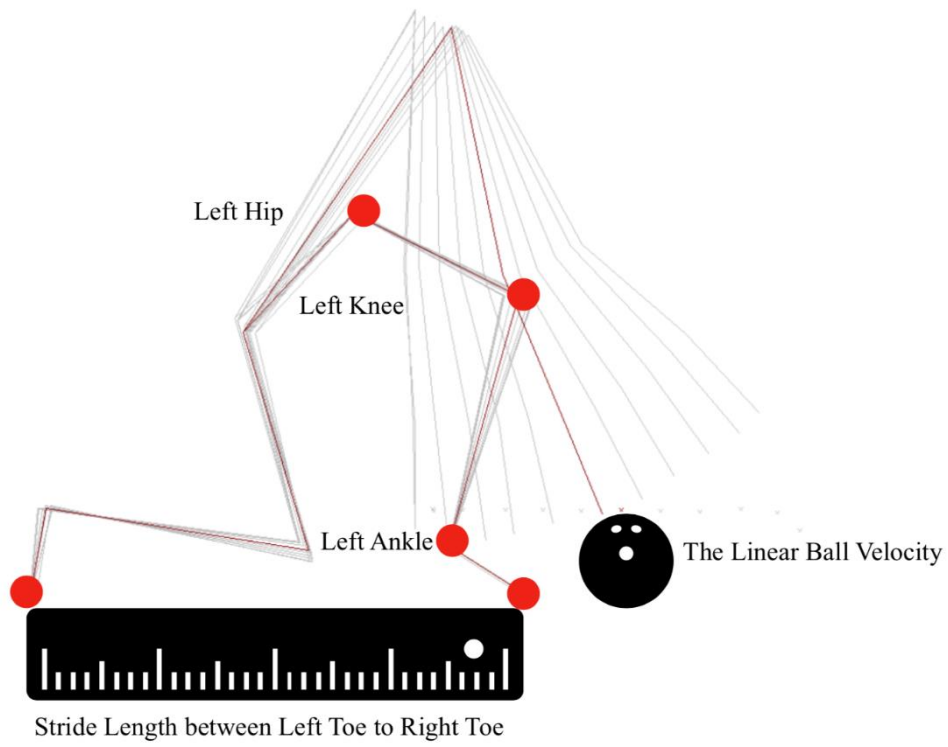
The 12 participants took part in the dynamic testing. Each participant was asked to bowl five balls in each type of footwear, so a total of 15 balls were collected for each participant and a total of 180 trials were collected. A candlepin bowling ball (mass: 1.1 kg; diameter: 0.1 m) was used in the study, Figure 13. The candlepin bowling ball was chosen because it does not require the bowlers to place their fingers into three holes drilled into the bowling ball and it was developed in 1880 in Worcester, Massachusetts. In each participant's ball delivery, he began his approach from the starting line and ended his last step on the force plate. All participants used four-step approach and planted their left front foot on the force plate to measure the vertical ground reaction force. Each participant had a one-minute rest between each ball and a three-minute rest between each type of footwear. The order of footwear condition was randomized to reduce any order effect.



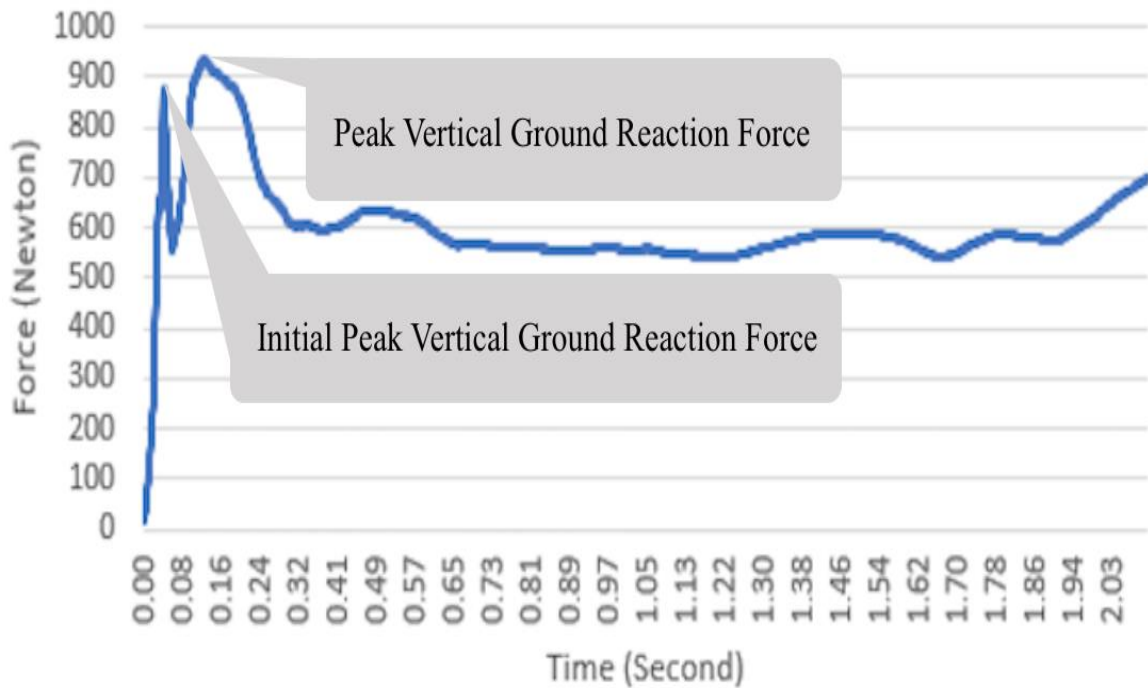
**Figure 13 USA Flag Candlepin Bowling Ball**  
(from BowlerStore.Com, 2019)

### **Data Processing and Analyses**

The Ariel Performance Analysis System (APAS) software was used to calculate the two-dimensional body joint angles and the velocities of left hip, knee, and ankle, stride length, and the linear ball velocity at the instant of ball release while the left foot was on the force plate, Figure 14. A digital filter function was applied with appropriate cut of frequency ( $x$  and  $y = 9$  Hz). The initial peak vertical ground reaction force and the peak vertical ground reaction force during the delivery were identified with the Vicon Nexus software (v. 1.8) to evaluate the amount of shock and force absorption with respect to each participant's body weight (body mass \* gravity: 9.81), Figure 15. The Butterworth filter function was applied to the vertical ground reaction force data from the static and dynamic testing to eliminate any noise.



**Figure 14 Kinematic Analyses**



**Figure 15 Kinetic Analyses**

## **Statistical Analyses**

All data were analyzed with SPSS (v. 25) software. A paired samples t-test was conducted at  $\alpha = 0.05$  between different shoes for the static testing. For the dynamic testing, a one-way repeated ANOVA ( $\alpha = 0.05$ ) for the initial peak vertical force (Fz), the rate of loading, and the peak vertical force to body weight ratio were compared between three different footwear conditions, followed by a t-test with Bonferroni adjustment if a significant difference was found. A one-way repeated ANOVA ( $\alpha = 0.05$ ) for the joint angles and the velocities of hip, knee, and ankle, stride length, and the linear ball velocity were compared between three different footwear conditions. Post-hoc pairwise comparisons were conducted using t-test with Bonferroni adjustment if a statistical significance was found.

## Results

### Kinetic Analyses of Static Testing

A dependent t-test was conducted between the traditional footwear with minimalist midsole and the modified footwear with E-TPU midsole. The results showed the modified footwear with E-TPU midsole had a statistical significant lower amount of vertical ground reaction force than the traditional footwear with minimalist midsole, Table 1. The findings were consistent with the hypothesis that the traditional bowling footwear with minimalist midsole would produce the highest vertical force as opposed to the modified footwear with E-TPU midsole.

**Table 1 Static Testing at the Heel Cup Region of Bowling Footwear**

Comparisons between Footwear	Means $\pm$ SD (Newton)	<i>p</i>
Traditional vs Modified	1,826.7 $\pm$ 84.3 vs 907.7 $\pm$ 33.8	.005*

\*Statistical significant at  $p < .05$

### Kinetic Analyses of Dynamic Testing

A one-way repeated measure ANOVA was conducted between the three footwear conditions (barefoot, traditional, and modified) on the initial peak vertical ground reaction force ( $F_z$ ) at  $\alpha = 0.05$ . A significant difference was found in the footwear main effect. A post-hoc t-test with Bonferroni adjustment was conducted at  $\alpha = 0.016$  ( $\alpha = 0.05/\#$  of comparisons =  $0.05/3 = 0.016$ ). The results showed there was a significant difference between barefoot and traditional footwear with minimalist midsole conditions and between barefoot and the modified bowling footwear with the E-TPU midsole conditions. Being barefoot showed a substantial higher initial peak vertical ground reaction force ( $1,045.7 \pm 377.2$  N) during the dynamic testing as compared to the traditional footwear with minimalist midsole ( $811.7 \pm 168.5$  N) and the modified bowling footwear with E-TPU midsole ( $682.1 \pm 116.8$  N), Table 2.

**Table 2 Kinetic Comparisons of the Initial Peak Vertical Force between Footwear Conditions**

Comparisons between Footwear	Means $\pm$ SD (Newton)	<i>p</i>
Barefoot vs Traditional	1,045.7 $\pm$ 377.2 vs 811.7 $\pm$ 168.5	.008*
Barefoot vs Modified	1,045.7 $\pm$ 377.2 vs 682.1 $\pm$ 116.8	.002*
Traditional vs Modified	811.7 $\pm$ 168.5 vs 682.1 $\pm$ 116.8	.004*

\*Statistical significant at  $p < .016$

In addition, a one-way repeated measure ANOVA was conducted between the three footwear conditions (barefoot, traditional, and modified) on the rate of loading (Fz (N)/Time (S)) at  $\alpha = 0.05$ . A significant difference was found in the footwear main effect. A post-hoc t-test with Bonferroni adjustment was conducted at  $\alpha = 0.016$  ( $\alpha = 0.05/\#$  of comparisons =  $0.05/3 = 0.016$ ). The results showed the rate of loading was significantly greater in the barefoot than the traditional and modified bowling footwear. Being barefoot produced  $100,265 \pm 75,332$  N/S of rate of loading during the dynamic testing compared to the traditional footwear with minimalist midsole's  $25,830 \pm 25,770$  N/S and the modified footwear with the E-TPU midsole's  $16,242 \pm 7,582$  N/S, Table 3. Being barefoot was not able to lower the rate of loading during the dynamic testing as the traditional footwear with minimalist midsole and the modified footwear with E-TPU midsole. There was no significant difference found in the peak vertical ground reaction force with respect to each participant's body weight, the body weight did not have influence to the peak vertical ground force between footwear conditions, Table 4.

**Table 3 Kinetic Comparisons of the Rate of Loading between Footwear Conditions**

Comparisons between Footwear	Means $\pm$ SD (Newton/Second)	<i>p</i>
Barefoot vs Traditional	100,265 $\pm$ 75,332 vs 25,830 $\pm$ 25,770	.007*
Barefoot vs Modified	100,265 $\pm$ 75,332 vs 16,242 $\pm$ 7,582	.002*
Traditional vs Modified	25,830 $\pm$ 25,770 vs 16,242 $\pm$ 7,582	.128

\*Statistical significant at  $p < .016$

**Table 4 Kinetic Comparisons of the Peak Vertical Ground Reaction Force to Body Weight between Footwear Conditions**

Ratio	Means $\pm$ SD			<i>P</i>
	Barefoot	Traditional	Modified	
Peak vertical force/body weight	1.35 $\pm$ .13	1.42 $\pm$ .23	1.38 $\pm$ .18	.271

\*Statistical significant at  $p < .05$

### Kinematic Analyses of Dynamic Testing

A one-way repeated measure ANOVA was conducted between the three footwear conditions (barefoot, traditional, and modified) on the joint angles and the velocities of hip, knee, and ankle, stride length, and the linear ball velocity at  $\alpha = 0.05$ . The results of this study indicated that there was no statistically significant difference between barefoot, traditional footwear with minimalist midsole design, and the modified footwear with E-TPU midsole design in the hip, knee and ankle joint angles during the last step of bowling delivery, Table 5. Similarly, no significant difference was found in the joint angular velocities of hip, knee, and ankle, Table 6. Moreover, the mean stride length ( $p = .314$ ) did not show any significant difference between three different footwear conditions (Barefoot:  $.78 \pm .12$  m, Traditional:  $.80 \pm .13$  m, and Modified:  $.80 \pm .10$  m), Table 7. Also, no significant difference was found in the mean linear ball velocity ( $p = .497$ ) between barefoot ( $2.05 \pm .33$  m/s), traditional ( $2.02 \pm .39$  m/s), and modified ( $2.01 \pm .39$  m/s), Table 8.

**Table 5 Kinematic Comparisons of the Joint Angle between Footwear Conditions**

Joint Type	Means $\pm$ SD (Degree)			<i>P</i>
	Barefoot	Traditional	Modified	
Left Hip	92.3 $\pm$ 9.9	94.0 $\pm$ 10.3	93.9 $\pm$ 9.9	.289
Left Knee	133.0 $\pm$ 14.5	131.9 $\pm$ 12.4	132.1 $\pm$ 14.5	.758
Left Ankle	111.6 $\pm$ 11.2	115.9 $\pm$ 8.6	117.7 $\pm$ 9.4	.123

\*Statistical significant at  $p < .05$



**Table 6 Kinematic Comparisons of the Joint Velocity between Footwear Conditions**

Joint Type	Means $\pm$ SD (Meter/Second)			<i>P</i>
	Barefoot	Traditional	Modified	
Left Hip	.61 $\pm$ .16	.58 $\pm$ .23	.53 $\pm$ .20	.535
Left Knee	.60 $\pm$ .21	.68 $\pm$ .22	.66 $\pm$ .29	.614
Left Ankle	.58 $\pm$ .19	.58 $\pm$ .32	.53 $\pm$ .29	.764

*\*Statistical significant at  $p < .05$*

**Table 7 Kinematic Comparisons of the Stride length between Footwear Conditions**

Joint Type	Means $\pm$ SD (Meter)			<i>P</i>
	Barefoot	Traditional	Modified	
Stride	.78 $\pm$ .12	.80 $\pm$ .13	.80 $\pm$ .10	.314

*\*Statistical significant at  $p < .05$*

**Table 8 Kinematic Comparisons of the Linear Ball Velocity between Footwear Conditions**

Ball	Means $\pm$ SD (Meter/Second)			<i>P</i>
	Barefoot	Traditional	Modified	
Linear Velocity	2.05 $\pm$ .33	2.02 $\pm$ .39	2.01 $\pm$ .39	.497

*\*Statistical significant at  $p < .05$*

## Discussion

The purpose of this study was to evaluate the effects of midsole construction (barefoot, traditional bowling shoes with minimalist midsole design, and the modified bowling shoes with E-TPU midsole design) on the amount of shock absorption and the mechanics of bowling delivery. The findings of the static testing from this study were consistent with a previous running footwear research study on shock absorption (Lloyd et al., 2013). Lloyd et al. (2013) found the vertical ground reaction force from the same static testing was 2,962 N for Vibram FiveFingers shoe, made of rubber bottom and minimalist cushion in attempt to mimic barefoot, compared to limited cushioned Nike Free Run's 775 N and Adidas' traditional cushioned shoe of 872 N. In this study the vertical ground reaction forces of the static testing for the traditional bowling footwear with minimalist midsole and the modified bowling footwear with the E-TPU midsole were  $1826.6 \pm 84.3$  N and  $907.6 \pm 33.8$  N, respectively. These findings were similar to Lloyd's study since both studies have demonstrated footwear that has greater and thicker cushion has the ability to attenuate greater amount of vertical ground reaction force.

Research in footwear has been primarily focused on impact attenuation and response to loading rate related to injury in running (Baltich et al., 2015; Clarke, Frederick & Cooper, 1983; De Wit et al., 1995; Kersting & Brüggemann, 2006; Nigg et al., 1987) and landing (Bowser et al., 2017; Fu et al., 2013; Nolan et al., 2005; Oliver et al., 2011; Soares et al., 2017; Zhang et al., 2005). Bowling footwear is a field that has yet been investigated extensively. Bowling delivery is unique because the lead foot acts as a break to absorb the impact force from the ground during landing; no toe off or push off is involved as in walking and running. Since landing is a critical part of movement in many sports skills, athletic footwear is designed with materials to address this movement in order to minimize injury. Soares et al. (2018) conducted a study to investigate the effects of athletic footwear on midsole thickness on the vertical force and the dynamic stability in single leg drop landing and found the initial peak vertical force on the non-dominant leg was  $2,884 \pm 547$  N for barefoot,  $2,726 \pm 480$  N for minimalist midsole,  $2,536 \pm 453$  N for moderate midsole,  $2,552 \pm 548$  N for thick midsole, and  $2,437$

$\pm 506$  N for oversize midsole. Moreover, the rate of loading on non-dominant leg was significantly greater in the barefoot than the other four athletic footwear conditions with different thicknesses midsole design (Soares et al., 2018). In this study the initial peak vertical force in the barefoot condition was significantly greater when wearing shoes. In addition, the rate of loading was significantly greater in the barefoot than in shoed conditions. Both studies demonstrated that footwear with greater and thicker cushioning has the ability to attenuate initial peak vertical force and the rate of loading. However, from a kinetic performance measure perspective, the modified footwear condition did not show significantly better shock absorption than the traditional and barefoot conditions since there was no significant difference found in the peak vertical ground reaction force with respect to each participant's body weight.

Research in athletic footwear has also been primarily focused on the kinematic analyses of lower extremity during running (Baltich et al., 2015; De Wit et al., 1995; Hardin et al., 2004) and landing (Hong et al., 2014; Oliver et al., 2011; Yeow et al., 2010; Zhang et al., 2005). Bowling is one of the sports that has features of walking, running and landing movements. The characteristics of gait cycle in bowling approach is similar to walking and running that contains the rear-foot contact, fore-foot contact, heel-off, and toe-off. Interestingly, the last step of bowling delivery is unique because the front foot acts as a slide and brake simultaneously during landing; no toe off or push off is involved as in walking and running. Since landing is a critical part of a basketball game, basketball shoes are designed with materials to address this movement in order to minimize injury. Zhang et al. (2005) conducted a study to examine the effects of various midsole densities of basketball shoes during landing activities, and the authors found that there was no significant difference in the hip and ankle joints for the range of motion and the maximal velocity between different midsole densities. Similarly, in this study significant difference was not found in the midsole cushioning and densities between barefoot, traditional bowling shoes with minimalist midsole design, and the modified bowling shoes with E-TPU midsole design in the lower extremity (hip, knee and ankle) joint angles and velocities during the last step of bowling delivery.

Research in bowling technique has been primarily focused on the kinematic analyses (Chu et al., 2002; Hung et al., 2012; Razman et al., 2010). In the mechanics of bowling delivery, lower extremity is crucial because the ability to slide the front foot consistently will affect bowler's ability to deliver the bowling ball more accurately (Razman et al., 2010). Chu et al. (2002) conducted a study to examine elite level ten-pin bowlers delivery technique comparing different parameters between male and female bowlers. The authors found that the stride length between front toe and back toe at release were  $1.16 \pm 0.20$  m for the male bowlers and  $1.09 \pm 0.06$  m for the female bowlers. In this study there was no significant difference between three different footwear conditions (Barefoot:  $0.78 \pm 0.12$  m vs Traditional:  $0.80 \pm 0.13$  m vs Modified:  $0.80 \pm 0.10$  m) for the stride length during the last step of releasing. The slight difference in the stride length of this study when compared with Chu et al.'s (2002) study may be due to different skill levels, midsole constructions on bowling footwear, and type of bowling (candlepin vs ten-pin). This study was conducted on the candlepin bowling, so the results may be different from the ten-pin bowling delivery since the mass of the bowling ball for the ten-pin is much greater, so a greater stride length may be needed in ten-pin bowling in order to provide better balance and stability during delivery. In addition, the linear ball velocity has commonly been considered as the reference of performance in many sports. In this study there was no significant difference found between the three different footwear conditions on the performance measure of the linear ball velocity at the instant of ball release.

Some limitations should be considered in this study. Twelve healthy college right-handed recreational male participants were invited to participate for the dynamic bowling testing. A limitation was that there was no guarantee that every participant was in the mood during the data collection. Therefore, it was assumed that all twelve participants put their maximum efforts on five balls in each type of footwear for a total of 180 trials. Additionally, the environmental condition was also one of the limitations in this study since temperature and humidity in the laboratory during the data collection were automatically controlled by a central air conditioning system in the building. Therefore, the circumstance in the laboratory may be different from conducting the study in a bowling alley. The

study was conducted on candlepin bowling, which the results may be different from ten-pin bowling delivery since the mass of the bowling ball for the ten-pin is much greater. This study used twelve male college aged students as participants, and the results may be different from that of more experienced bowlers as participants. Experienced or higher skilled bowlers may have better consistency in the mechanics of their bowling delivery which may improve the variability of the results. Moreover, this study used male participants as subjects, and the results may be different from having female participants to take part in the study. In addition, this study was conducted with two-dimensional analysis since the primary underarm motion of the bowling delivery occurred in the sagittal plane, and the participants in the study were asked to bowl the ball straight with maximum effort. Previous literature has also showed studies conducted with 2D motion analysis on softball windmill pitching with the similar rationale (Ashley et al, 2012). Nonetheless, future studies are warranted with a 3D motion analysis to obtain a comprehensive understanding of the bowling delivery. Furthermore, this study took place at the Biomechanics Laboratory, providing for a preliminary understanding on the mechanics of bowling delivery. The results may be different from conducting the study at a bowling alley.

## Conclusion

The purpose of this study was to evaluate the effects of midsole construction (barefoot, traditional bowling shoes with minimalist midsole design, and the modified bowling shoes with E-TPU midsole design) on the amount of shock absorption and the mechanics of bowling delivery. The results from this study indicate that bowling footwear with the E-TPU material provided lower amount of initial peak vertical ground reaction force and rate of loading. Moreover, the results from this study indicate no significant difference in the joint angles and velocities of hip, knee and ankle, stride length, the linear ball velocity and the peak vertical ground reaction force to body weight ratio between these conditions. The findings of this study provided a preliminary understanding on the effects of the E-TPU material on shock absorption in bowling footwear. In addition, the findings of this study suggest that midsole construction of bowling footwear has minimal impact to the mechanics of bowling delivery. This study provides an important preliminary understanding on the mechanics of bowling delivery. The results of the study enable practitioners to have a better understanding on the effects of shock absorption on footwear with E-TPU material, so proper footwear can be worn by the bowlers to minimize initial impact force. Sports footwear developers may use this information to construct appropriate footwear to minimize injury. Future studies are warranted to examine and compare the E-TPU material footwear with the traditional cushion material footwear to assess if the E-TPU material is superior. Also, research can be conducted to evaluate 3D motion analysis with experienced bowlers at the bowling alley and the internal joint forces and torques of bowling delivery mechanics with the E-TPU material footwear to have a comprehensive understanding of bowling footwear development.

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