ASSESSMENT OF WEDGE AND FLARE DESIGNS OF SHOES ON BASKETBALL MOVEMENTS

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ASSESSMENT OF WEDGE AND FLARE DESIGNS OF SHOES ON BASKETBALL MOVEMENTS

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“Don’t measure yourself by what you have accomplished, but what you should have accomplished with your ability.”
– John Wooden

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SUMMARY

The ankle sprain is a common injury in basketball. A mechanism for this injury occurs when landing improperly from a jump. The concept of wedge and flare designs in shoes is (1) to offer benefit in reducing the potential for an ankle sprain while (2) not hindering performance or usability concerning basketball movements that are needed for successful play. The purpose was to take conceptual designs of the wedge and flare through an iterative design process. Therefore, the objectives were to fabricate shoe prototypes with these conceptual designs, to test the performance of these prototypes, and to develop the next iteration of design based upon the results of testing.

Design criteria for the wedge and flare were identified and tested with objective and subjective parameters concerning stability at vertical jump landing while not hindering performance or usability during running, cutting and jump takeoff movements. A series of pilot studies revealed that the wedge was not worth pursuing due a potential risk increasing ankle injury in addition to discomfort provided by the wedge. In addition, the cutting movement was very difficult to monitor for consistent trials.

Therefore, the flare designs that were tested yielded the following observations: (a) the flare did not hinder running movements and the users did not perceive running impairment or comfort issues; (b) the flare did hinder jump takeoff movements and the control yielded the greatest jump height, but the users did not perceive impairment or comfort issues; (c) the user did not perceive impairment, comfort or stability issues with the cutting movement; (d) the flare did provide stability at jump landing, and the user did perceive stability and did not perceive any issue with comfort.

With these results, the next iteration of design would utilize a 2 cm flare that would improve the jump takeoff impairment while maintaining the objective and subjective stabilizing effects provided by the first iteration flare. In addition, the next

iteration of 2 cm flare included design criteria with respect to actual shoe construction parts and new conceptual designs to help address the issues identified with the first generation flare. An illustration of an overall shoe design example with the next generation flare is presented. The results of this design process are discussed.

CHAPTER 1

INTRODUCTION

PROBLEM

The lateral ankle sprain, also called an inversion ankle sprain, is a very common injury in basketball [1]. Approximately 85% of ankle sprains presented at a sports medicine clinic in the U.S. were inversions involving the lateral ankle ligaments [2]. In basketball, the lateral ankle sprain accounts for 38% and 45% of all injuries for men and women, respectively [3]. The mechanism for this ankle injury primarily occurs when players land incorrectly from a jump on a court surface [4-6] or upon another competitor's foot [4, 7-8]. Other situations [4, 8-9] include sudden stopping, a sharp twist or turn, collision, fall, tripping or a change of direction while running [8].

Because of this frequency, prophylactic taping and ankle-foot orthoses (AFO), which include nonrigid or semi-rigid bracing, have been developed and is considered to be the state of the art [10-11] in preventing ankle sprains [12]. The ability of these prophylactic methods to provide restriction to joint displacement has been well investigated and is rather clear [13-22]. However, there is concern that the restrictive qualities can be sufficient enough to impair athletic performance [16, 23-24].

Sudden and uncontrolled inversion range of movement can load the lateral ankle ligaments beyond its physiological limits and can result in the spraining or rupture of those ligaments. It is thought that reducing the magnitude and rate of loading on the lateral ankle ligaments can minimize sprain severity. Thus, the assessment of rearfoot inversion displacement has been the primary research focus in understanding the stabilizing effects of taping, AFO's, and shoe height [25-26]. Many studies have simulated sudden but controlled ankle inversion through the use of trapdoors or a tilting platform [27-35]. This method of simulation is attached to the foot, and it lets the foot move through a guided inversion range of motion in order to assess the restriction of rearfoot displacement.

The role of shoes in ankle sprain prevention [26, 36] is unclear and unconvincing [37-38]: high-top shoes were reported to have a protective effect [39]; low-top shoes were more protective than high-top shoes [40]; high-top shoes with inflatable support chambers lower the risk of ankle injury, although not statistically significant [41]; and the newness of a shoe was reported to play a more important role than shoe height in preventing ankle sprains [37].

Figure 1. (Left) Forefoot lateral flare and (Right) forefoot valgus wedge

Although the primary research focus has been on shoe height [41-46] for ankle sprain prevention, it is believed other design characteristics of the shoe can significantly influence its mechanical function [47]. No studies on shoe insole or midsole design were found to investigate this topic area. Specifically, no studies were found to investigate the forefoot valgus wedge design of the shoe insole and the forefoot lateral flare design of the shoe midsole on ankle stability during basketball sports movements, as seen in Figure 1. Because of this, the scope of this thesis sought to investigate the development of these features on the design front – what should be the design criteria, can its stabilizing effects be designed for a specific basketball movement, do its stabilizing effects impair other basketball movements, and if these features can be designed, how does the user accept them? The foundational body of knowledge gained from this study on design may be used further down the road to refine insole and midsole designs, and perhaps to determine if these features lower the risk of ankle sprain injury.

With regard to shoe design, the objective and subjective parameters of performance were used to drive the development of the forefoot valgus wedge and forefoot lateral flare. The objective parameters are based upon kinematic metrics and performance metrics during basketball movements. The basketball movements include running, cutting and jump take off and jump landing. The goals of these objective parameters were to investigate (a) how they can provide stability to the ankle joint during the landing from a standstill vertical jump, and (b) how they may impair performance during running, cutting and jumping movements.

Subjective parameters were based upon user feedback on the shoe designs concerning perceived impairment of performance, stability and comfort obtained by a questionnaire. The goals of the questionnaire were to gauge user acceptance and pinpoint any usability issues. Both objective and subjective parameters are used to the drive and inform the next iteration of design.

SPECIFIC AIMS OF THE STUDY

1. To design the forefoot lateral flare and valgus wedge into shoes according to design criteria.
2. To evaluate the objective parameters of performance of the designs in order:
    a. to quantify the kinematic metrics of stability during jump landing, which is represented by the rearfoot angle at impact, range of motion and eversion rate
    b. to quantify the inversion rate during running, cutting and jumping to assess any performance impairment.

c. to quantify the time to run, time to cut and jump height to assess any performance impairment

3. To evaluate subjective feedback obtained by questionnaires in order:

   a. to identify perceived impairment of performance during running, cutting and jumping.

   b. to identify perceived qualities of stability during running, cutting and jumping.

   c. to identify perceived qualities of comfort during running, cutting and jumping.

4. To utilize these objective and subjective evaluations in order:

   a. to inform the next iteration of design

   b. to support or not support wedge or flare designs into basketball shoes

SIGNIFICANCE OF THE STUDY

The role of shoes in ankle sprain prevention [26, 36] is unclear and unconvincing [37-38]. Although variation in the design of basketball footwear has led to recommendations such as increased ankle collar height, use of external support straps or stays to strengthen upper shoes, and independently tied internal boots to increase both stability and proprioception [46], the evidence to support such changes is scant. None of these studies of shoes for basketball provide convincing evidence of a role for shoe style in the prevention of ankle injuries [38].

Although these studies were targeted toward shoe design for ankle sprain prevention, the primary goal of this study was not to prove that wedge and flare prevent ankle sprains. Instead, it was to investigate a design process of the wedge and flare whose results may lay a foundational body of knowledge on design and its ability to provide ankle stability; this in turn may be investigated and refined in future investigation for ankle sprain prevention. Thus, the significance of this study is twofold. First, the knowledge gained from this study can help footwear designers understand the implications of wedge and flare designs in basketball shoes; specifically, its influence on sports movements and to what extent subjects accept them. In addition, the knowledge gained can inform the next iteration of design. Second, since the wedge and flare are common shoe modifications used for pathological deformities, the knowledge gained from this study can also provide a point of interest for orthotists and pedorthists to investigate the potential use of a wedge and flare to help patients return to sports.

CHAPTER 2

BACKGROUND RESEARCH

ETIOLOGY OF ANKLE SPRAINS

The ankle consists of three articulations: the talocrural joint, the subtalar joint (STJ), and the distal tibiofibular syndemosis [48]. The talocrural joint is a mortise joint that is formed by the articulation of the distal tibia, fibula, and dome of the talus [49]. The talocrural joint in isolation behaves like a hinge joint allowing mainly plantarflexion and dorsiflexion [12]. The STJ is formed by the articulation between the plantar aspect of the talus and the calcaneus [48], and these two bones are referred to as the rearfoot [50]. Rearfoot inversion and eversion is measured in this thesis. This articulation allows supination and pronation described as triplanar motion [51-52]. Triplanar motion occurs in the frontal, sagittal and transverse planes. Therefore, supination involves inversion, plantarflexion and adduction but is dominated by inversion where as pronation involves eversion, dorsiflexion and abduction but is dominated by eversion [53-54]. The talocrural joint is supported by the anterior talofibular ligament (ATF), the calcaneofibular ligament (CFL) and the posterior talofibular ligament (PTF) at the lateral aspect [55]. The locations of these ligaments are illustrated in Figure 2. During lateral ankle sprains, the ATF is usually injured first and CFL can be injured second [56]. If the force is great enough, then the PTF can be injured too [57].

The ATF is taut in plantarflexion [57-61], and it is the first ligament to resist inversion when the foot is plantarflexed [51, 62-63]. The CFL exhibits strain primarily in dorsiflexion [59-60]. The ATF is also the weakest lateral ankle ligament and has an ultimate load (N) of 139 ± 24 [64] to 231 ± 129 [65] for complete rupture. The CFL has an ultimate load (N) of 307 ± 142 [65] to 346 ± 55 [64]. The foot often lands in plantarflexion and inversion from a vertical jump [57, 66-68]. For these reasons, the

ATF is the most commonly damaged ligament in the lateral ankle sprain [3, 19, 51, 56, 62, 69-74].

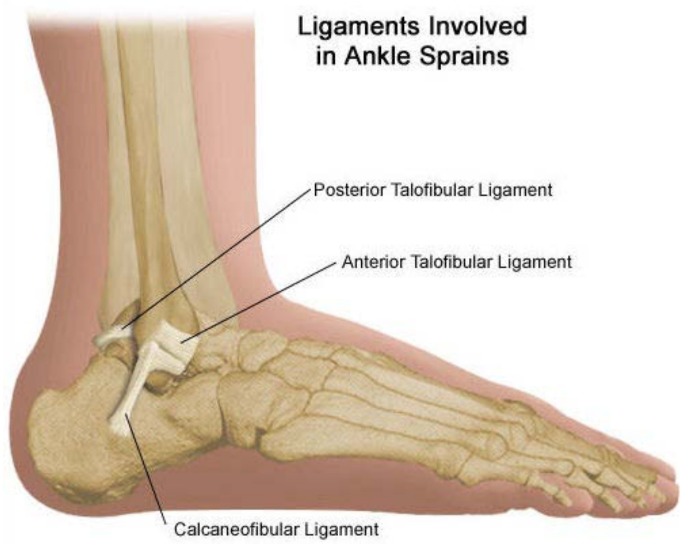


Figure 2. Ligaments involved in lateral ankle sprains [75]

Most lateral ankle sprains are caused by high magnitudes of suddenly occurring external STJ inversion moments, which is a result of the magnitude and location of the ground reaction force (GRF) at initial foot contact [76-77]. A greater moment arm along the STJ axis and subsequent increased moment to initiate sudden ankle inversion occur when the center of plantar pressure is deviated medially [76] or toward the forefoot [68]. If a player's foot is inverted during initial contact with the ground, deformation of the lateral aspect of the midsole and outsole material of the shoe may move the ground reaction force vector more medially and increase the inversion moment arm [78].

These external inversion moments, if they occur suddenly enough and are of sufficient magnitudes, will prevent the central nervous system (CNS) from having sufficient time to produce internal STJ eversion moments (from the peroneal brevis and longus) that are necessary to decelerate or oppose the STJ inversion motion [79]. The peroneal muscles can develop tension to stiffen the ankle but the time to develop tension is too slow for the injury event [34]. An ankle sprain may occur in 40 ms, which is the time when peak vertical GRF occurs when landing from a jump [42]. Initiating sudden inversion with healthy subjects in a standing position, peroneal muscle reaction times have been reported to be 57-58 ms [80] to 69 ms [31]. For subjects with ankle instability, longer peroneal reaction times up to 85 ms have been reported [30]. Even if the peroneal muscles can be activated in time, the magnitude of the inversion moment is far greater than can be resisted by those muscles [24, 77, 81-82].

BIOMECHANICS OF LIGAMENTS

Given the prevalence of the ATF injury, it is important to address the biomechanics of ligaments and its role in the mechanism and etiology of lateral ankle sprains. Ligaments join bones and provide stability to joints [83]. The ATF joins the anterior portion of the distal fibula to the neck of the talus [62]; the CFL extends from the distal fibula and inserts posterolaterally on the calcaneus [84]; the PTF originates from the posterior portion of the distal fibula and inserts on the posterolateral tubercle of the talus [85-86].

Ligaments are viscoelastic and exhibit time-dependent behavior [83]. This means the stress response of a ligament is dependent upon not only the magnitude of strain but also strain rate [64, 83, 87]. Changes in strain rate will alter the mechanical properties of ligaments [88]. When strain rate increases, the slope of the linear region of the stress-strain curve become steeper [88]. A steeper slope in this region correlates to an increased elastic modulus, showing greater stiffness [89]. However, as stiffness increases, the ligament is likely to reach plastic range sooner and eventually rupture [25, 88].

It is important to recognize that the talocrural and STJ move in supination during lateral ankle sprains [63]. With regards to the biomechanics of ligaments, this displacement can produce strain, and the rate at which this displacement occurs is related to the strain rate experienced by the ligaments. Since injuries to the ATF occur with the inversion portion of supination [56], it is important to assess the rate of inversion displacement as it may be a direct indicator of strain rate, which is an important predictor of ligamentous failure [83, 88]. Many cadaveric studies have been performed to study the mechanical properties of the lateral ankle ligaments [61, 64-65, 90-92]; the results by Siegler et. al. can be seen in Table 1 as a point of reference.

Table 1. Mechanical Properties of the ATF and CFL [65]

Property	ATF	CFL
Initial Length (cm)	1.784 ± 0.305	2.769 ± 0.330
Cross-sectional Area (cm^2)	0.129 ± 0.077	0.097 ± 0.065
Ultimate Load (N)	231 ± 129	307 ± 142
Ultimate Elongation (cm)	0.246 ± 0.076	0.366 ± 0.071
Yield Force (N)	222 ± 133	289 ± 138
Yield Elongation (cm)	0.226 ± 0.081	0.343 ± 0.061
Ultimate Stress (MPa)	24.20 ± 16.91	46.22 ± 36.62
Ultimate Strain	0.15 ± 0.06	0.13 ± 0.03
Yield Stress (MPa)	22.59 ± 16.91	43.64 ± 35.85
Yield Strain	0.14 ± 0.07	0.13 ± 0.02
Elastic Modulus (MPa)	255.5 ± 181.3	512.0 ± 333.5

PRIOR ART

Because of the frequency of lateral ankle sprains, prophylactic taping (see Figure 3) and ankle-foot orthoses (see Figure 4), which include nonrigid or semi-rigid bracing, have been developed and is considered to be the state of the art [10-11] in preventing ankle sprains [12]. It was postulated that these methods prevent ankle sprains through enhanced proprioception [30, 93-99], mechanical support [43, 97, 100-101] and/or movement restriction [20, 24, 93-94, 102-108]. The skin traction or skin pressure due to taping or ankle-foot orthoses may enhance proprioception for proper landing by providing sensory cues of plantar surface position and orientation [24, 30, 95, 101, 109-110]. However, many studies report mechanical support or movement restriction to decrease the risk of ankle injury in players with a history of ankle injuries [4, 15, 30, 38-40, 47, 82, 101, 103, 111]. Mechanical support is provided to ankles with joint laxity from previous ligament damage [48]. This can prevent recurrent ligament injury [82] by returning the rearfoot to a more neutral position prior to ground contact [101, 110]. In a similar manner, the movement restriction in plantarflexion, eversion and inversion range of motion is provided by taping [13-15] and ankle foot orthoses [16-22].

Figure 3. Athletic taping [112]

The supportive quality of nonrigid and semi-rigid bracing is reported to be comparable [20, 113-115] or superior to that of tape [21, 105, 107, 116-117]. However, both [20, 105-106, 116, 118] taping [15, 20-22, 40, 104-107, 113, 116, 118-121] and bracing [15, 116] lose its restrictive qualities after varying periods of exercise and sports activity. The drawbacks of taping include: there is no definitive conclusion on the influence of taping technique on ankle movement restriction [15, 24, 105, 107, 114, 116];

the chosen taping technique vary by person [10, 122]; taping is time consuming and expensive [39, 95]; and skin irritations can occur [40, 78]. In contrast [10, 15-16, 37, 39-40, 103, 105, 115], bracing is more cost effective because it can be self applied; it is reusable, readjustable, and washable; and skin problems are less common. There is also concern that the restrictive qualities can be sufficient enough to impair athletic performance [16, 23-24]. Further study is necessary to determine the effect of prolonged ankle brace use on athletic performance, ankle musculature and ligament function [16, 123].

Figure 4. (Left) Semi-rigid bracing [124] (Right) Nonrigid bracing [125]

The assessment of rearfoot displacement has been the primary research focus in understanding the mechanical effects of taping and bracing [25]. The ability of these prophylactic methods to provide restriction to joint displacement has been well investigated and is rather clear [13-22]. The reduction of the rate of inversion is highly influential in protecting the ATF during lateral ankle sprains because of its loading implications on the ligaments [83, 88]. If ankle bracing and taping can slow the rate at which the ankle moves into full inversion, the ligaments may be able to better handle the stresses place on them [33, 126]. Only a handful of studies were found to assess the rate of joint displacement and to support these prophylactic methods actually reducing inversion velocity [27, 33, 127]. Cadaveric studies have verified the inversion resistance [47, 128] and the stabilizing effects under inversion and axial compression loading [129] provided by prophylactic taping and ankle-foot orthoses.

PATENT SEARCH

Patents were found featuring flare and wedges designs for various orthotic purposes, and some patent claims had footwear designed specifically for anti-ankle inversion. For the purpose of recognizing prior art of flares and wedges for footwear, the following are listed:

1. Patent #5875569 [130] – Athletic shoe with anti-inversion protection

   This patent utilizes a wing member projecting outward and laterally from the midsole, between the ankle and the ball of the foot. When the ankle begins to overturn, the wing tip engages the ground to resist overturning.

2. Patent #6557271 [131] – Shoe with improved cushioning and support

   Abstract: An article of footwear of the present invention includes a sole and an upper portion, which forms a shell for enclosing a user's foot therein. The shell has a collar for extending around a user's ankle and a suspension system extending between the upper portion and the sole. The suspension system including an energy storage member, which transfers reaction forces from the sole to the shell generally at the collar whereby the energy storage member reduces overturning moment forces on the user's ankle when lateral forces are applied to the article of footwear.

3. Patent #4989349 [132] – Shoe with contoured sole

   This patent seeks to approximate being barefoot by conforming to the natural shape of the foot, particularly the sides. By having an outer contour of the edge portion of the shoe for the foot, natural stability is provided to the foot in an inverted or everted mode.

4. Patent #4043058 [133] – Athletic training shoe having foam core and apertured sole layers

   This patent utilizes a foam core border along the lateral aspect of the shoe and along the forefoot and heel at the medial aspect for support and cushioning.

5. Patent #7334350 [134] – Removable rounded midsole structures and chambers with computer processor-controlled variable pressure

   This patent utilizes a removable midsole that copies the features of the underlying support of the foot via shoe sole compartments that inflate with liquid, gas or gel. The purpose of this is to provide natural stability, support and cushioning to the structures of the foot.

6. Patent #6775929 [135] – Athletic shoe or sneaker with stabilization device

   This patent utilizes two straps and two lateral support bumpers at the midsole to prevent acute angles for inversion stress protection.

7. Patent #6725578 [136] – Joint protection shoe construction

   This patent utilizes a midsole or insole where the lateral side is elevated higher than the medial side, which forms a lateral wedge. This is coalesced to support for the arch and is claimed to reduce knee and hip torques during walking, running or standing.

8. Patent #5345701 [137] – Adjustable orthotic

   This patent utilizes removable wedge attachments to be inserted into a shoe system at the forefoot or rearfoot for valgus or varus correction.

9. Patent #4620376 [138] – Forefoot valgus compensated footwear

   This patent provides a greater thickness at the lateral aspect of the insole than at the medial aspect, which provides a valgus wedge. This upward slope begins at the midfoot and ends at the tip of the foot.

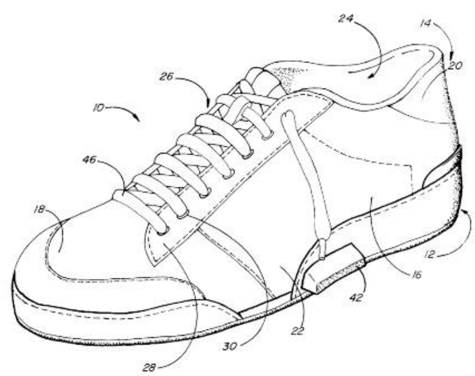


Figure 5. Patent #5875569 [130]

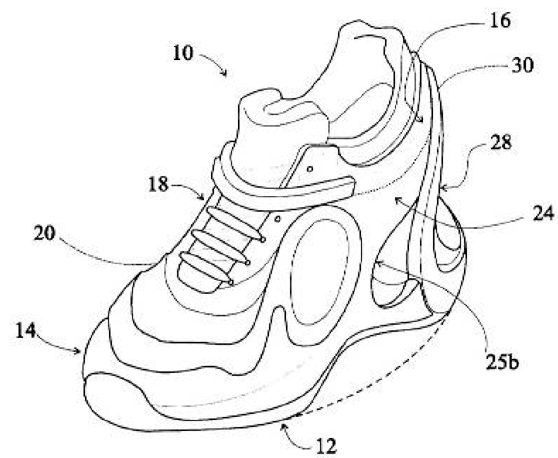


Figure 6. Patent #6557271 [131]

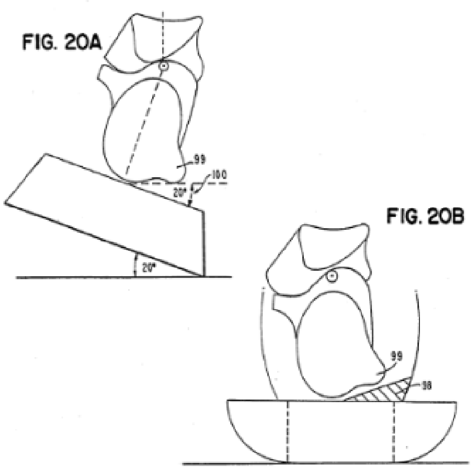


Figure 7. Patent #4989349 [132]

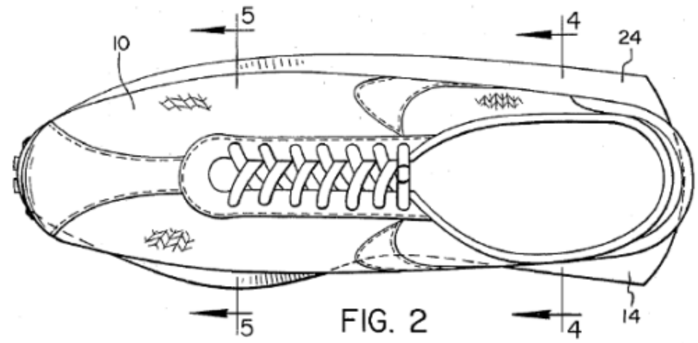


Figure 8. Patent #4043058 [133]

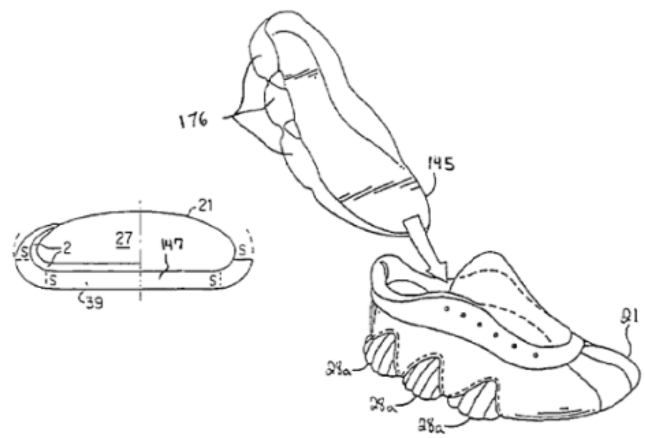


Figure 9. Patent #7334350 [134]

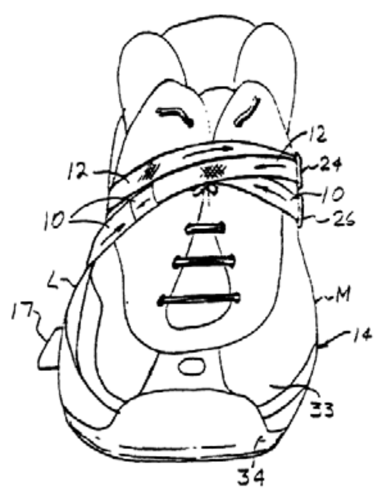


Figure 10. Patent #6775929 [135]

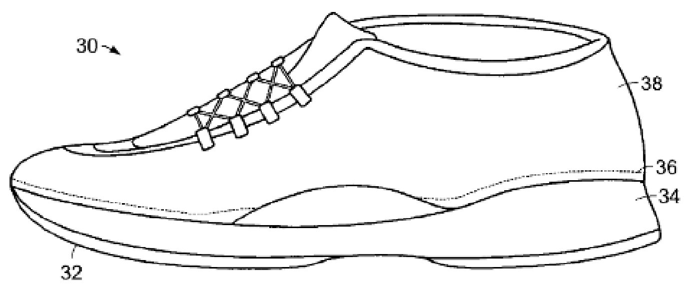


Figure 11. Patent #6725578 [136]

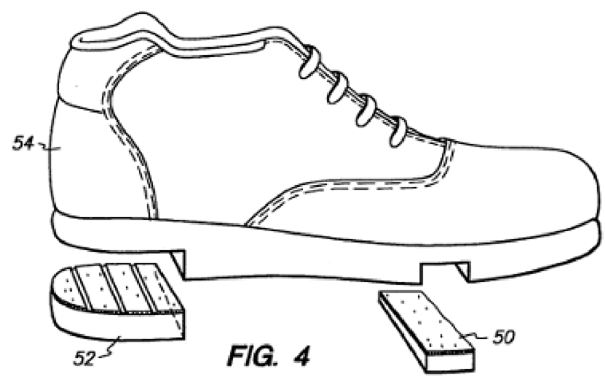


Figure 12. Patent #5345701 [137]

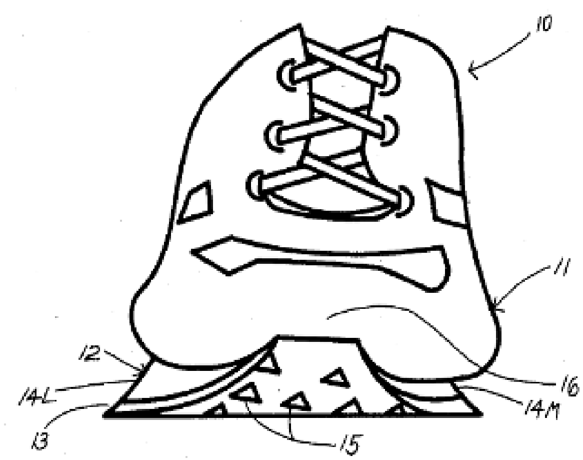


Figure 13. Patent #4620376 [138]

CHAPTER 3

FLARE AND WEDGE

THEORY

Two common modifications to a shoe are the forefoot lateral flare and the forefoot valgus wedge. The orthotic purpose of the flare is used to provide stability to an unstable foot or ankle [139] and to resist inversion or eversion [140]. This design acts as an outrigger, adding to the medial-lateral stability of the shoe and the foot. The modification consists of a strip of firm material added to the medial or lateral side of the shoe and provides a wider base of support for the foot [141]. The lateral flare might be added only to the heel area or it could include the entire side of the shoe, providing a greater surface area for ground contact and will help the foot to feel more stable [139, 142]. The orthotic flare on the lateral aspect of the heel has been investigated during running conditions on controlling: maximum pronation and total rearfoot movement [143]; initial and total pronation and impact forces [144]; and kinematics of the calcaneus and tibia [145].

The forefoot valgus wedge is believed to encourage ankle eversion [140] or preventing foot supination [146] around the midtarsal and STJ axis [147] by bringing the ground up to the plantar aspect of the foot [148]. The orthotic implications of the valgus wedge (located at the rearfoot, forefoot or rearfoot-to-forefoot) has been widely investigated in: reducing knee varus torque in patients with medial knee osteoarthritis during walking [149-156]; determining the predictive relationship between the changes in foot pressure patterns [157] or location center of pressure [158] and the relative magnitude of knee adduction moments during gait; inducing foot pronation and determining its effect on knee kinematics [159], the mechanics of the rearfoot and hip

[160], and the mechanics of the rearfoot, knee, hip, and pelvis [161-162] and for those with unstable ankles [163] during walking.

In this thesis, the forefoot lateral flare and valgus wedge of a shoe are believed to influence the pronation moment arm (and consequently the external STJ pronation moment). These designs can increase the moment arm along the STJ axis to either increase the external pronation moment or decrease the external supination moment at initial ground contact [164] due to its location at the lateral aspect of the forefoot.

The forefoot valgus wedge will elevate the lateral aspect of the forefoot, specifically the 4th and 5th metatarsal heads. Due to the elevation provided by the wedge, the pronation moment arm from the STJ axis to the point of GRF application is increased, which will either increase the external pronation moment or decrease the supination moment about the STJ. A lateral flare at the forefoot is located from the 5th metatarsophalangeal joint to styloid process of 5th metatarsal head. Similarly, it is designed to provide more surface area (material) in order to extend the lateral distance from the point of GRF application to the STJ axis. Essentially, the lateral flare is extending the pronation moment arm of the shoe, which will either increase the external pronation moment or decrease the supination moment about the STJ.

Since the wedge and flare designs for the shoe can affect the external pronation moment, the foot-ankle complex can experience a stabilizing effect. Stabilization can be characterized by an increased ankle eversion rate and is expected from these designs when initial ground contact occurs in the forefoot region. Typically, initial ground contact occurs at the forefoot from a vertical jump landing [165-167], which can be a favorable situation for stabilizing the ankle as improper jump landing has been identified as a mechanism of ankle sprain injury. Although favorable for this scenario, however, the wedge and flare of the shoe may externally hinder the supination moment about the ankle. Supination is necessary for propulsive movements during vertical jump takeoff, push off period of running, and cutting maneuvers.

Stabilization of the ankle during vertical jump landing is necessary for continued, successful basketball play, and so is the player's ability to jump high, run fast and cut quickly. Therefore, if the wedge and flare are to be designed into a basketball shoe, then the conditions under which its stabilizing effect is needed to perform must be considered. Likewise, the circumstances under which its stabilizing effect may hinder other basketball movements must be considered too. Design criteria for the wedge and flare are laid out in the ensuing section and describe these potential tradeoffs and compromises.

DESIGN CRITERIA OVERVIEW

In determining design criteria of shoes for basketball, the following questions should be addressed [168]:

- Which foot movements cause the most injuries?
- Which athletic tasks and skills are most critical in terms of successful play or injury?
- What must the shoe do to minimize stress, and how does it achieve it without imposing on other movements?

WHICH FOOT MOVEMENTS CAUSE THE MOST INJURIES?

Lateral ankle sprains are caused by high magnitudes of suddenly occurring external STJ inversion moments, which is a result of the magnitude and location of the ground reaction force (GRF) at initial foot contact [76-77]. Initial contact from a vertical jump landing typically occurs at the forefoot [165-167] and with the foot in plantarflexion and inversion [6, 57, 66-68]. A greater inversion lever arm along the STJ axis and subsequent increased moment to initiate sudden ankle inversion occur when the center of plantar pressure is deviated medially [76] or toward the forefoot [68]. For instance, if a player's foot is inverted during initial contact with the ground, deformation of the lateral aspect of the midsole and outsole material of the shoe may move the GRF vector more medial and increase the inversion moment [78], as seen in Figure 14.

During cutting maneuvers, the medial side of the rearfoot touches the ground first, producing a larger lever arm for an increased inversion moment [9], as seen in Figure 14. Cutting maneuvers require high braking forces in the horizontal plane to cut toward a new line of progression [169] but these forces are likely to result in repeated injury in subjects with functional ankle instability due to significant increases in stress on the ankle joint structures [170].

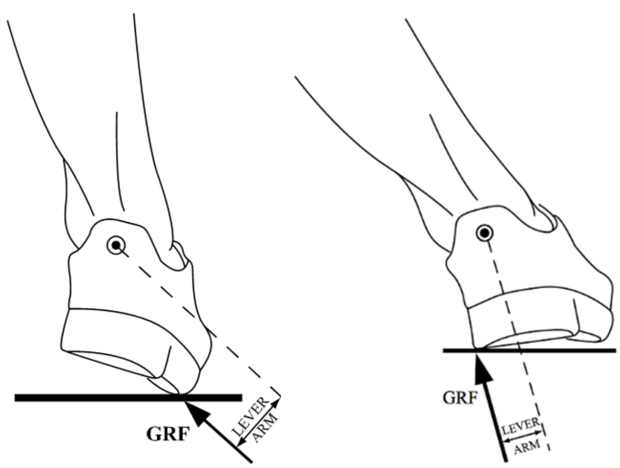


Figure 14. Indicated are the possible inversion lever arms between the GRF and the estimated STJ axis (Left) forefoot landing and (Right) cutting maneuver

WHICH ATHLETIC TASKS AND SKILLS ARE MOST CRITICAL IN TERMS OF SUCCESSFUL PLAY OR INJURY?

A list of athletic tasks and skills necessary for successful basketball play are identified in Table 2. In an analysis of a videotaped NBA game [171], it was reported the average number of jumps was 70 from all positions, and the average distance run was 2.1 miles at an average pace of 9 mph. In addition, over 1000 walking/shuffling steps were counted.

A kinetic [171] and kinematic [172] analysis of running, cutting and jumping movements performed on 24 professional basketball players have been investigated in Table 2; however, a shoe model was undisclosed. The kinematic analysis about the ankle can be seen in Table 3. The performance of each of these tasks and movements emphasize GRF directions in the vertical (jumping and landing), anteroposterior (propulsive and braking impulses) and mediolateral (cutting and shuffling) [171]. Thus, the design of the wedge and flare must consider these movements.

Table 2. Athletic Tasks and Maneuvers in Basketball

Sports Movement	Specific Movement
Running	• Sprinting / jogging • Quick start / stop
Jumping	• Rebounding • Jump shot takeoff / landing • Vertical jump takeoff / landing • Layup takeoff / landing
Cutting	• Pivoting / spinning • Side-to-side shuffle • Sudden change of direction

Table 3. Frontal Plane Kinematics of Sports Movements [172]

Sports Movement	A	B	C	D	E
Running	4.2	-6.6	-208.7	18.7	351.0
Cutting	7.4	-5.1	-244.1	19.0	397.3
Jump Takeoff	5.4	-0.1	-1.3	22.9	333.1
Jump Landing	13.1	-1.3	-206.8	13.6	54.7

Positive values indicate supination; Negative values indicate pronation

A. Rearfoot at Footstrike (º)

B. Max Pronation (º)

C. Max Pronation Velocity (º/s)

D. Max Supination (º)

E. Max Supination Velocity (º/s)

WHAT MUST THE SHOE DO TO MINIMIZE STRESS, AND HOW DOES IT ACHIEVE IT WITHOUT PERTURBING OTHER MOVEMENTS?

External STJ supination moments, if they occur suddenly enough and are of sufficient magnitudes, will prevent the central nervous system (CNS) from having sufficient time to produce internal STJ pronation moments that are necessary to decelerate or oppose the STJ supination motion [79]. As described in the previous section, the shoe can be designed for increasing the external pronation moment by increasing the pronation lever arm from the STJ axis to the GRF application point.

A forefoot lateral flare and valgus wedge are proposed to increase the external eversion moment by increasing the eversion lever arm from the STJ axis to the GRF application point. An illustration of this effect provided by the flare can be seen in Figure 15. If these features increase the eversion moment upon landing, then an increase maximum eversion rate (°/s) – a quality of stability – is expected.

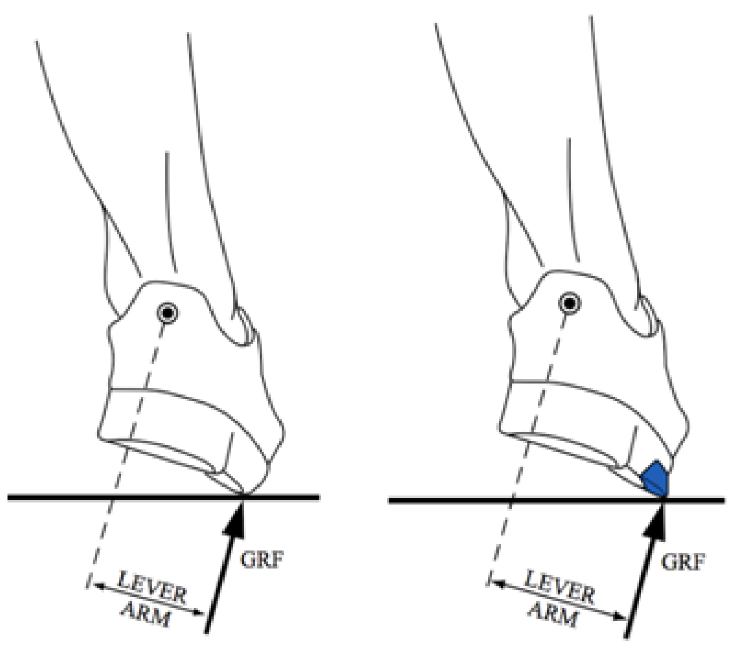


Figure 15. Indicated is a possible increase of the eversion lever arm between the GRF and the estimated STJ axis (Left) shoe without flare and (right) shoe with flare

However, the stability provided by these shoe modifications may have an undesired influence upon athletic movements that are needed for successful basketball play – movements where supination is necessary for propulsion such as the pushoff period of running, cutting to a new line of progression, and vertical jump takeoff. These athletic movements may be affected by the flare due to the additional material potentially opposing supination motion and the wedge due to a slight elevation at the lateral forefoot. Maximum inversion velocity can potentially be reduced, which in turn may influence the forces expressed by the foot on the ground and hinder athletic performance. This impairment may be indicated by reduced time to sprint, reduced time to cut to a new line of progression, and/or a reduced jumping height. These objective parameters are described in detail in the Methods section. Thus, the inherent compromise of designing the flare and wedge is maximizing the stabilizing effects without hindering athletic maneuvers necessary for successful basketball play.

DESIGN CRITERIA

Since the wedge and flare are modifications to two components of a shoe (insole and midsole), the collective function of the shoe must first be discussed. Cheskin et. al. recommend that a court shoe for basketball should be designed to perform and provide the following functions [168]:

(a) Stability – shoe's ability to resist excessive or unwanted motions of the foot
(b) Cushioning – attenuate high GRF in the rearfoot and forefoot
(c) Traction – shoe-surface interaction should not be "fixed" or allow slippage
(d) Flexibility – utilize toe spring, forefoot flex points, and appropriate upper material
(e) Durability – shoe should not breakdown during game play
(f) Weight – for energy considerations; should not weigh down the athlete
(g) Breathability – to allow ventilation of heat and climate management of sweat
(h) Comfort – proper fit to the waist, heel and girth of the last; user acceptance

The design criteria essential for the flare and wedge of a basketball shoe are determined to address the following:

- Stability – provide stability during jump landing
- Weight – minimize the mass added to the shoe; material and technical considerations
- Comfort – maximize comfort and acceptance of the user during athletic movements
- Do not hinder running, cutting and jump takeoff movements

Thus, the design of the flare and wedge must provide stability, as described previously, during vertical jump landing without impairing running, cutting and jumping maneuvers. The mass of the wedge and flare must be kept to a minimum, as introducing excessive weight to the overall shoe may impair the athlete. Comfort is evaluated by subjective feedback of wedge and flare designs.

HYPOTHESES

The overall goal of this thesis was to obtain evidence to inform the next design iteration and to provide evidence to support or not to support wedge or flare designs into basketball shoe designs. This was obtained by objective and subjective evaluations of wedge and flare designs. The parameters of the objective evaluation measured stability (rearfoot angle at impact, range of motion and eversion rate upon jump landing), performance impairment (rearfoot inversion rate during running, cutting and jumping), and corresponding performance metrics (time to sprint, time to cut and jump height). The subjective evaluation obtained feedback concerning perceived performance impairment, stability and comfort to determine user acceptance.

Wedge and flare designs tested the following hypotheses during running, cutting and jumping maneuvers: (1) an increase in flare size will reduce: [a] max inversion rate during running, cutting and jump takeoff and [b] time to sprint, time to cut and jump height; (2) an increase in wedge size will reduce: [a] max inversion rate during running, cutting and jump takeoff and [b] the time to sprint, time to cut and jump height; (3) an increase in flare size will increase eversion rate during jump landing compared to a shoe with no flare; (4) an increase in wedge size will increase eversion rate during jump landing compared to a shoe with no wedge; (5) user will not perceive performance impairment with the flare and wedge compared to the control; (6) user will perceive more stability with the flare and wedge than with the control; (7) user will not perceive less comfort with the flare and wedge than with the control.

It should be noted that after the pilot studies revealed problems with the wedge interventions and the cutting movement, only a portion of the hypotheses could be tested. Because of these limitations, only the following hypotheses were able to be tested: (1) an increase in flare size will reduce: [a] max inversion rate during running and jump takeoff and [b] time to sprint and jump height; (2) an increase in flare size will increase eversion rate during jump landing compared to a shoe with no flare; (3) user will not perceive performance impairment with the flare compared to the control; (4) user will perceive more stability with the flare than with the control; (5) user will not perceive less comfort with the flare than with the control.

CHAPTER 4

RESEARCH METHODOLOGY

EXPERIMENTAL DESIGN

Running, cutting and jumping movements were conducted to test the objective and subjective parameters of performance of the wedge and flare. A pilot study was performed to determine if measurable kinematic differences could be seen between the control, wedge and flare shoe conditions. The results of the pilot study were used to refine the methods for subject testing, which is explained in the ensuing sections.

INCLUSION AND EXCLUSION CRITERIA

The experimental procedures were approved by the Georgia Tech Institute Review Board (IRB# H10151). Informed consent was obtained from all subjects and can be seen in Appendix A.

Male individuals (18 years or older) who play basketball regularly (for at least two years) or exercises on a regular basis (at least 3 hours per week) were able to participate. These requirements were set forth in order to obtain subjects who could perform the basketball maneuvers with controlled coordination and effort. In addition, subject shoe size must fit between men's US 9-12, as those were the range of sizes available. Exclusionary criteria include having a current ankle injury (within the past 3 months) or having a history of lower limb injuries. These criteria were assessed by having the subject answer a series of questions prior to their involvement in the study.

DESCRIPTION OF BASKETBALL MOVEMENTS

The three basketball movements used in this study were a 14 foot sprint, a cutting maneuver and a standstill vertical jump. All subjects were encouraged to perform all trials with maximum effort, and three valid trials were recorded for each movement. All trials and conditions were randomized.

The sprint was a distance of 14 feet, where the starting and finishing points were indicated by tape on the ground, as seen in Figure 16. This distance was within the capture volume provided by the Vicon cameras and was chosen as it approximates the distance from the free throw line to the backboard. A valid sprint trial was when the right foot made entire contact within FP2. The cutting maneuver began with the same starting point as the sprint. But a new line of progression was 45 degrees from FP2 and was indicated by tape on the ground, as seen in Figure 16. A valid cutting trial was when the right foot made contact with FP2.

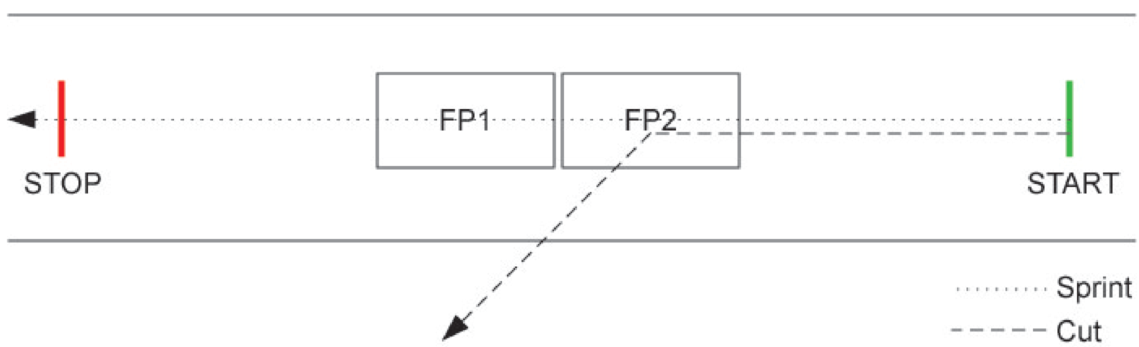


Figure 16. Diagram of the sprint and cutting movements

The vertical jump trial was performed with the subject standing with only the right foot on FP2. A countermovement via arm swing and or squatting was allowed. A valid trial was when the subject was at complete standstill prior to jump, made complete right foot landing within FP2, and "stuck" the landing. Sticking the landing made it easier to identify the time at which landing was completed.

EQUIPMENT

The ensuing sections describe the process and materials used to construct the shoe conditions in addition to the hardware used for the motion capture analysis.

SHOE CONDITIONS AND MATERIALS

There were a total of 5 conditions: one control, two wedge and two flare. The descriptions of these conditions are summarized in Table 4. In Figure 17, an illustration of the flare and wedge dimensions with respect to the shoe can be seen. These dimensions correspond to the anatomical locations seen in Table 4. In the clinical setting, it is unusual to have a wedge of more than 6 mm, with 4 mm being typical, as higher values than these tend to cause the foot to slide down the created incline without providing any additional benefit [147].

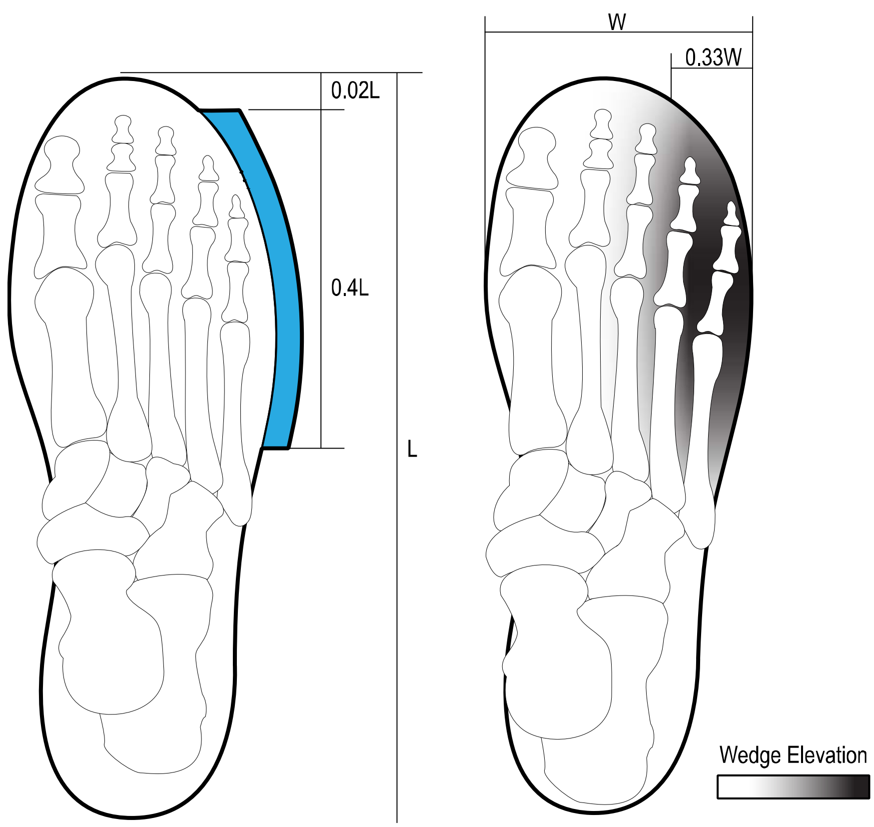


Figure 17. Illustration of the Flare and Wedge Dimensions

Table 4. Description of Shoe Conditions

Condition	Dimension	Anatomical Location
Control	N/A	N/A
Flare 1	1 cm	5th MTPJ to styloid process of 5th metatarsal head
Flare 2	2 cm	5th MTPJ to styloid process of 5th metatarsal head
Wedge 1	3 mm	4-5 Metatarsal head
Wedge 2	6 mm	4-5 Metatarsal head

All shoe conditions were prototyped with a low-top, board-lasted canvas upper (Zoo York Middletown; Skechers U.S.A., Inc., Manhattan Beach, CA) that has a non-rigid heel counter and no sidewall, as seen in Figure 18 and 19. A low-top model with a non-rigid heel counter was chosen since high-top shoes [26] in addition to rigid heel counters [168] have an effect on inversion and eversion. A laser cutter was used to cut the plantar profile of the control and flare conditions from a single density sheet of rubber (Shore-A 65, PO 9223 24 Iron Softflex Black), as seen in Figure 20. The durometer of a material is used to indicate its hardness; in addition, the shore-A scale is used for softer plastics and rubbers and is used to categorize the durometer. The laser cutter was also used to cut the profile of the insole from a sheet of EVA and cork blend (JMS Bio-Kork, Shore-A 55±5). The wedge conditions were cut from the same material.

Figure 18. Upper without Sole (left) lateral view (right) plantar view

Figure 19. Zoo York Middletown [173]

Figure 20. Sole Designs from laser cutter

A hook and loop system with a shear strength of 211 kPa and pull-apart strength of 18 N (force to pull-apart 1 inch wide strip) were used to attach the control and flare conditions to the upper, as seen in Figure 21 and 22. This method allows the conditions to be swapped easily and allowed the use of a single pair of upper's. The wedge conditions were inserted into the upper. Cut-outs were made to the shoe upper to accommodate the markers. The mass of each shoe condition can be seen in Table 5, and was measured by a Denver Instrument scale (Model S403, Bohemia, NY).

Figure 21. Hook and loop system for the upper

Figure 22. Hook and loop system of the upper for a right shoe and sole

Table 5. Mass (g) of Men's Size 9, 10 and 11 Shoe Conditions

SHOE CONDITION	M9 L/R		M10 L/R		M11 L/R	
Control	250.8	251.3	267.9	270.3	291.9	293.2
Flare 1	255.9	254.2	272.1	274.2	295.3	296.5
Flare 2	257.2	258.8	275.9	279.2	300.4	301.2
Wedge 1	-	-	290.9	292.4	-	-
Wedge 2	-	-	294.5	296.0	-	-

MOTION CAPTURE SYSTEM

The motion analysis set-up was a 6 camera Vicon 8i system with two Bertec force plates. Since force plate 2 (FP2) was the only functioning one, it was used for all trials. The Vicon (Los Angeles, CA) and Bertec (Columbus, OH) systems sampled at 120 Hz and 1080 Hz, respectively. Both static (Ergocal 9.5 mm marker) and dynamic (Ergocal 240 mm Wand with 14 mm markers) calibrations of the cameras were performed prior to obtaining movement trials, and the force plates were zeroed.

For the static calibration of the subject, 14 mm reflective markers were placed on the locations in Table 6. A picture of these tracking markers can be seen in Figure 23. Tracking markers were needed to record movement. Segment definition markers were necessary to define segments in the software but not necessary to record movement. This marker configuration was selected to provide the best ability to measure ankle kinematics and was selected according to the recommendations by the kinematic analysis software and by pilot studies. It should be noted that this marker system calculates rearfoot and inversion and eversion; it does not reveal forefoot inversion or eversion. Pictures of the shoe prototypes with the cutouts for the reflective markers can be seen in Figure 24.

Table 6. Reflective Marker Locations

Part	Anatomic Location	Tracking or Segment Definition
KNEE	Lateral epicondyle of the knee Medial epicondyle of the knee	SD SD
SHANK	Cluster set of four markers [174-175]	T
ANKLE	Lateral malleolus Medial malleolus	SD SD
FOOT	Top of the second metatarsal head Medial aspect of the first metatarsal head Lateral aspect of the fifth metatarsal head Posterior aspect of the calcaneus	T T & SD T & SD T

Figure 23. Reflective marker set used to capture ankle kinematic data

Figure 24. Shoe prototypes with flare and windows to accommodate markers

DATA ANALYSIS

All marker data were filtered with a low pass, fourth order Butterworth filter at a cutoff frequency of 6 Hz. All force plate data were filtered with a low pass, second order Butterworth filter at a cutoff frequency of 50 Hz. The Visual3D (Germantown, MD) software by C-motion was used to perform kinematic analysis, and code written in MATLAB (Natick, MA) was used to perform the kinetic analysis. The static calibration of the subject was used to define the joint coordinate system (JCS) of the lower body. The default Cardan sequence for the calculation of all joint angles was XYZ, where the default sign conventions for describing the ankle joint angles were:

Right Ankle: (Dorsiflexion +) (Inversion +) (Adduction +)

Left Ankle: (Dorsiflexion +) (Eversion +) (Abduction +)

The JCS was set as the midpoint between the markers of the lateral and medial malleoli, as seen in Figure 25. Therefore, the reported values for the frontal plane coupled rearfoot motion with forefoot motion. All inversion and eversion calculations indicate rearfoot inversion and eversion, and this JCS could not be used to calculate any forefoot motion.

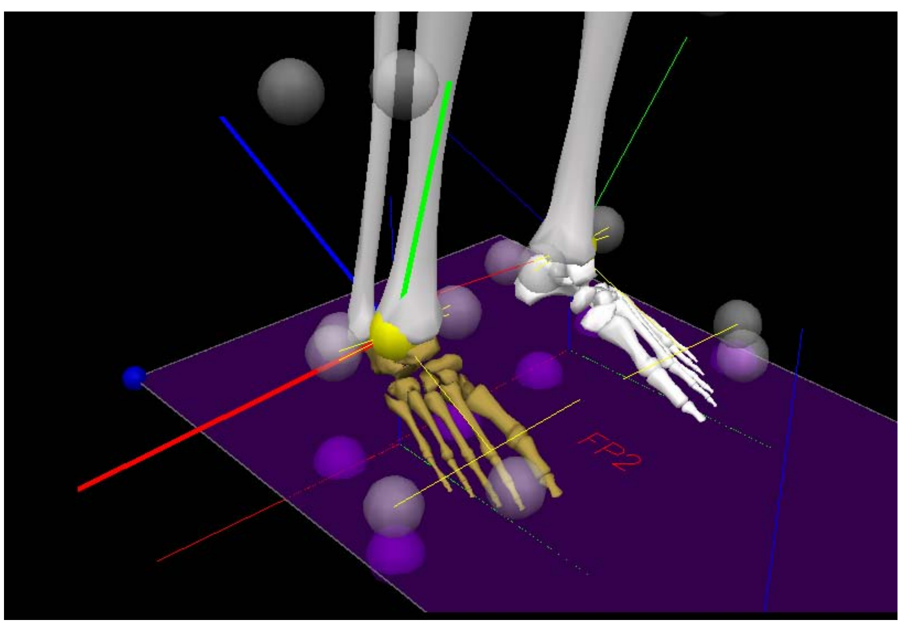


Figure 25. Joint coordinate system used by Visual3D

All kinematic analyses are reported for the right ankle. The default lab coordinate system (LCS) by Vicon was defined as X (anterior/posterior), Y (medial/lateral) and Z (vertical). However, the LCS was changed to the default recognized in Visual3D – X (medial/lateral), Y (anterior/posterior), and Z (vertical). This was done to keep consistent sign directions when ankle joint angle and velocity were calculated. All ankle joint velocities were calculated with respect to the LCS. In addition to the marker set listed in Table 6, reference markers mirrored the Foot markers in the XY plane of the lab coordinate system; this was done to yield a zero angle of the ankle in the sagittal plane during subject calibration.

KINEMATIC AND PERFORMANCE METRICS

The original kinematic and performance metrics used to analyze the shoe designs on the basketball sports movement are summarized in Table 7 and 8. The importance to obtain each metric and when it is measured are explained. However, it should be noted that a pilot study revealed problems with the cutting movement, and therefore the metrics listed for cutting were not able to be calculated. The reasons for these problems are explained in the Results section.

Table 7. Kinematic Metrics

Movement	Kinematic Metric
Running	**Max inversion rate (°/s)** Calculated from heel strike to toe off of the right foot.
Cutting	**Max inversion rate (°/s)** Calculated at pushoff.
Jump Takeoff	**Max inversion rate (°/s)** Calculated at takeoff, which is the start of flight.
Jump Landing	**Max eversion rate (°/s)** **Angle at Impact (°)** **ROM (°)** Calculated during impact

Table 8. Performance Metrics

Movement	Performance Metric
Running	**Time to sprint (s)** Calculated in Visual3D, when the X component of the center of mass model displaced 14 feet.
Cutting	**Time to sprint (s)** Calculated from the force plate data when (> 20 N) to (< 20 N)
Jump Takeoff	**Jump height (in)** Flight time was calculated from the force plate data when (0 N) to (> 0 N). Jump height was calculated with $h=0.5g(t_{\text{flight}})^2$

RUNNING

- Inversion rate – This kinematic metric was calculated to determine if supination motion was hindered during the pushoff period.
- Time to sprint – This performance metric was calculated because if pushoff was hindered, then the time to complete the sprint may have been hindered.

CUTTING

The cutting task was performed but no kinematic or performance metrics were calculated due to the difficulty in maintaining consistent trials. However, this movement was still performed in order to obtain user feedback concerning performance impairment, stability and comfort. This is discussed in the Results chapter.

JUMP TAKEOFF

- Inversion rate – This kinematic metric was calculated to determine if supination motion was hindered during the pushoff period at jump take off.
- Jump height – This performance metric was calculated because if pushoff was hindered, then jump height may be lowered.

JUMP LANDING

- Eversion rate – This kinematic metric was calculated to test the hypothesis that the flare conditions experienced an increased pronation moment compared to the control. The eversion rate reflects a stabilizing effect during jump landing.
- Rearfoot angle at impact – This kinematic metric was calculated to determine if the flare conditions had influenced the rearfoot angle at impact compared to the control, which could compromise the idea of stability. A greater inversion angle with the flare conditions at impact compared to the control condition could represent a greater implication and potential for an inversion ankle sprain [172] – "rolling over."
- Range of motion during impact – Prior literature concerning taping and AFO's for ankle stability determined that movement restriction at the ankle joint is a metric of performance, and potentially an indicator of ankle sprain prevention. Along these lines, ROM during impact was calculated to determine if the flare conditions allowed more movement during landing than the control.

QUESTIONNAIRE

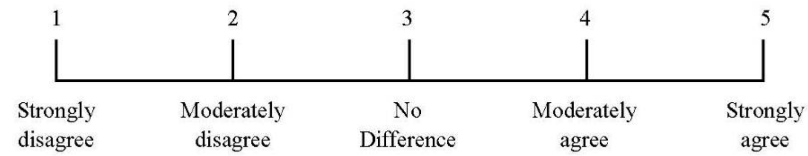
A subjective evaluation was used to obtain user feedback on perceived impairment, stability and comfort. User acceptance and compliance are important aspects because shoes equipped with flares and wedges, if shown effective, can only be effective if they are worn during the game. After three valid trials of a running, cutting or jumping movement with each condition, the subject completed a questionnaire. The questionnaire utilized 5 point Likert scales, where 1 represented disagreement to the statement, 3 represented a neutral or moderate agreement, and 5 represented extreme agreement.

1. Performance restriction, in which the perceived impairment of performance due to the flare and wedge was rated for each task performed in the agility course.

(a) My running was impaired by this shoe.

(b) My cutting maneuver was impaired by this shoe.

(c) My jump was impaired by this shoe.



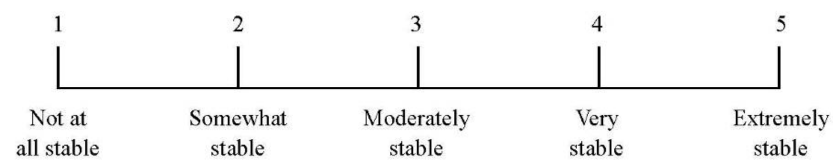
2. Stability, in which the perceived stabilizing effect provided by each flare and wedge was rated for each task performed in the agility course.

(d) How stable did you feel with this shoe during running?

(e) How stable did you feel with this shoe during the cutting maneuver?

(f) How stable did you feel with this shoe jumping?

(g) How stable did you feel with this shoe landing from the jump?

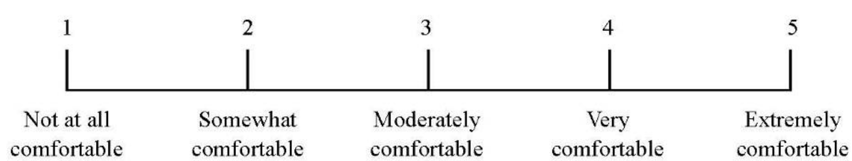


3. Comfort, the satisfaction with each flare and wedge concerning the feet.

(h) How comfortable were your feet with this shoe during running?

(i) How comfortable were your feet with this shoe during the cutting maneuver?

(j) How comfortable were your feet with this shoe jumping?



CHAPTER 5

RESULTS

SUBJECTS

A total of nine male subjects were recruited. The mean and range age, weight (kg) and height (cm) can be seen in Table 9. Four subjects reported to exercise up to three hours per week; four subjects reported to exercise four to six hours per week while one subject reported to exercise more than seven hours per week.

Table 9. Anthropometric Data of the Subjects (*n* = 9, all males)

PARAMETER	MEAN (SD)	RANGE
Age (years)	23.6 (1.0)	22 – 25
Weight (kg)	75.2 (4.1)	68 – 83
Height (cm)	175.3 (3.6)	170 – 180

PILOT STUDY

The pilot study tested the control, both wedge conditions and both flare conditions on running, cutting and jumping movements. The results of this study yielded two important observations. First, inconsistent measurements were obtained from the cutting movement. For instance in Table 10, the standard deviation for the max inversion rate calculation was about 25 to 28 °/s for the wedge conditions. This standard deviation was large and would make it difficult to perform a statistical analysis with the small number of subjects used in this study, and ultimately could not be used to test the shoe performance. It was determined that the cause for the inconsistent trials was whether or not the right foot was in line with the original line of progression at the time of the cut, as seen in Figure 26. This deviation was seen likely due to the anticipation of performing the cutting maneuver. For these reasons, the kinematic and performance metrics seen in Table 7 and 8 were not calculated for the cutting movement; however, the subjects still performed this movement to gather feedback for the subjective parameters.

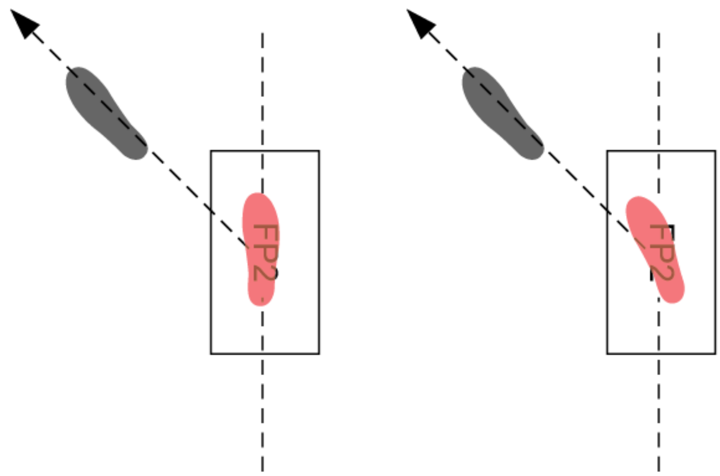


Figure 26. Varied foot position at the time of cut

Table 10. Pilot Study – Inversion Rate at Cutting

INTERVENTION	**MEAN** (°/s)	**SD**
Control	100.4	9.39
Wedge 1	171.6	25.95
Wedge 2	130.6	28.78

The second observation regarded the wedge conditions. The wedge was reported to be uncomfortable, as demonstrated by the in-lab observations of poor performance during the basketball movements. Discomfort was so great that full effort could not be performed. Another consideration – in order to place the insole into the shoe, the reflective markers must be removed from the foot. This causes a host of problems for the quality of data as a new subject calibration was required each time a marker was removed. Once removed, markers can never be placed in the same exact spot, and thus it necessitates a new subject calibration. This would in turn prolong the entire testing procedure and could have exposed the subject to disinterest and boredom.

More importantly, the inversion angle at impact increased with the wedge conditions as seen in Table 11. The angle at impact is a very important consideration concerning the mechanism of inversion ankle sprain injury, and as the pilot study had suggested, it would potentially put subjects at an increased risk for ankle sprain injury. In Table 12, the eversion rate at jump landing yielded a standard deviation of 100.94 °/s, which would it make if extremely measure any statistically significant differences.

For these reasons, the wedge was determined not worth pursuing and dropped from the study entirely; the hypotheses concerning the wedge conditions and the cutting movement were not tested. Therefore, the results reported hereafter address objective and subjective parameters of the control, flare 1 and flare 2.

Table 11. Pilot Study - Rearfoot Angle at Impact at Jump Landing

INTERVENTION	**MEAN** (°)	**SD**
Control	4.1	0.77
Wedge 1	15.2	1.96
Wedge 2	18.9	1.72

Table 12. Pilot Study – Eversion Rate at Jump Landing

INTERVENTION	**MEAN** (°/s)	**SD**
Control	-151.5	11.83
Wedge 1	-129.6	23.81
Wedge 2	-191.0	100.94

OBJECTIVE PARAMETERS

The results for the kinematic and performance metrics obtained for the objective parameters listed in Table 7 and 8 are reported here. Means and standard deviations for the control, flare 1 and flare 2 during the running, jump takeoff and jump landing movements are seen in Figure 27 to 33. The statistical analyses of the interventions can be seen in Table 13 to 19. A three-way ANOVA was used for this statistical analysis with $p<0.1$ to reject the null hypothesis, which was defined as the group means (control, flare 1 or flare 2) were equal. If the null hypothesis was rejected, then a Tukey test for post hoc comparisons was used to determine which group means were different.

For the running movement, the max inversion rate ($p=0.105$) and time to sprint ($p=0.232$) did not yield any difference across the interventions. For the jump takeoff movement, the max inversion rate ($p=0.001$) did show significant differences across the interventions; flare 2 was different from the control and flare 1, but there was no difference between the control and flare 1. At jump takeoff, flare 2 resulted in a slower max inversion rate than both the control and flare 1 condition. In addition, jump height ($p=0.008$) did show significant differences across interventions; control was different from flare 1 and flare 2, but flare 1 and flare 2 are not different. Flare 2 yielded the lowest jump height while the control yielded the highest jump height.

For the jump landing, rearfoot angle at impact ($p=0.271$) and range of motion during impact ($p=0.112$) did not yield any difference across the interventions. All subjects landed with the foot in inversion. However during jump landing, max eversion rate ($p=0.002$) did show significant difference across the interventions; flare 2 was different than control and flare 2, but there was no difference between control and flare 1. Flare 2 and flare 1 demonstrated faster max eversion rates during jump landing than the control, with flare 2 demonstrating the fastest max eversion rate.

Figure 27 to 34 show the mean value within the bar graph, and the error bars represent the standard deviation.

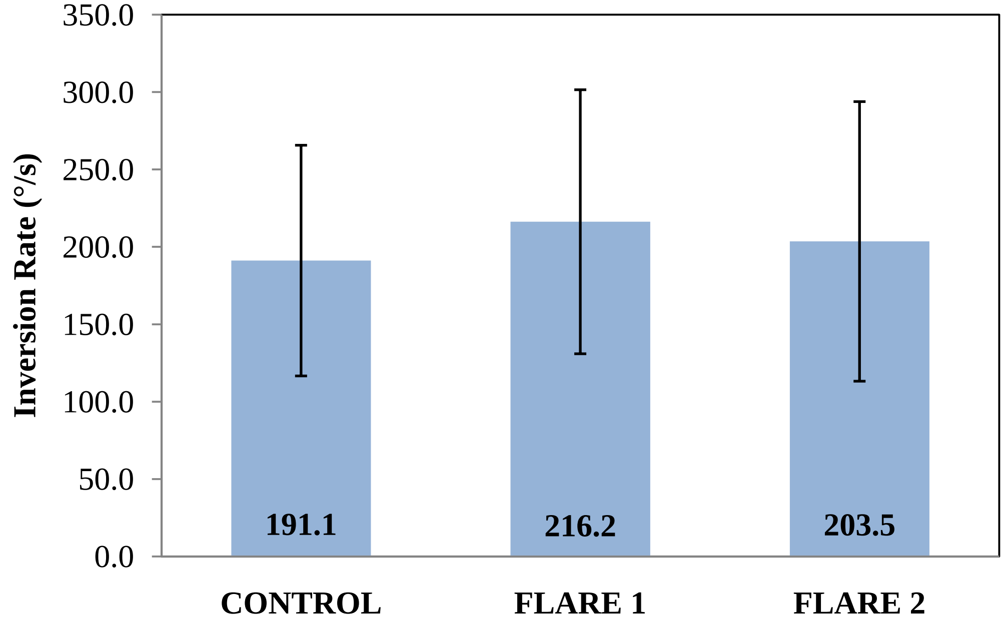


Figure 27. Running – Mean max inversion rate (No significant difference; p=0.105)

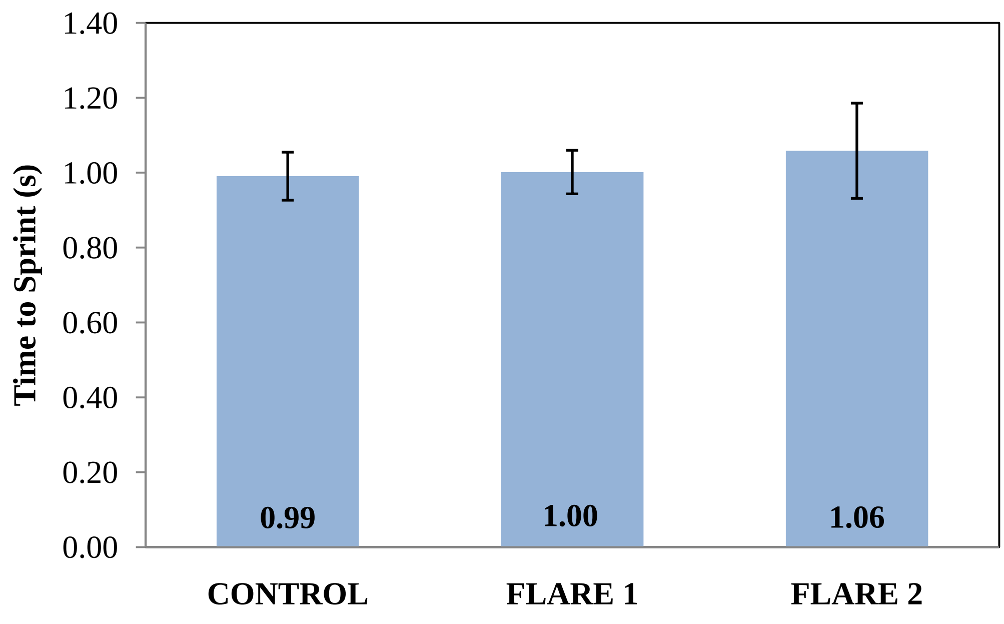


Figure 28. Running – Mean time to sprint (No significant difference; p=0.232)

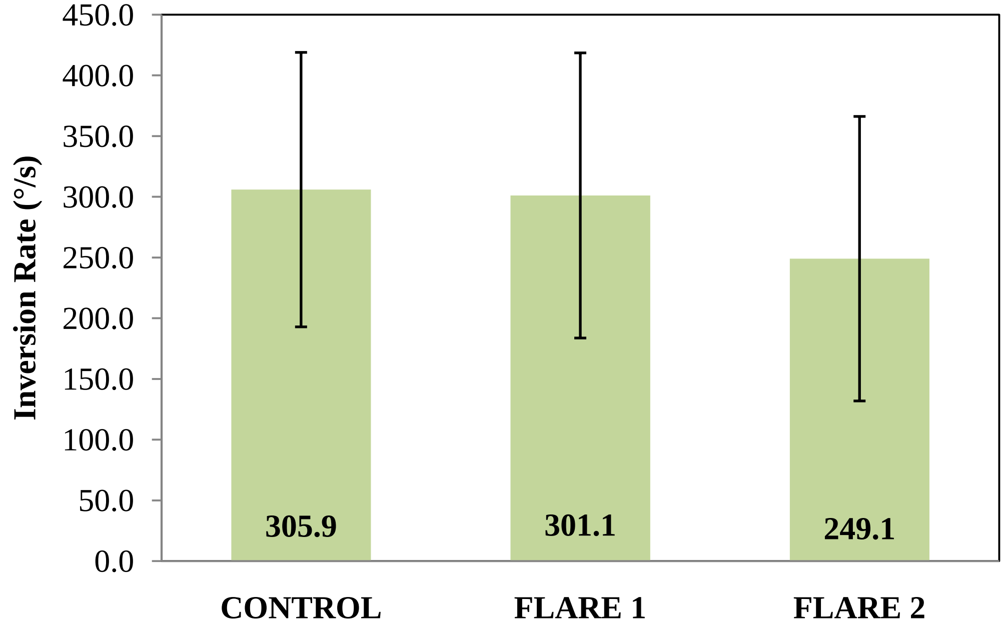


Figure 29. Jump takeoff – Mean max inversion rate (Significant difference: flare 2 different between control and flare 1; p=0.001)

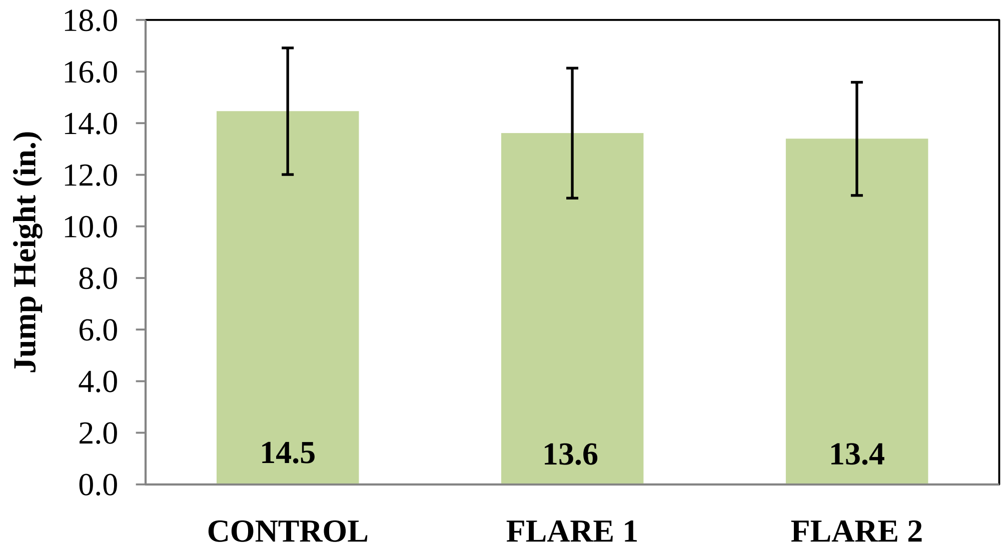


Figure 30. Jump takeoff – Mean jump height (Significant difference: control different between flare 1 and 2; p=0.008)

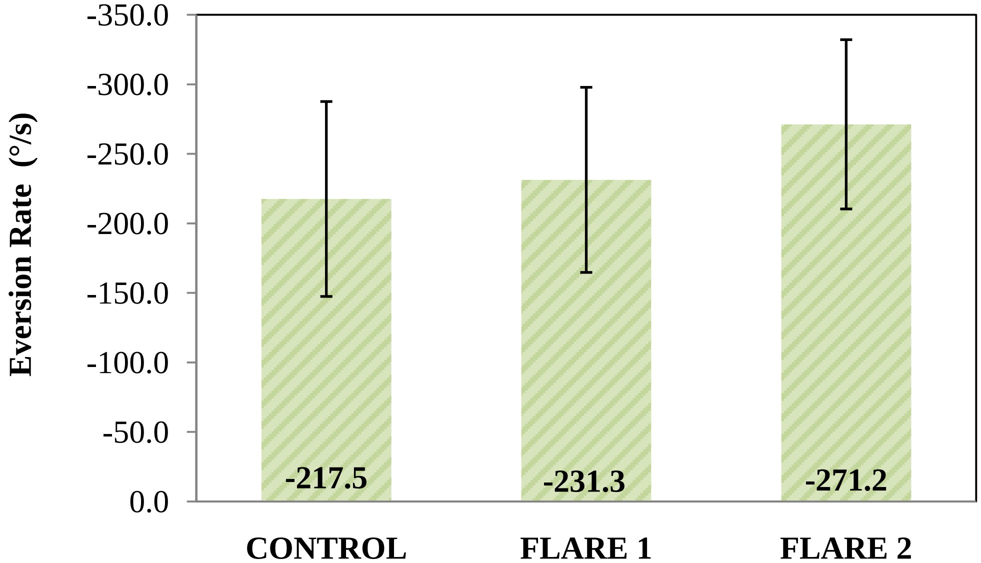


Figure 31. Jump landing – Mean max eversion rate (Significant difference: flare 2 different between control and flare 1; p=0.002)

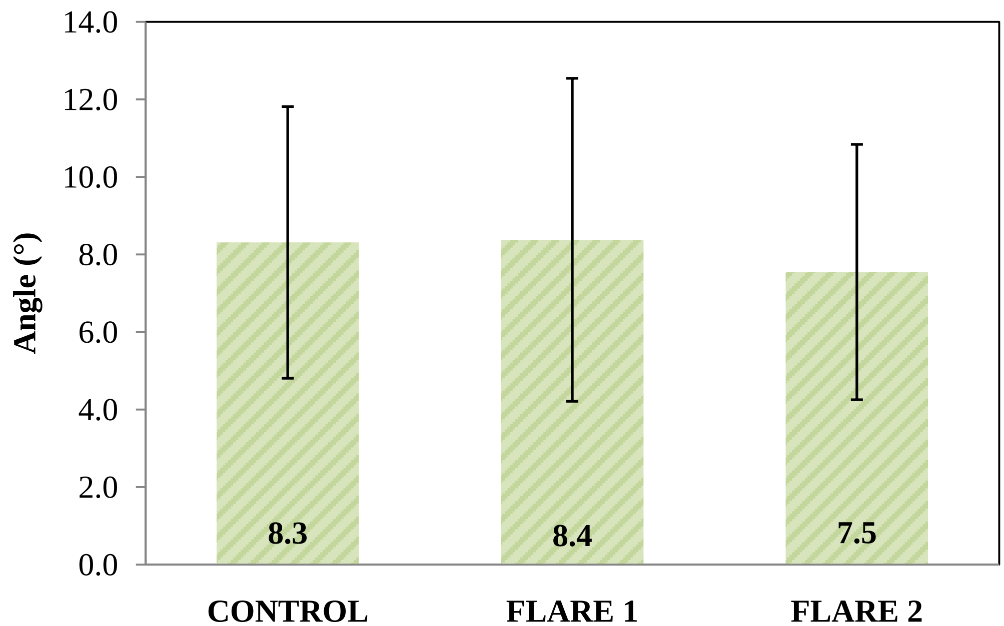


Figure 32. Jump landing – Mean rearfoot angle at impact (No significant difference; p=0.271)

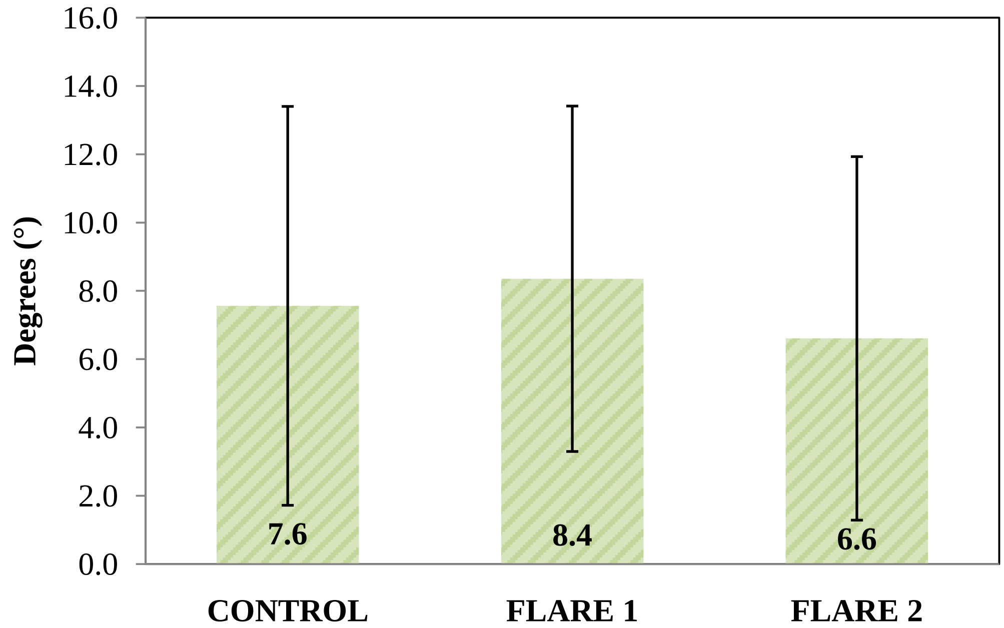


Figure 33. Jump Landing – Mean range of motion during impact (No significant difference; p=0.112)

Table 13. Running – Max Inversion Rate (p = 0.105)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	191.1	14.3	74.5	95.5	327.6
Flare 1	27	216.2	16.4	85.3	104.8	371.2
Flare 2	27	203.5	17.4	90.3	57.6	366.1

Table 14. Running – Time to Run (p = 0.232)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	0.9906	0.0123	0.0641	0.8981	1.082
Flare 1	27	1.0016	0.0112	0.0581	0.9363	1.1017
Flare 2	27	1.0585	0.0245	0.1272	0.9462	1.422

Table 15. Jump Takeoff – Inversion Rate (p = 0.001)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	305.9	21.8	113	118.9	461.2
Flare 1	27	301.1	22.6	117.4	158.3	482.4
Flare 2	27	249.1	22.5	117.2	99.1	461.1

Table 16. Jump Takeoff – Jump Height (p = 0.008)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	14.466	0.472	2.454	11.821	20.902
Flare 1	27	13.617	0.485	2.52	10.265	19.898
Flare 2	27	13.396	0.422	2.193	10.639	19.678

Table 17. Jump Landing – Rearfoot Angle at Impact (p = 0.271)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	8.31	0.674	3.504	3.121	16.826
Flare 1	27	8.377	0.802	4.165	3.136	17.779
Flare 2	27	7.546	0.634	3.293	2.744	14.654

Table 18. Jump Landing – Range of Motion During Impact (p = 0.112)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	7.56	1.12	5.84	1	25.23
Flare 1	27	8.355	0.973	5.058	2.632	26.488
Flare 2	27	6.61	1.02	5.32	1.25	21.99

Table 19. Jump Landing – Eversion Rate (p = 0.002)

Intervention	N	Mean	SE Mean	StDev	Minimum	Maximum
Control	27	-217.5	13.5	70.1	-373.3	-120.1
Flare 1	27	-231.3	12.8	66.6	-399.4	-138.7
Flare 2	27	-271.2	11.7	60.9	-381.5	-147.9

SUBJECTIVE PARAMETERS

The following details the feedback provided by the subjects. For statistical analysis, a Kruskal-Wallis test was used; $p<0.1$ was used to reject the null hypothesis. Tables 20 to 26 contain the tabulated results from the questionnaire and the analysis between the interventions and the user's perceived performance on impairment, stability and comfort. The tabulated results show the distribution of the total scores responded by the subject for each intervention. Since there were a total of nine subjects for this study, each intervention has nine responses for each questionnaire on impairment, comfort and stability. The max total score for impairment, comfort and stability was 15, 20 and 15 respectively; a total score that is closer to a max score would indicate that a subject strongly agreed to performance impairment, felt extremely stable, or felt extremely comfortable. The minimum total score for all topics would be 3, which mean that a subject strongly disagreed to performance impairment, felt extremely unstable, or felt extremely comfortable. The central total score for impairment and comfort would be 9, which mean that a subject felt no difference in impairment or moderately comfortable, respectively. A central total score for stability would be 12, which means that a subject felt moderately stable.

Tables 27 to 34 contain tabulated results from the questionnaire and the analysis between the interventions and running, cutting, jump takeoff and jump landing. The tabulated results show the distribution of the total number of responses to each score for each intervention and basketball movement. For example in Table 27, there were a total of 12 responses for a score of 3 concerning all questions about the running movement. Therefore, there were nine subjects and three questions for each intervention yielding a total of 27 responses for running, cutting and jump takeoff. For jump landing, there was only one question, which yielded a total of 9 responses.

IMPAIRMENT, STABILITY AND COMFORT

In Table 20 and 21, no difference (p=0.160) was found concerning the interventions and performance impairment; however, this p-value was close to the cutoff p<0.1. In Table 20, a couple of important issues exist. First, all interventions had a large range of responses (from a sum score of 3 to 11), which means that some subjects had perceived impaired performance and others did not. Second, the control had a high median value of 9 in Table 21, which means that subjects may have suggested more impaired performance with the control over the flare conditions. In regards to this observation, it should be noted that the descriptors of the Likert scale for the questions on impairment may have been poorly constructed; a total score of 9 would result if the subject selected “3 – No difference” for all questions. Five total scores were 9 or lower for the control, suggesting no difference to strong disagreement concerning impairment. However, four total scores were either 10 or 11, suggesting the subjects had perceived impairment with the control intervention – an unexpected contradiction. This note is elaborated in greater detail in the Discussion section.

In Table 22 and 23, difference (p=0.061) was found concerning the interventions and stability. The median score for Flare 2 was 15 whereas the median score for the control and flare 1 was 13. No difference (p=0.555) was found concerning the interventions and comfort as seen in Table 24 and 25. The flare conditions appear to not negatively impact comfort.

Table 20. Impairment – Sum

Intervention	3	4	5	6	7	8	9	10	11	All
Control	1	0	0	2	0	1	1	2	2	9
Flare 1	1	1	1	3	1	1	0	1	0	9
Flare 2	1	2	0	2	1	1	1	1	0	9
All	3	3	1	7	2	3	2	4	2	27

Table 21. Impairment – Kruskal-Wallis: Sum vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	9	9.000	18.1	1.88
Flare 1	9	6.000	11.6	-1.13
Flare 2	9	6.000	12.4	-0.75
Overall	27		14.0	

H = 3.57 DF = 2 P = 0.167
H = 3.66 DF = 2 P = 0.160 (adjusted for ties)

Table 22. Stability – Sum

Intervention	10	11	12	13	14	15	16	17	All
Control	1	1	2	1	2	2	0	0	9
Flare 1	0	2	2	2	0	0	1	2	9
Flare 2	0	0	0	1	2	2	3	1	9
All	1	3	4	4	4	4	4	3	27

Table 23. Stability – Kruskal-Wallis Test: Sum vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	9	13.00	10.4	-1.67
Flare 1	9	13.00	12.7	-0.59
Flare 2	9	15.00	18.9	2.26
Overall	27		14.0	

H = 5.51 DF = 2 P = 0.064
H = 5.61 DF = 2 P = 0.061 (adjusted for ties)

Table 24. Comfort – Sum

Intervention	8	9	10	11	12	All
Control	2	4	1	1	1	9
Flare 1	0	4	2	2	1	9
Flare 2	2	3	1	2	1	9
All	4	11	4	5	3	27

Table 25. Comfort – Kruskal-Wallis: Sum vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	9	9.000	12.3	-0.80
Flare 1	9	10.000	16.1	-0.98
Flare 2	9	9.000	13.6	-0.18
Overall	27		14.0	

H = 1.08 DF = 2 P = 0.582
H = 1.18 DF = 2 P = 0.555 (adjusted for ties)

Table 26. Kruskal-Wallis: Grand Sum vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	9	30.000	13.4	-0.26
Flare 1	9	30.000	11.7	-1.08
Flare 2	9	31.000	16.9	1.34
Overall	27		14.0	

H = 2.01 DF = 2 P = 0.365
H = 2.06 DF = 2 P = 0.358 (adjusted for ties)

RUNNING, CUTTING, JUMP TAKEOFF AND JUMP LANDING

No difference was detected between the interventions and running (p=0.577), cutting (p=0.832) and jump takeoff (p=0.931). Thus, the flare conditions did not negatively impact running, cutting or jump takeoff. In Table 27 and 28, when answering questions about the running movement, subjects selected both a median and mode score of 3. In Table 29 and 30, when answering questions about the cutting movement, subjects selected both a median and mode score of 3. In Table 31 and 32, when answering questions about the jump takeoff movement, subjects selected both a median and mode score of 3. In Table 33 and 34, when answering questions about the jump landing movement, subjects selected both a median and mode score of 3 for the control but a 4 for the flare conditions.

For the jump landing movement, difference (p=0.011) was detected between the interventions and jump landing; flare 2 differed from the control and flare 1. When answering questions about the jump landing movement, no subjects selected a score of 1 across all interventions. For flare 2, none of the responses scored a 1 or 2 but 6 of the 9 total responses scored a 4.

Table 27. Running – Tabulated Responses by Score

Intervention	1	2	3	4	5	Total # of Responses
Control	1	4	12	10	0	27
Flare 1	4	3	13	7	0	27
Flare 2	2	4	13	7	1	27
All	7	11	38	24	1	81

Table 28. Kruskal-Wallis: Running vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	27	3.000	44.1	0.84
Flare 1	27	3.000	37.9	-0.85
Flare 2	27	3.000	41.0	0.01
Overall	81		41.0	

H = 0.96 DF = 2 P = 0.620

H = 1.10 DF = 2 P = 0.577 (adjusted for ties)

Table 29. Cutting – Tabulated Responses by Score

Intervention	1	2	3	4	5	Total # of Responses
Control	1	5	15	6	0	27
Flare 1	2	9	8	8	0	27
Flare 2	2	7	9	9	0	27
All	5	21	32	23	0	81

Table 30. Kruskal-Wallis: Cutting vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	27	3.000	42.2	0.34
Flare 1	27	3.000	38.9	-0.57
Flare 2	27	3.000	41.9	0.24
Overall	81		41.0	

H = 0.33 DF = 2 P = 0.848
H = 0.37 DF = 2 P = 0.832 (adjusted for ties)

Table 31. Jump Takeoff – Tabulated Responses by Score

Intervention	1	2	3	4	5	Total # of Responses
Control	2	3	12	9	1	27
Flare 1	3	3	12	8	1	27
Flare 2	5	1	9	12	0	27
All	10	7	33	29	2	81

Table 32. Kruskal-Wallis: Jump Takeoff vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	27	3.000	41.7	0.20
Flare 1	27	3.000	39.5	-0.40
Flare 2	27	3.000	41.8	0.21
Overall	81		41.0	

H = 0.16 DF = 2 P = 0.923
H = 0.18 DF = 2 P = 0.913 (adjusted for ties)

Table 33. Jump Landing – Tabulated Responses by Score

Intervention	1	2	3	4	5	Total # of Responses
Control	0	3	5	1	0	9
Flare 1	0	2	2	3	2	9
Flare 2	0	0	1	6	2	9
All	0	5	8	10	4	27

Table 34. Kruskal-Wallis: Jump Landing vs. Intervention

Intervention	N	Median	Ave Rank	Z
Control	27	3.000	8.3	-2.62
Flare 1	27	4.000	14.6	0.28
Flare 2	27	4.000	19.1	2.34
Overall	81		14.0	

H = 8.29 DF = 2 P = 0.016
H = 9.06 DF = 2 P = 0.011 (adjusted for ties)

RESULTS OF THE HYPOTHESES

Since the pilot studies revealed problems with the wedge and cutting movement, only a portion of the proposed hypotheses could be tested. The following hypotheses were tested: (1) an increase in flare size will reduce: [a] max inversion rate during running and jump takeoff and [b] time to sprint and jump height; (2) an increase in flare size will increase eversion rate during jump landing compared to a shoe with no flare; (3) user will not perceive performance impairment with the flare compared to the control; (4) user will perceive more stability with the flare than with the control; (5) user will not perceive less comfort with the flare than with the control.

The results of the objective and subjective parameters listed in this chapter with respect to the hypotheses are listed in Table 35.

Table 35. Results of the Hypotheses

Hypothesis #	Result	Description
1	Not Supported	Flare size did not reduce inversion rate during running (p=0.105) and the time to sprint (p=0.232).
	Supported	Flare size did reduce inversion rate during jump takeoff (p=0.001).
	Partially Supported	The control was significantly different with jump height than the flare conditions (p=0.008).
2	Supported	Increase in flare size did increase eversion rate during jump landing (p=0.002).
3	Supported	User did not perceive performance impairment with the flare compared to the control (p=0.160).
4	Supported	User did perceive more stability with the flare than with the control (p=0.061).
5	Supported	User did not perceive less comfort with the flare than with the control (p=0.555).

CHAPTER 6

DISCUSSION

LIMITATIONS OF THE STUDY

A few comments on the limitations of the study will be made before a discussion on the results of the study. As described in the Methods chapter, the marker set used in this study was used to calculate rearfoot inversion and eversion. Therefore, the reported frontal plane kinematic values are the coupling of rearfoot motion with forefoot motion. Also the other limitations of the study relate to the small number of subjects used. The flare's mechanism of operation considers those who land forefoot first. This study happened to test two subjects who landed heel first; despite this, significant differences were indeed found with the flare interventions. Although all subjects were regular exercisers, not all of the subjects who volunteered for this study had basketball experience. Finally, the sports movements used in this study were representative of basketball movements but were not entirely accurate to in-game situations. The subjects were asked to complete movements with full effort, but the expressed effort is not necessarily true to in-game activity; many factors such as dribbling with a ball or the presence of a touching goal for the vertical jump were not included. Implications of these limitations are elaborated throughout this chapter.

INTRODUCTION

A summary of the statistical analysis can be seen in Table 36 to 38. The check symbol (✓) indicates that a difference was detected while the no symbol (⃠) indicates that a difference was not detected. Differences between the interventions and the objective and subjective parameters were detected; the ensuing paragraphs will discuss these results, inspect within subject data and non-measured feedback to drive discussion on informing the next iteration of design because the size of this study was small.

Table 36. Summary of Objective Parameters

	Running		Jump Takeoff	
Intervention	**Inversion Rate**	**Time to Sprint**	**Inversion Rate**	**Jump Height**
Control	⃠	⃠	⃠	✓
Flare 1	⃠	⃠	⃠	⃠
Flare 2	⃠	⃠	✓	⃠

	Jump Landing		
Intervention	**Eversion Rate**	**Angle**	**ROM**
Control	⃠	⃠	⃠
Flare 1	⃠	⃠	⃠
Flare 2	✓	⃠	⃠

Table 37. Summary of Subjective Parameters

Intervention	Impairment	Stability	Comfort
Control	⃠	⃠	⃠
Flare 1	⃠	⃠	⃠
Flare 2	⃠	✓	⃠

Table 38. Summary of Parameters on Basketball Movements

Intervention	Running	Cutting	Jump Takeoff	Jump Landing
Control	⃠	⃠	⃠	⃠
Flare 1	⃠	⃠	⃠	⃠
Flare 2	⃠	⃠	⃠	✓

Concerning the objective parameters, the results of the present study indicate that flare 2 has a negative influence on jump takeoff, and it yielded the slowest max inversion rate. Also, the flare interventions have a negative influence on jump height as the control yielded the highest jump height. Finally, flare 2 has a positive influence on jump landing, and it yielded the fastest max eversion rate. The flare interventions did not negatively influence the running movement, the angle at impact or the range of motion during the jump landing movement. It appears that these findings partially support the statements in the hypothesis that: (1) an increase in flare size will reduce rearfoot inversion rate during running and jumping maneuvers and will reduce the time to sprint and jump height and (2) an increase in flare size will increase rearfoot eversion rate during jump landing compared to a shoe with no flare. Concerning the subjective parameters, the results of the present study indicate that flare 2 has an influence on stability and jump landing. A significant difference was not found with impairment, comfort, running, cutting and jump takeoff.

RUNNING AND TIME TO SPRINT

No significant difference was found between the interventions and the inversion rate, the time to sprint or impairment, stability and comfort on the running movement. This means that the flare conditions did not negatively impact the inversion rate or the time to sprint, and the user did not express any usability problem during this movement. Looking at the group means, range for the max inversion rate is 191.1 to 216.3 °/s, while the range for the time to sprint is 0.99 to 1.06 s. In a kinematic study of 24 professional basketball players [172] by McClay et al., the mean max supination rate during running was 351.0 °/s (SD=187.93°/s); however, the model of shoe used in this study was not disclosed. An evaluation was made of the linear relationship between inversion rate and the time to sprint using Pearson’s correlation. An analysis using Pearson’s correlation coefficient indicates a non-statistically significant linear relationship between inversion rate and running r= -0.1304 (p=0.2460) with a cutoff of $p<0.05$.

Upon further inspection of the within subject data from the questionnaires, it was revealed in Table 20 that the sum scores exceeded 10 or more by four of the nine subjects. This range is closest to the max score of 15, possibly suggesting that these four subjects “moderately to strongly agreed” to impairment with the control over the flare conditions, which is a contradiction to what was expected by the hypothesis. This is an important observation and is thought to be attributed to two factors: the descriptors of the Likert scale and/or the randomization of interventions and basketball movements. Three of these four subjects tested the control condition last; the other tested the control second. These three subjects tested both flare conditions before the control, and thus the subjects may have expressed agreement to impairment with the control in response to possible residual effects from the shoes with flares.

In this questionnaire, the impairment utilized the Likert scale to express agreement to a statement; stability and comfort utilized the Likert scale to express feelings to a question. The descriptors of the Likert scale for the questions on impairment may have been poorly constructed. The score of 1 (strongly disagree) and 3 (no difference) may be confusing to the subject when responding to the statement, “My running was impaired by this shoe.” To this, four of the nine subjects scored 3. A subject may have felt no difference between a shoe condition and running impairment, and thus immediately checked a score of 3 based on the description alone. Essentially, the four of the nine subjects may have agreed to the description for score 3 rather than agreement to the statement. The words “no difference” in of itself do not express a level of agreement to the statement; this misguided wording does not execute the intended purpose of this Likert scale. Instead, if the subject truly felt no difference between a shoe condition and running impairment, then a score of 1 or 2 (the subject strongly disagrees or moderately disagrees that "My running was impaired by this shoe") is more appropriate for expressing agreement to the statement.

Therefore, this caveat perpetuates through the impairment questions concerning cutting and jumping. For these reasons, design decisions for the next iteration of flare design utilizing subjective results on the running, cutting and jumping movements must be viewed with caution. Although no significant difference was found, the individual subject may have expressed agreement to impairment but may have been missed due to the poor setup of the questionnaire.

CUTTING

No significant difference was detected with the responses provided by the subjects concerning the cutting movement. No subjects scored 5; 76 of the 81 total responses scored 2 to 4. Therefore, based on the subjective feedback alone, the flare interventions did not negatively impact performance, stability or comfort during cutting.

However, there was no kinematic data to support or not support flare designs concerning this movement. Significant kinematic data is critical to making a design decision but was not able to be provided in this study. Perhaps, in the testing phase of the next iteration of design, the cutting movement could be monitored more closely to obtain controlled, consistent and valid trials. To help with this, an alternative method to measuring ankle kinematics could use high speed films to monitor proper foot placement during the cutting movement. Nonetheless, the performance testing of the next iteration of flare design should obtain kinematic data on the cutting movement to provide objective evidence and support for flare designs in shoes.

JUMP TAKEOFF AND JUMP HEIGHT

The fact that flare 2 had significant difference to the control condition during the jump takeoff movement demonstrates that a kinematic and performance restriction existed for subjects who were regular exercisers and/or basketball players. Looking at the group means, flare 2 yielded a max inversion rate that was approximately 19% slower than the control. With respect to within subject data, the slowest and fastest max inversion rate at jump takeoff for flare 2 was 99.1 and 461.1 °/s, respectively. In the kinematic study by McClay et al. [172], the mean max supination rate at jump takeoff was 333.1 °/s (SD=87.55°/s). With a range of this magnitude, it is difficult to interpret how the individual subject was impacted by the objective impairment, as no significant differences were detected with the responses provided by the subjects concerning impairment on jump takeoff. Although the objective parameters demonstrated impairment, the subjects did not perceive any impairment. In addition, the subjects did not feel any comfort or stability issues during jump takeoff. Upon further exploration of the within subject responses, all subjects responded with a score of 1 to 3 for all questions, which demonstrate that subjects "strongly disagreed" or felt "no difference" to the flare 2 intervention on jump takeoff. No verbal remarks by subjects or observations concerning impairment were noted in lab. The next iteration of flare design must consider the kinematic impairment on jump takeoff but that subjects may not able to notice it at all.

Continuing with the jump takeoff movement, jump height was significantly different with control over the flare interventions. Looking at the group means, jump height with flare 2 was approximately 1.1 inches lower than the control. Again, no significant difference was detected with the subjective feedback concerning impairment and jump takeoff; this poses a problem in that it is difficult to discern if the individual subject truly perceived any usability problems with the flare when in fact jump height was reduced. The subjects may not have felt or perceived any impairment for two possible reasons. First, this difference in jump height is representative of the group mean but not necessarily revealing of the individual subject. Upon further inspection of the within subject data, two subjects jumped higher with the flare 2 condition when compared to the control condition. One subject jumped approximately a half inch higher; the other subject jumped nearly 0.1 inch higher. This may be attributed to the randomization of the interventions and trials. For both of these subjects, the flare 2 condition was the first intervention to be tested while the jumping movement was the second and third movement to be tested; this was at the very beginning where the subject is fresh and may not have been exposed to any fatigue factors. Second, given the vertical jump testing protocol, it may have been difficult for the subject to perceive such a jump height difference or impairment in the laboratory setting. It was noted that all subjects used a countermovement and consistently used the same jumping technique for all trials.

It is suspected that the subjective outcome of the flare design on the jumping movement would have provided clearer insight if a touching goal was introduced. For example, a touching goal would be a basketball rim elevated above the subject and with the subject beneath the rim. A touching goal could have provided the subject with a competitive incentive. This perspective would allow the subject to track mental notes on jump height performance.

The negative implications of a flare design on jump height during a competitive basketball setting needs to be addressed. Would the athlete perceive a jump height difference; would in-game activity be impacted? The subjects who volunteered for this study are casual exercisers and do not necessarily have jumping abilities that are competitive to that of a professional basketball player. If these subjects were the intended target market for basketball shoes with flare designs, then perhaps the flare and jump height would have tremendous implication for in-game basketball activity. A potential jump height impairment could have implications on successful basketball play – grabbing a rebound, blocking shots or pulling off a successful jump shot. However, the same could not necessarily be said if the stakeholders were NBA athletes as it is not logical to inform design decisions on stakeholders who were not involved as part of the design process; further investigation is needed with this population of subjects. Great consideration on the distinct athletic level of a stakeholder is owed to the next design iteration of the flare concerning jump takeoff.

A Pearson's correlation coefficient was performed to determine if there was a relationship between max inversion rate at jump takeoff and jump height. R was calculated to be 0.41 (p=0.0348), which is a positive relationship and of significant strength and can be seen in Figure 34. Since $p<0.05$, this Pearson's correlation coefficient indicates a statistically significant linear relationship between inversion rate at jump takeoff and jump height. For these data, the mean (SD) for inversion rate was 305.9 (113.0) and for jump height 14.5 (2.5).

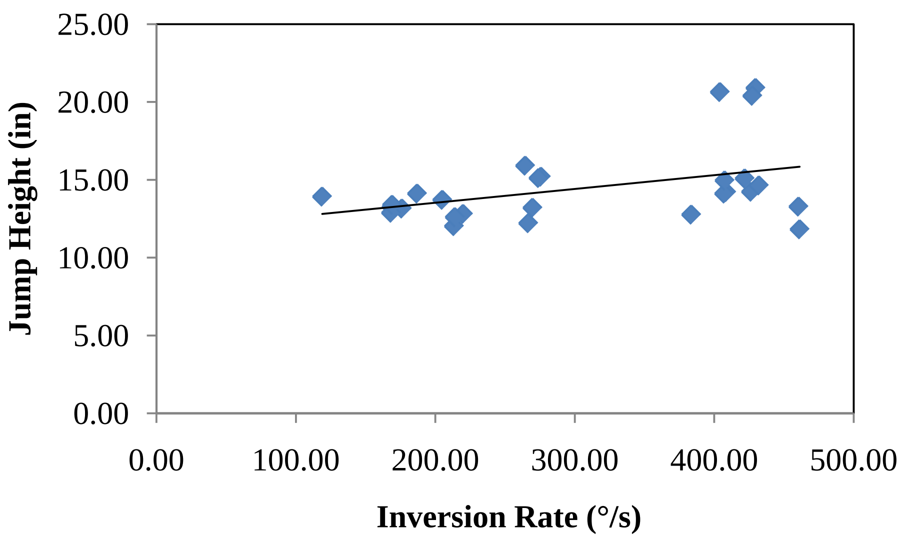


Figure 34. Pearson's correlation coefficient, r=0.41 (p=0.0348)

The flare conditions were shown to support the hypothesis that an increase in flare size would reduce the inversion rate at jump takeoff and reduce the jump height, but it was not known if the reduction of the inversion rate at jump takeoff is correlated to lower jump heights. The influence of the flare on inversion rate and its implication on jump height is considered in the next iteration.

The fact that flare 2 had significant difference on eversion rate during jump landing demonstrates that a metric of stability was provided. This finding supports the hypothesis that an increase in flare size would increase rearfoot eversion rate during jump landing compared to a shoe with no flare. Significant differences were detected in the responses provided by the subjects with flare 2 concerning stability and jump landing. It was noted during testing that all but two subjects landed with the forefoot first; the other two subjects landed with the heel first.

Although the findings found statistical difference and is supportive of the hypothesis, a closer look at the within subject data reveal unique observations that deserve attention as it may ultimately have implications informing the next iteration of flare design. First, looking at the group means, flare 2 yielded a max eversion rate that was approximately 25% faster than the control. With respect to the within subject data, the overall range of the max eversion rate was faster with flare 2 (-147.9 to -381.5 °/s) over the control (-120.2 to -373.3 °/s). In the kinematic study by McClay et al. [172], the mean max pronation rate at jump landing was reported to be -206.8 °/s (SD=82.73).

Upon further inspection of the within subject kinematic data, it was noticed that two subjects were measured to have faster eversion rates with the control over flare 2. The mean difference of the eversion rate between the control and flare 2 for these two subjects were 6.79 °/s (SD=30.75) and 8.18 °/s (SD=21.15). Both of these subjects scored “normal” according to the Redmond Foot Posture Index [176], which indicates a neutral foot posture. In addition, one of these two subjects landed heel first across all trials. Upon further examination of the subjective responses concerning flare 2 and stability during jump landing, the subject who landed heel first scored a 4 while the other subject, a forefoot striker, scored a 5.

These two unique subjects potentially challenge the mechanism by which a flare is thought to have an effect – both of these subjects unexpectedly landed with a faster eversion rate with the control over flare 2. However, the subject who landed heel first expressed feeling “very stable” with flare 2 but “moderately stable” with the control; the inconsistency is that the subject believed to feel more stable with flare 2 although he was a heel striker. Conversely, the subject who landed forefoot first expressed feeling “extremely stable” with flare 2 but “moderately stable” with the control – this was expected as stated in the hypothesis. Although feeling more stable with flare 2 and being a forefoot striker, the kinematic measurements of this subject challenge the hypothesis that a larger flare would increase the eversion rate at jump landing because faster eversion rates were reported with the control over flare 2.

Aside from these two subjects, the range of mean difference of the eversion rate between the control and flare 2 is -27.27 to -121.63 °/s. In addition, five of the other seven subjects scored 4, one scored 3 and the other scored 5; most of these subjects felt “very stable” with flare 2. Thus, the subjective feedback of the remaining subjects was in agreement with their kinematic results.

What these observations and findings on flare designs mean to stability, jump landing and in-game basketball activity need discussion. In Chapter 3, the introduction of a flare into a shoe can provide stability during jump landing, which is a benefit in reducing the potential for an ankle sprain. In Chapter 4, three metrics to represent the qualities of stability were identified: eversion rate, angle at impact, and range of motion during impact. If the flare were to increase the eversion moment upon jump landing, then an increase in eversion rate is an expected measure and a representation of this stabilizing effect. It was shown that the flare was significantly different regarding eversion rate at jump landing. Also, the position of the foot as it first touches the ground is thought to demonstrate a potential for an ankle sprain. If the foot is already supinated at touchdown, the GRF moment arm about the STJ axis may be greater, causing excessive supination [68]. A shoe must provide stabilization against rotation of the ankle if it is to provide support against the inversion stresses that frequently cause ankle sprains [26]. The flare was shown not to influence the angle at impact, and thus supports this quality of stability.

Finally, range of motion (ROM) during impact is an important metric of stability to consider; it was demonstrated that no statistical difference was found between the interventions and ROM. None of the interventions was shown to produce more movement at the ankle joint. Inversion ROM restriction has been the primary research focus to test the performance of prophylactic taping and AFO's. Upon further inspection of the within subject data, all ROM values were positive, meaning none of the interventions moved the foot into more inversion – a positive outcome for the flare.

Since a greater eversion rate was seen, it is possible that the foot was moved to a greater eversion angle (with the flare conditions compared to the control) after complete impact but was not quantitatively analyzed in this study. A greater eversion angle after complete impact can have injurious implications up the chain, and could expose the athlete to knee or lower back injuries. However, no statistical difference was found between the interventions and comfort on jump landing; subjects did not feel that any of the interventions negatively impacted comfort. These effects can become more apparent during in-game basketball play.

Although this idea of stability was supported with the flare designs and shows great promise during a standstill vertical jump, it is unknown how the flare would perform during in-game basketball activity where rigorous jumping movements are of the norm. A standstill vertical jump can be seen in a basketball game but jumping movements are much more likely to be done on the move and in a much rapidly changing environment. In this situation, it is difficult to predict how the metrics of stability would perform. However, more revealing subjective insight concerning impairment, stability and comfort would be expected since jumping movements while on the move are more physically demanding and require greater motor control. Because of this complexity, the potential for the user to notice minor differences should become more apparent.

CHAPTER 7

NEXT ITERATION OF DESIGN

DESIGN GOALS

The current flare designs have two problem areas that deserve attention in the next iteration of design: (a) of primary concern is the performance impairment on the inversion rate at jump takeoff and on jump height and (b) the uncertain objective and subjective stabilizing effects during more rigorous jumping movements. For these two areas, the design goals of the next iteration should:

(1) Reduce inversion rate impairment at jump takeoff and determine if the new design negatively impacts jump height.

(2) Maintain the stabilizing qualities achieved in the present study with the new design and be validated with more rigorous jumping movements.

(3) Maintain the non-impairing qualities achieved in the present study – do not hinder both objective and subjective parameters during running and cutting, and on impairment, stability and comfort during these movements.

In addition, a more defined stakeholder should be encompassing these design goals. A more in-depth selection of subjects could benefit performance testing. Stricter recruitment criteria may include: forefoot strikers only, competitive basketball players only - not casual exercisers, similar foot postures as scored by the Redmond Foot Posture Index, and perhaps similar subject height, weight and age. This type of vigilant approach with subjects may provide more supportive data and insight into flare performance.

DESIGN CRITERIA OF FLARE IN RELATION TO SHOE CONSTRUCTION

The investigation of the first design iteration had emphasis on performance testing – to measure flare effects, to determine if the results support flare designs into shoes, and whose results could then be used to improve flare designs. In this iteration, shoe prototypes were fabricated loosely and rather plainly; the flare embodies a block shape. In the next iteration, the design criteria will emphasize more forethought, planning and organization from a footwear construction and manufacturing perspective; the flare will no longer embody a block.

The first iteration has established promise to support flare designs into shoes. With this in mind, it is now important to consider how shoe construction methods can dictate how the flare can be designed into the overall scope of shoe design, and how new design concepts can stem from that.

This perspective is important for a few reasons: (1) there are many players in a footwear design team that influence the final aesthetic treatment of a shoe; to work alongside with this, the design criteria of the next flare iteration need not be a dictation but rather generalized rules that fit within shoe construction methods and maintain its functional purpose; (2) this will allow flexibility for future aesthetic treatment while incorporating new design concepts in order to test and execute its new design goals. Since flare 2 revealed significant differences, the next iteration of design will maintain a 2 cm lateral extension. Therefore, the rules seen in Table 39 can be used to design a general 2 cm flare into a shoe. From this, new flare concepts can be designed, prototyped, and tested for its performance while anticipating future aesthetic treatment. Figures 35 to 38 illustrate an example of which parts of the shoes can be constructed to achieve a 2 cm flare.

Table 39. Design Criteria for Overall Flare Design in Relation to Shoe Construction

Shoe Part	How to Incorporate Flare	Material
Midsole	- Push out sidewall thickness (the sidewall is used to hide the intersection between the upper and the sole). - This added dimension will take up a part of the 2 cm requirement.	EVA Shore 50-55A
Bottom Plate	- Take the area of interest of the bottom plate and extend it. - This extension will then be over molded onto the sidewall. - This added dimension will take up the remaining part of the 2 cm requirement	Rubber Shore 70A

Notes:

- The thickness of the sidewall in addition to the over molded portion of the bottom plate should be 2 cm, which is the flare. See section view in Figure 38.
- The 2 cm requirement is measured from the insole, which is essentially the footprint or the plantar area of the foot that is occupied inside the shoe. See Figure 36 and 37.
- If the over molded portion of the bottom plate is undesired, then the sidewall thickness must assume the entire 2 cm requirement; vice versa.
- These rules will manifest itself in many shapes and forms in anticipation for future aesthetic treatment and the design language befitting of a chosen brand.

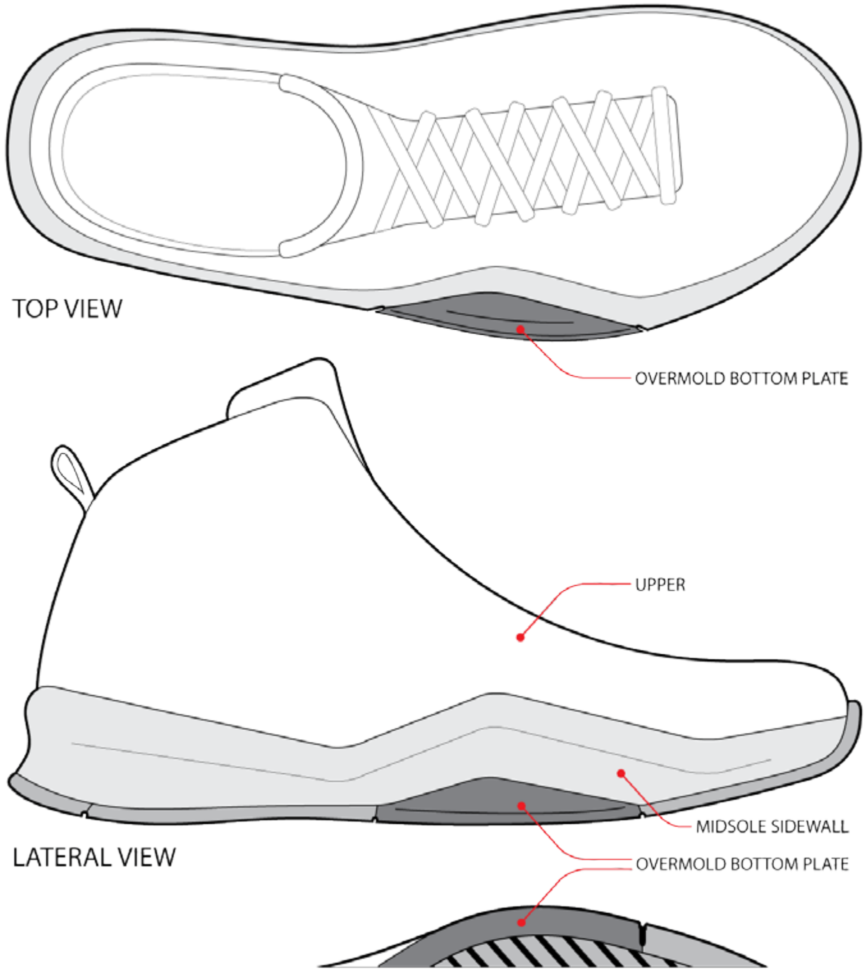


Figure 35. Illustration and overview of parts described in Table 35

In Figure 35, the parts of interest to the 2 cm flare are the midsole sidewall and the over molded portion of the bottom plate. The distal and proximal location of the 2 cm lateral extension with respect to overall shoe dimensions will be explained in the next section.

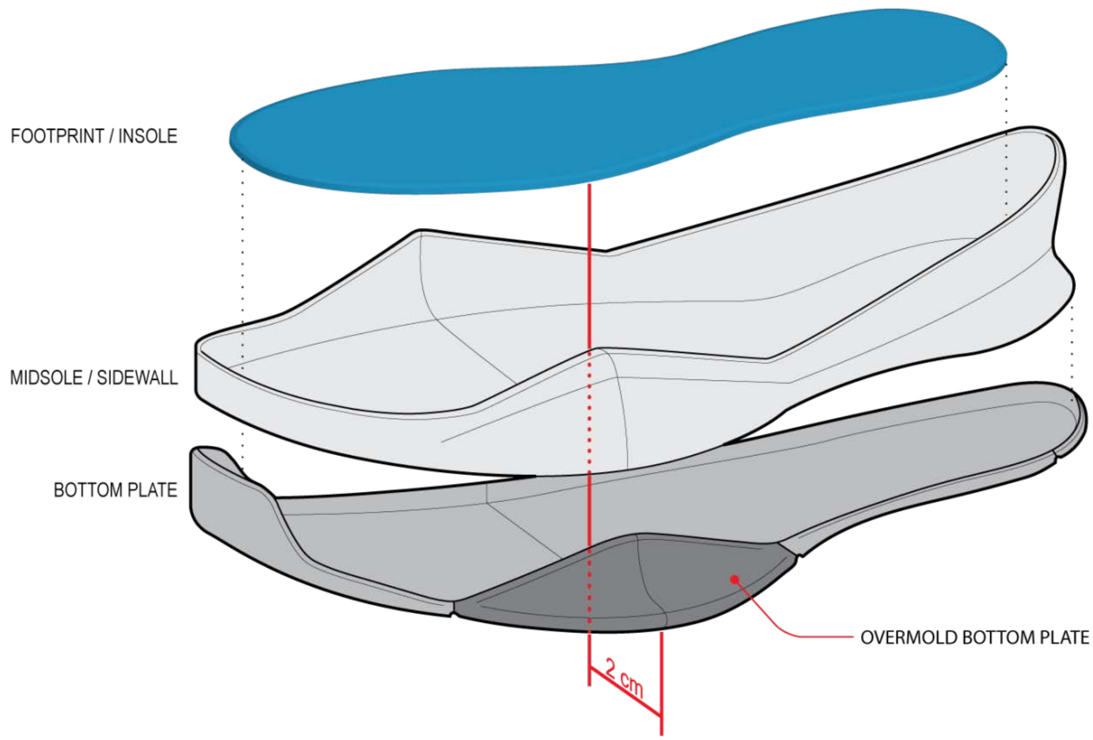


Figure 36. Exploded view of the insole, midsole and bottom plate interaction

Figure 36 illustrates an example of how the insole (or footprint), midsole (and sidewall) and the bottom plate interact. The insole is a piece inserted into the shoe to provide additional cushioning between the foot and the midsole. It is the piece that is in closest contact to the plantar area the foot, and it represents the footprint or the plantar area occupied by the foot. The insole is also called a foot bed and is removable.

The midsole is the primary source of cushioning between the foot and the ground. In many athletic shoes, the midsole is exposed to the environment (sidewall) and can have many aesthetic details molded into it. However, it is not unusual for the midsole to be covered with other materials such as mesh or leathers. The advantage of a sidewall is that it hides the interaction between the upper and the adhesion areas and stitched areas to the midsole. This allows a smooth and aesthetic transition which demonstrates attention to craft. The flare design criteria listed in Table 39 will utilize the sidewall from the midsole to help achieve a 2 cm extension.

The bottom plate is used to provide traction and durability to the shoe. It is essentially the tread on a tire. This piece is often injection molded, due to intricate patterns and color treatment. The bottom plate is glued to the bottom of the midsole. Some bottom plates are molded into the midsole design. As described in Table 39, a portion of the bottom plate can be extended laterally and over molded onto the sidewall of the midsole. This will allow the remaining 2 cm requirement to be completed.

Finally in Figure 36, the 2 cm measurement is made from the lateral aspect of the insole to the outer aspect of the over molded portion of the bottom plate. This can also be seen in Figure 37 but from the top and bottom views. Please note again the form and shape seen in these figures are examples of how the overall flare would manifest into the overall shoe design. It is not a final or finished product.

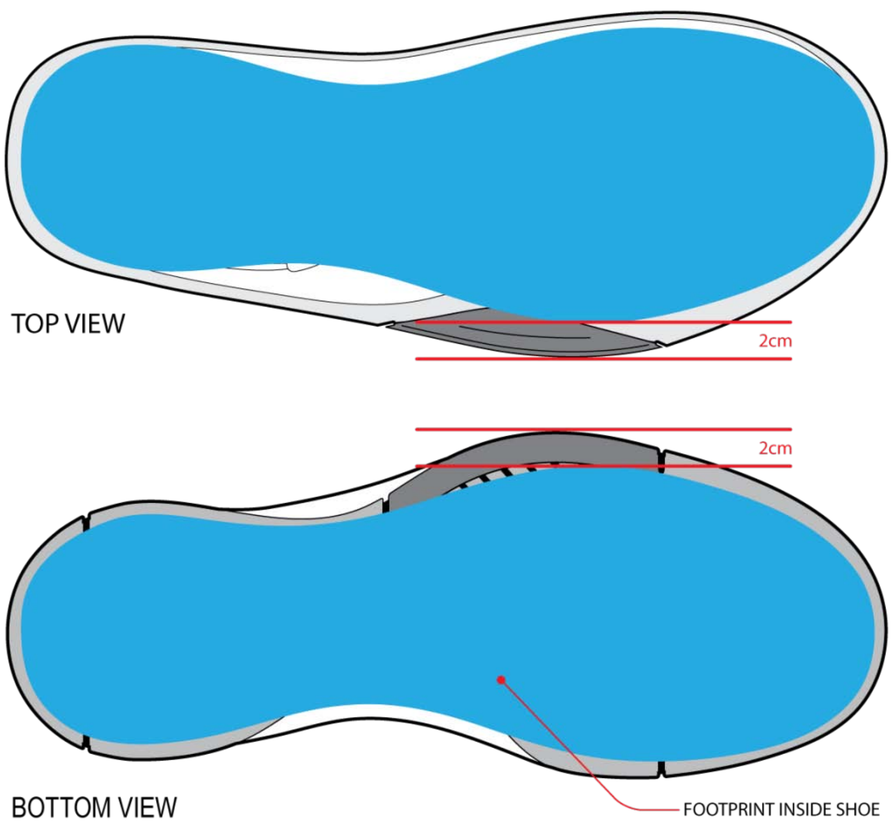


Figure 37. Overall 2 cm flare from the top and bottom view

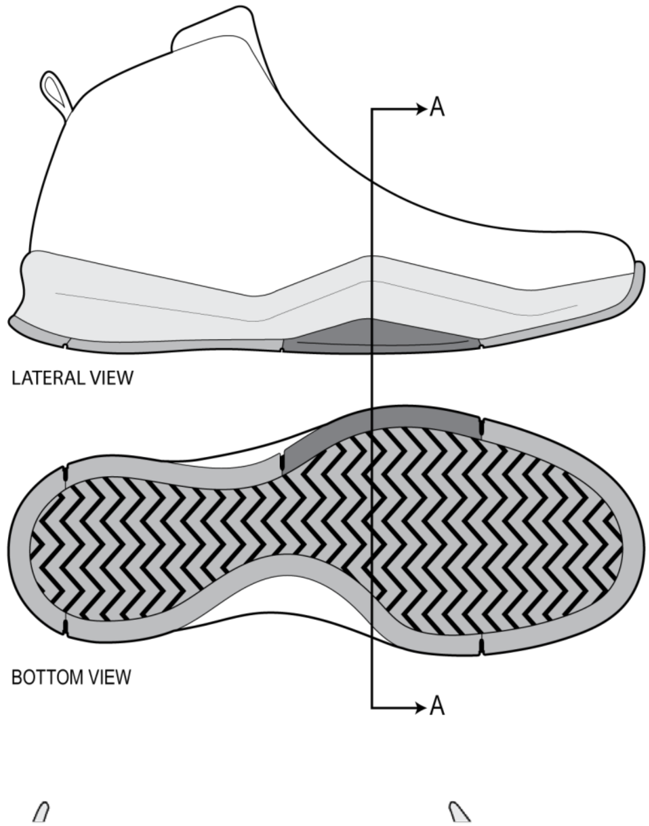


Figure 38. Section view of 2 cm flare measured from midsole to bottom plate

In Figure 38, the 2 cm measurement can be seen from inside or the midsole sidewall or the outer aspect of the insole to the outer aspect of the bottom plate. Please note that the sidewall is pushed out, which adds thickness and dimension to the 2 cm requirement. The design criteria listed in Table 39 allow a 2 cm flare to be added in the overall shoe design; this can now accommodate the design criteria of the new concepts that address the new design goals.

NEW DESIGN CONCEPTS

Figures 35 to 48 illustrate an example of the rules of incorporating a flare design into the overall shoe design, as described in Table 39. It is not an example of a final shoe product. However, with these illustrations and rules in mind, new design concepts of the flare that will help achieve the new design goals can be explored.

Since the results of the first iteration indicate potential issues with inversion rate at jump takeoff and with jump height (design goal 1), the new concepts must address this. In addition, the new concepts must maintain the stabilizing effects during jump landing (design goal 2), and not hinder both objective and subjective parameters during running and cutting, and on impairment, stability and comfort (design goal 3). However, these latter goals must be tested.

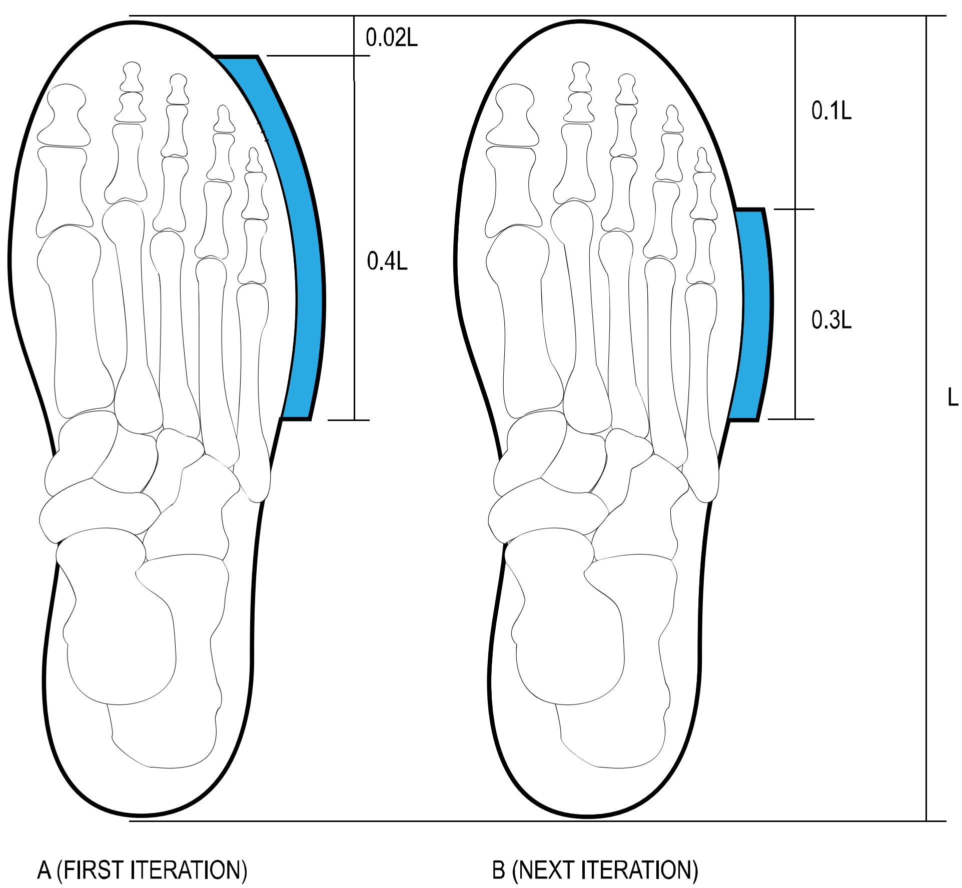


Figure 39. Flare location A and B with respect to overall shoe dimensions

To deal with design goal (1), the next iteration flare describing its proximal and distal location with respect to the overall shoe dimensions is introduced in Figure 39. However, the first and next iteration flare locations can be applied with all new design concepts. The next iteration flare location shows a generous removal of flare material in the distal region. The idea behind this is to also allow less material to interfere with supination at toeoff, thus potentially encouraging faster inversion rates. This will also reduce the flare mass added to the shoe, which is a design criterion set forth in the initial flare design. However, with less material in the distal region, it is quite possible that design goal (2) may not perform as well because there may be less potential that the pronation lever arm will be increased with the GRF at jump landing.

In Table 40, the design criteria of the new flare concepts are summarized. Again, it will not dictate the final aesthetic appearance but will be a reflection of the construction guidelines set forth in Table 39.

Table 40. Summary of New Design Concepts and Criteria

Concept	Description and Flare Location
(1) Radius Edge See Figure 40	- Overmold edge thickness should be (~ 1/8 inch) - Full radius fillet for the entire flare length - Flare extension is 2 cm - Flare location: A and B
(2) Sloped Area See Figure 41	- Slope the plantar area of the flare (~ 8°) upward, starting from the midsole sidewall to overmold edge - Flare extension is 2 cm - Flare location: A and B
(3) Segmented Flare See Figure 42	- Segment the entire length of flare into individual flares - Width of individual flare can be 1/8" - The number of individual flares will be what can fit into the entire length of the flare, which is based on shoe size and on which Flare location concept (A or B) that is chosen - Flare extension is 2 cm - Flare location: A and B

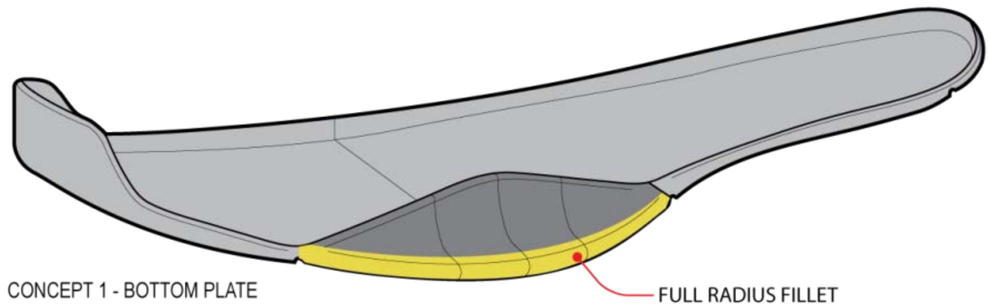


Figure 40. New design concept 1 with full radius fillet

Concept 1 has a full radius fillet that will run the entire length of the flare, as seen in Figure 40. It can be applied to both proposed flare location A and B. It is recommended that the flare thickness be approximately 1/8 inch or more for molding considerations. Instead of a square edge as seen in the first iteration, the curvature provided by the fillet may allow less resistance during supination motion at toeoff. This in turn can help the foot achieve a greater inversion rate at jump takeoff, tackling design goal (1). Jump height can also improve but would need testing to support this; design goals (2) and (3) will need to be tested as well.

In a similar fashion, concept 2 will have the plantar area of the flare slope upwards from the medial to the lateral direction, as seen in Figure 41. It would start from the midsole sidewall to the outer edge of the overmold piece. This concept can also be applied to both flare location A and B, as long as the same slope incline is maintained. A slope of ~ 8° is proposed and was the calculated mean from the max inversion angle at jump takeoff of the subjects from the first iteration testing. This proposed angle is simply a starting point to test its effect, and can be adjusted or discarded after further investigation. It is thought that the noncontact area provided by the slope will provide unhindered room for foot supination at jump takeoff, incorporating design goal (1). However, design goal (2) and (3) may not perform as well since the additional room would require more inversion of the foot at initial impact from jump landing. Safety should not be compromised but angle at impact will need to be monitored closely with this concept.

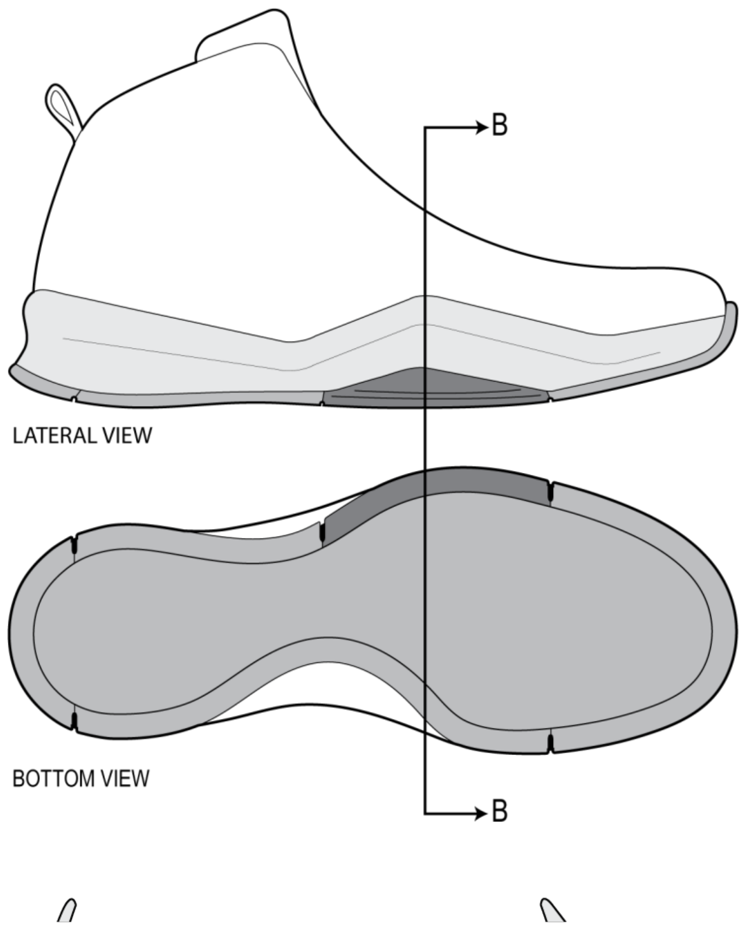


Figure 41. Section view of new design concept 2 with a sloped flare

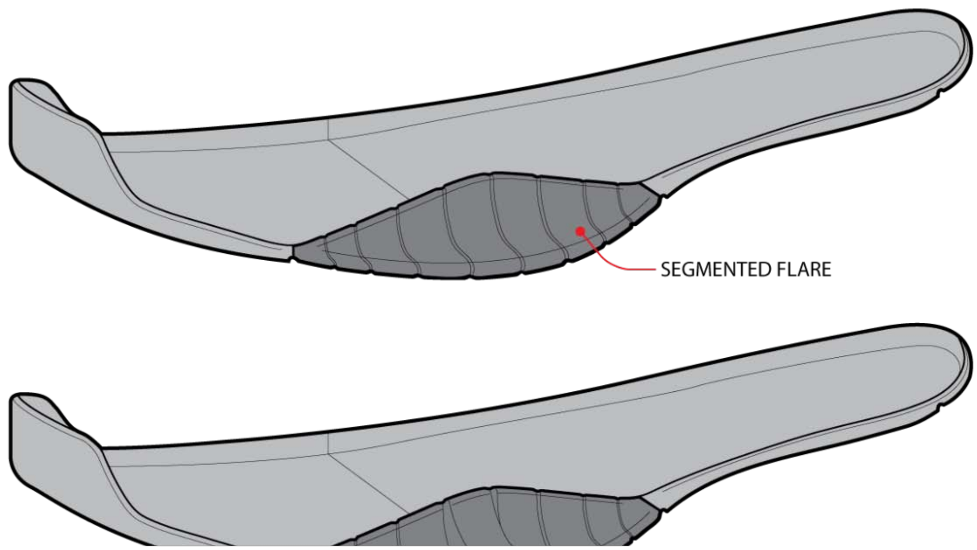


Figure 42. Segmented flare from of new design concept 3

Concept 3 is a flare that contains divided sections – essentially, a series of smaller flares, as seen in Figure 42. The idea behind the divided sections is that the resistance provided by the flare during supination at jump takeoff is distributed to the flare segments upon which it is directed. However, it is unknown if each individual flare or if the entire flare would be in contact with the ground at the time of toeoff but was developed in consideration of design goal (1). However, since the divided sections are flexible, it may negatively impact the stabilizing qualities needed in design goal (2). In this scenario, the GRF acts upon a section of the flare rather than the entire flare segment seen in the first iteration. Thus, it would hypothesized that design goal (2) may not perform as well. Further testing would be needed to support these decisions.

CONCEPT 1 RENDERING

A sample illustration of concept 1 with respect to the overall shoe design can be seen in Figure 43 and 44. These figures illustrate the curvatures and dimensions expected to be seen in concept 1 when developing a final shoe product. In addition, other shoe features such as a herringbone pattern, heel counter and finger loop are illustrated.

Figure 43. Illustration of Concept 1

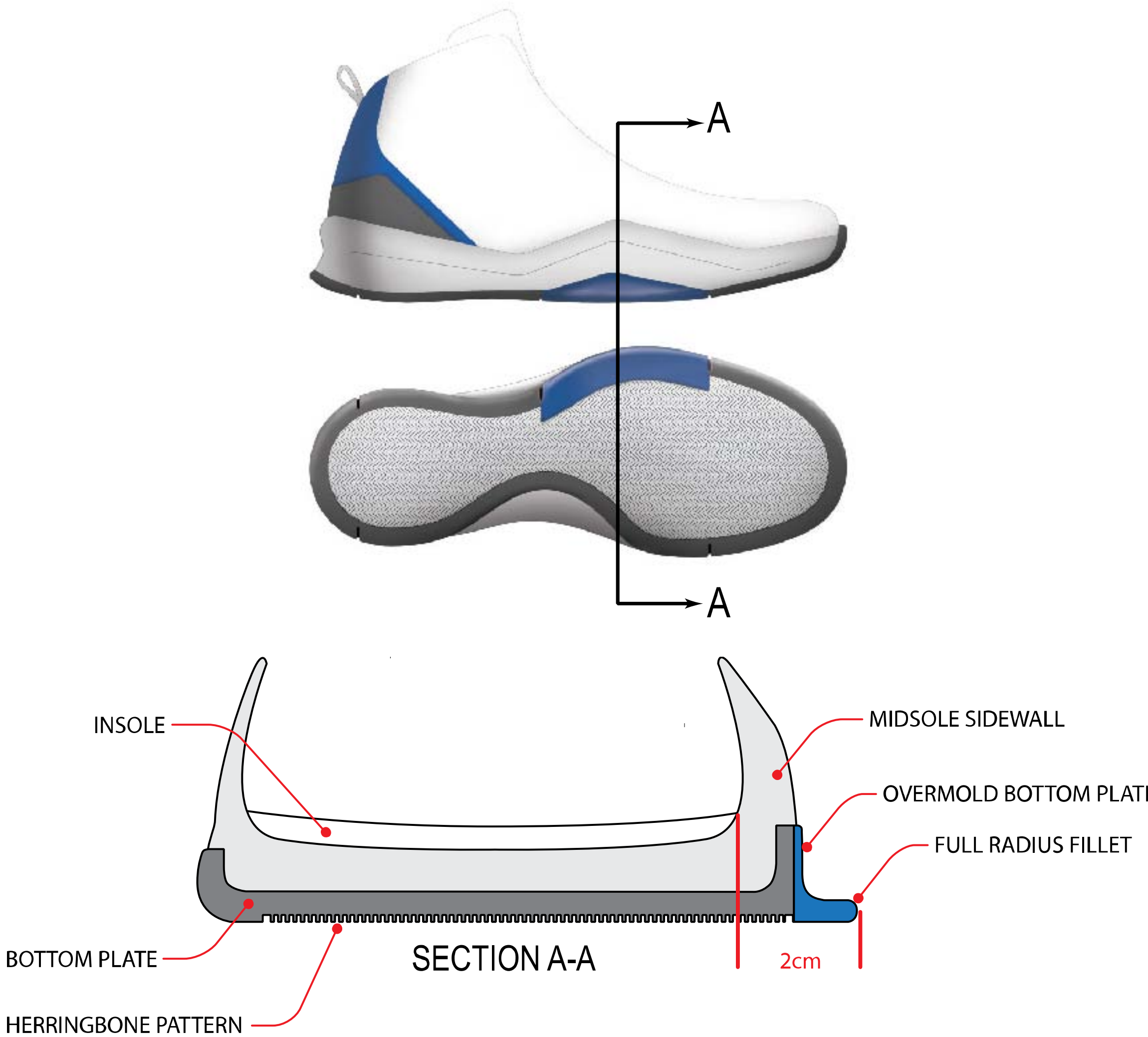


Figure 44. Section view of concept 1 illustration

TESTING PROCEDURES

A similar approach should be taken to test the performance of the new design concepts – both objective and subjective parameters are needed. The same kinematic and performance metrics described in Table 7 and 8 should be used to evaluate the objective parameters of the new design concepts during running, cutting and jumping movements. However, as described previously, including data during a cutting movement will help provide more insight about the flare as cutting is an essential movement in basketball. In addition, a jumping movement that is more rigorous and representative of in-game basketball activity can help delineate the stabilizing effects provided by the flare. In regards to the subjective parameters, consistency is required with all Likert scales – the impairment questions should utilize a Likert scale to express feelings to the question rather than expressing agreement to a statement. Keeping this consistency will prevent any confusion by the subject, and will provide more useful data.

APPENDIX A: CONSENT FORM

GEORGIA INSTITUTE OF TECHNOLOGY

Project Title: "Assessment of orthotic/shoe interventions on basketball movements."

Investigators:
- **Principal Investigator** – Géza F. Kogler, Ph.D., C.O.
- **Co-Investigator** – Dale Kim

Research Consent Form
You are being asked to be a volunteer in a research study. The study title is: "Assessment of orthotic/shoe interventions on basketball movements."

Purpose
The purpose of this study is:

- To learn how the body responds to the use of a new shoe design during three basketball movements, which include running, changing direction, and jumping.
- To measure motion of the body with a special video camera.
- To measure forces during three basketball movements with a special instrument imbedded in the floor or treadmill.
- To take the information collected and determine how running, changing direction, and jumping are affected with our new shoe design.
- We expect to enroll 10 people in this study.

Exclusion/Inclusion Criteria:

- If you have a history of dizziness or problems with balance you should not participate in this study. Contact the investigator immediately.
- If you have a current ankle injury or a history of lower leg injuries you should not participate in this study. Contact the investigator immediately.
- Participants in this study must play basketball or exercise on a regular basis.

Procedures:
If you decide to participate in this study, your part will involve:

- Scheduling two visits for the study that may take up to 2 hours per visit.

You will be asked to take part in the following activities during your two visits:
(Applicable conditions are checked, all others are blacked out)

_____ Walk **_____ in place**
_____ on a treadmill
_____ over ground

_____ Run **_____ on a treadmill**
_____ over ground
_____ while stepping on easily read marks on the ground

_____ Jump from a standstill

_____ Wearing new shoes provided by the researcher on your: ___ ankle/feet

- Each test may take up to 5 seconds of activity. During the tests, you will be allowed plenty of rest and water if you need it.

- You may have round (10 mm) markers stuck on your legs with tape. Special video cameras may measure the motion of your body in each of the study conditions. The measurement equipment is the same used in video game and movie industries.

- Sensors located in the floor may measure the pressures beneath your shoe.

Risks or Discomforts
The following risks or discomforts may occur as a result of your participation in this study:

- Since you may be running and jumping, certain risks and discomforts may apply. The risks may include increased heart rate or muscle fatigue. Every effort will be made to minimize these risks by selecting only conditioned subjects. Please contact the investigator if you feel discomfort or any other symptoms.

- The risks involved in this study are no greater than the risks you may experience during normal daily exercise activity.

Benefits
There are no direct benefits to you joining this study. However, we hope to use the knowledge we gain to improve the design of basketball shoes.

Compensation to You
You will not be compensated for your participation in this study.

Confidentiality
The following procedures will be followed to keep your personal information confidential in this study:

- All the information collected from you will be kept private to the extent allowed by law.
- Your indentifying information will be kept in locked files. Only laboratory staff will be allowed to look at the information for the purpose of science.
- Your name and any other facts about you will not appear when results of this study are presented or published.
- Some representative video may be archived for scientific reference.
- Any video tapes recorded in this study will be kept secured in the same manner as the written files. If any pictures or videos are to be presented for scientific purposes all identifiable characteristics (i.e. subject's faces) will be blocked from view.
- To make sure that this research is being carried out in the proper way, certain organizations will be allowed to review the records. They are: a) Georgia Institute of Technology Institutional Review Board and b) The office of Human Research Protections.

Costs to you
There are no costs to you except for your time.

In Case of Injury/Harm
If you are injured as a result of being in this study, please contact the principal investigator, Dr. Géza F. Kogler by telephone (217) 691-1265 as soon as possible after any necessary emergency medical attention has been received. Neither the Principal Investigator nor the Georgia Institute of Technology has made arrangements for payment of costs associated with any injury resulting from participation in this study.

Subject Rights

- Your participation in this study is voluntary. You do not have to be in this study if you do not want to be.
- You have the right to change your mind and leave the study. You may leave at any time without giving any reason.
- Any new information, that may make you change your mind about being in this study, will be given to you.
- If requested, you will be given a copy of this consent form to keep for your records.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study or Your Rights as a Research Subject

- If you have any questions about this study, you may contact Dr. Géza F. Kogler by telephone (217) 691-1265 or e-mail (geza@gatech.edu).
- If you have any questions about your rights as a research subject, you may contact Ms. Kelly Winn, Georgia Institute of Technology at (404) 385-2175.
- If you sign below, it means that you have read (or have had read to you) the information in this four-page consent form, and are indicating that you would like to be a volunteer in this study.

____
Subject Name (print)

____
Subject Signature, Date

____
Name of Person Obtaining Consent (print)

____
Signature of Person Obtaining Consent, Date

Consent Form approved by Georgia Tech IRB from 21 May, 2010 to 20 May, 2011

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