MODIFYING MIDSOLE STIFFNESS OF BASKETBALL FOOTWEAR AFFECTS FOOT AND ANKLE BIOMECHANICS

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ABSTRACT

Background: There is a growing incidence of foot injuries in basketball, which may be from the sport's repetitive, forceful multi-directional demands. Modifying midsole stiffness of the basketball shoe has been reported to alter ankle motion and plantar forces to reduce the risk of injury; however, the effects on anatomical, in-shoe foot (metatarsal), motion is not well understood.

Purpose: The purpose of this study was to identify differences in foot and ankle biomechanics between basketball shoes with differing midsole stiffness values during single-leg jump landings. It was hypothesized that a stiffer midsole would elicit lower 1st metatarsophalangeal joint (MTPJ) dorsiflexion angles, higher ankle dorsiflexion angles, and higher plantar forces and relative loading in the distal foot.

Study Design: Experimental cross-sectional study.

Methods: Twenty high school and collegiate-aged basketball players performed a single-leg side drop jump and a single-leg cross drop jump in a pair of standard basketball shoes and a pair of shoes modified with a fiberglass plate to increase midsole stiffness. Three-dimensional motion analysis and flexible insoles quantified foot and ankle kinematics and plantar force distribution, respectively. Separate 2 (footwear) x 2 (task) repeated measures ANOVA models were used to analyze differences in 1) ankle kinematics, 2) 1st metatarsophalangeal kinematics, 3) maximal regional plantar forces, and 4) relative load.

Results: The stiffer shoe elicited decreased peak ankle plantarflexion (mean difference = 5.8°, $p=0.01$) and eversion (mean difference = 6.6°, $p=0.03$) and increased peak ankle dorsiflexion angles (mean difference = 5.0°, $p=0.008$) but no differences were observed in 1st MTPJ motion ($p>0.05$). The stiffer shoe also resulted in lower peak plantar forces (mean difference = 24.2N, $p=0.004$) and relative load (mean difference = 1.9%, $p=0.001$) under the lesser toes.

Conclusions: Altering the midsole stiffness in basketball shoes did not reduce motion at the MTPJ, indicating that added stiffness may reduce shoe motion, but does not reduce in-shoe anatomical motion. Instead, a stiffer midsole elicits other changes, including additional ankle joint motion and a reduction in plantar forces under the lesser toes. Collectively, this indicates that clinicians need to account for unintended compensations that can occur throughout the kinetic chain when altering a shoe property to alleviate a musculoskeletal injury.

Level of Evidence: 2b

Keywords: Basketball, midsole stiffness, metatarsal injury, jumping

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INTRODUCTION

The significant multi-directional demands of basketball have led to a high incidence of non-contact traumatic and overuse injury rates.^{1,2} Most of these injuries occur in the lower extremity³ with over 25% of all injuries occurring at the foot and ankle.⁴ While ankle sprains capture a majority of foot and ankle injuries in basketball athletes, there appears to be a growing incidence of foot fractures, specifically to the metatarsals.⁵⁻⁷ Most metatarsal injuries result in surgical intervention, followed by significant time lost for injury,⁶ and basketball players are at a high-risk for re-injury after return to sport.⁸ Abnormal plantar loading and/or excessive foot motion during high-level decelerating activities like jumping, landing, and changing directions have been suggested as contributors to the increased risk of metatarsal injuries in these athletes.^{7,9}

Current practice to alter loading and decrease excessive foot motion to prevent future or rehabilitate previous metatarsal injury often includes modification of the structural properties of the shoe.^{10,11} While walking, greater midsole stiffness has been reported to lower forefoot range of motion in the sagittal plane, decrease rearfoot inversion and adduction angles, and increase rearfoot abduction angles.¹² During running, stiffer shoes are reported to promote altered lower extremity movement strategies, increased ankle joint moments, and overall running economy.^{13,14} Increasing midsole stiffness of running shoes has also been shown to redistribute plantar loading and improve performance during jumping^{15,16} and cutting¹⁷ tasks. Collectively, these studies justify the alteration of midsole stiffness for isolated foot and ankle pathologies in standard running shoes.

Numerous differences exist between sport-specific footwear and within footwear designed for the same sport.¹⁸ Clinicians should cautiously interpret findings from the running shoe literature prior to modifying footwear for multi-directional sport athletes. To date, there has been diminutive investigation of the effect of midsole stiffness on multi-directional sport-specific footwear, especially basketball shoes. Other than one study reporting mild to moderate improvements in sprint and agility times and no change in vertical jump height in basketball shoes

with greater midsole stiffness,¹⁹ evidence for altering midsole stiffness properties in basketball footwear is lacking. Specifically, the effect of midsole stiffness properties on biomechanical strategies during common basketball demands is unknown. The purpose of this study was to identify differences in foot and ankle biomechanics and athletes' perceived comfort between basketball shoes with differing midsole stiffness values during single-leg jump landings. It was hypothesized there would be no differences in perceived comfort and a stiffer midsole would elicit lower 1st metatarsophalangeal joint (MTPJ) dorsiflexion angles, higher ankle dorsiflexion angles, and higher plantar forces and relative loading in the distal foot. Additionally, this study aimed to identify differences in foot and ankle biomechanics between a lateral- and medial- directed single-leg jump landing.

METHODS

Subjects

Twenty-one high school and collegiate aged basketball players volunteered to participate in the study. Upon arrival to the biomechanics laboratory, subjects were briefed on the risk and benefits of participating in the study and consent forms were completed. One subject was excluded due to technical issues, leaving 20 for inclusion in the final analyses (age 18.0 ± 1.8 yrs, height 185.9 ± 6.2 cm, mass 80.6 ± 9.2 kg, BMI 23.4 ± 2.3 kg/m²). Inclusion criteria consisted of: 1) age 14-25 years old, and 2) current participation on an organized and competitive basketball team. Potential subjects were excluded if they had a history of lower extremity injury in the previous six months. The average experience of the participants on an organized basketball team was 10.3 years (range 3-17). Informed written consent or parental permission was obtained from each subject prior to data collection. The protocol was approved by the High Point University Institutional Review Board. Funding for the study was provided by adidas International.

Footwear

Each participant was fitted with two pairs of identically-sized basketball shoes (adidas D Rose 5 Boost, Portland, OR, USA) (Figure 1). One pair of shoes was the standard off-the-shelf version, while the other

Figure 1. Picture of the footwear used in this study with masked regions of plantar loading.

pair was modified with a fiberglass plate to increase midsole stiffness. Shoes were tested in a randomized order and participants were blinded to footwear conditions. Each participant completed visual analog scales immediately following testing that separately assessed comfort, shock absorption, stability and control, traction, and safety.¹⁸

Procedures:

A three-dimensional motion analysis system was used to identify lower extremity kinematics during each trial. Lower extremity kinematics were captured using an electromagnetic motion analysis system (trakSTAR™; Ascension Technologies, Inc., Burlington, VT) controlled by Motion Monitor® software (Innovative Sports Training, Inc., Chicago, IL). Electromagnetic sensors used to measure lower extremity movement were six degrees of freedom sensors. As previously published,²⁰ 8 mm sensors were secured to the lateral thigh, tibial shaft, and the sacrum, and 2mm sensors were attached to the foot on the medial side of 1st phalange, medial side of the 1st metatarsal, lateral side of the 5th metatarsal, cuboid and calcaneus. Kinematic data were collected at a sampling rate of 200Hz.

A flexible in-shoe pressure distribution measuring insole was inserted into the left shoe (pedar®, novel GMBH, Munich, Germany) and sampled at 200 Hz. Data was collected only on the left foot to double the system constrained sampling rate and match the kinematic measurement. Prior to data collection, each insole was calibrated to 900 kPa. A telemetric signal from the pedar® unit was sent to a laptop computer to allow wireless data collection. Synchronized video was used in conjunction with the pressure data to assist in identification of the appropriate steps during data reduction.

Participants completed a series of jumping and cutting tasks on a basketball court surface in a pre-determined order. Of the six tasks, only the basketball-specific single-leg side drop jump (SDJ) and cross drop jump (CDJ) were included in these analyses. These tasks were chosen because of their combination of a single-limb landing and movement in the frontal plane that is frequently required during basketball competition. Both the SDJ and CDJ were initiated from a 30-cm box, with participants completing three trials of each task. During the SDJ (Figure 2a), participants stood on the box on their right limb, dropped anterolaterally to their left and landed with their left foot in a 61 x 91 cm target area. Immediately upon landing, participants completed a maximal vertical jump towards a basketball suspended overhead that was previously set to their maximal reach during a standard countermovement jump. During the CDJ (Figure 2b), participants dropped anteromedially to their right, landing with their left foot in the same target area and immediately performed a maximal vertical jump. All participants were familiarized to each jumping task by a demonstration from a member of the research team and by completing one to two practice trials.

Data reduction

All biomechanical variables were analyzed during the entire first landing of each task from initial contact (total insole force exceeding 20N) to toe-off (total insole force less than 20N). Kinematic data were filtered at 12 Hz low-pass filter (fourth order, zero-lag Butterworth filter) (Motion Monitor, Innovative Sports Training, Inc.). Ankle dorsiflexion and first MTPJ dorsiflexion were calculated based on the

Figure 2. *Jump landing tasks performed in this study: side drop jump (A) and cross drop jump (B).*

anatomically and footwear mounted electromagnetic sensors. Ankle and first metatarsophalangeal (MTP) joint motion were calculated from Euler angle definitions relative to the initial neutral standing position (feet spaced 35 cm apart with toes facing forward to determine each subject's neutral alignment and anatomically define each foot segment). Kinematic data were exported and synchronized with pressure data within MATLAB (MathWorks, Natick, MA, USA) via a transistor-transistor logic (TTL) pulse that was

generated when the plantar pressure measurement system began data collection.

A regional analysis of the foot was performed utilizing nine separate “masks”, or areas, consisting of medial and lateral heel, medial and lateral midfoot, medial, central, and lateral forefoot, hallux, and the lesser toes (Groupmask Evaluation, Novel GMBH, Munich, Germany) (Figure 1).²¹ Maximum force and the force time integral for each region were

calculated. The force time integral in each individual region was divided by the force time integral for the total plantar foot surface to determine the relative load in each region.

Statistical analysis

Separate 2 (footwear) x 2 (task) repeated measures analysis of variance (ANOVA) models were used to analyze differences in 1) ankle kinematics (degrees), 2) 1st MTP kinematics (degrees), 3) maximal regional plantar forces (N), and 4) relative load (%). Post hoc pairwise comparisons using paired t-tests were performed to examine differences for statistically significant main effects of footwear x task interaction. Paired t-tests were used to examine differences in subjective footwear ratings of each shoe. The significance level was set a priori for all analyses at $\alpha = 0.05$. Partial eta-squared effect sizes (ES) were calculated for all statistically significant differences, with values 0.06-0.14 interpreted as a moderate effect size and greater than 0.14 as a large effect size.²²

RESULTS

Biomechanical differences between footwear

Ankle kinematics showed a significant footwear main effect ($\lambda = 0.53$, $p = 0.03$), such that the stiffer shoe elicited decreased peak ankle plantarflexion ($p = 0.01$, ES = 0.29) and eversion ($p = 0.03$, ES = 0.23), and increased peak ankle dorsiflexion ($p = 0.008$, ES = 0.31) (Figure 3A). There was no significant difference between shoes in 1st MTP motion ($p > 0.05$).

There was a significant main effect for footwear in peak plantar force ($\lambda = 0.14$, $p = 0.001$). Lower peak forces were seen in the lesser toes ($p = 0.004$, ES = 0.36) in the stiffer shoe (Figure 3B). Similarly, a significant main effect in relative load was identified ($\lambda = 0.15$, $p = 0.002$), with pairwise comparisons showing lower relative load in the lesser toes ($p = 0.001$, ES = 0.47) in the stiffer shoe (Figure 3C).

There were no significant differences between shoes in the participants' subjective rating of comfort (standard: 7.7 ± 1.5 , stiff: 7.1 ± 1.6 , $p = 0.08$), shock absorption (standard: 7.3 ± 1.8 , stiff: 6.6 ± 2.1 , $p = 0.17$), stability and control (standard: 7.7 ± 1.4 , stiff: 7.9 ± 1.3 , $p = 0.50$), traction (standard: 7.7 ± 1.6 , stiff: 7.9 ± 1.2 , $p = 0.31$), or safety (standard: 8.4 ± 1.1 , stiff: 7.9 ± 1.8 , $p = 0.18$).

Biomechanical differences between tasks

There was a significant task main effect for ankle kinematics ($\lambda = 0.35$, $p = 0.001$). The SDJ elicited greater peak ankle plantarflexion angles ($p < 0.001$, ES = 0.57) and lower peak dorsiflexion ($p = 0.02$, ES = 0.24) and eversion ($p = 0.009$, ES = 0.31) angles than the CDJ. There was no significant difference between tasks in 1st MTP motion ($p > 0.05$) (Figure 3A).

The peak force had a significant task main effect ($\lambda = 0.05$, $p < 0.001$), such that the CDJ elicited greater peak force in the lateral midfoot ($p < 0.001$, ES = 0.53), and hallux ($p = 0.001$, ES = 0.47), and lower peak force in the medial forefoot ($p = 0.01$, ES = 0.29), and lesser toes ($p = 0.01$, ES = 0.29) than the SDJ (Figure 3B). Additionally, a significant task main effect was found for relative load ($\lambda = 0.09$, $p < 0.001$). Specifically, greater relative loads were found during the CDJ in the lateral forefoot ($p < 0.001$, ES = 0.49), and hallux ($p = 0.002$, ES = 0.40) and during the SDJ in the medial forefoot ($p = 0.007$, ES = 0.33), middle forefoot ($p = 0.004$, ES = 0.36) and lesser toes ($p = 0.007$, ES = 0.32) (Figure 3C).

Footwear x Task interaction

There were no significant footwear x task interactions for ankle kinematics ($\lambda = 0.884$, $p = 0.72$), 1st MTP kinematics ($\lambda = 0.99$, $p = 0.65$), peak force ($\lambda = 0.54$, $p = 0.46$), or relative load ($\lambda = 0.52$, $p = 0.42$).

DISCUSSION

Results of this study indicate that modifications in midsole stiffness of a basketball shoe can alter foot and ankle biomechanics during single-leg jump landings. This modification is commonly used in clinical settings, as it may reduce the risk of foot injury and/or allow for quicker return to play by reducing MTP and interphalangeal joint motion. These results indicate the stiffer midsole had no statistically significant effects on first MTPJ motion but did decrease force under the lesser toes. However, in the stiffer footwear condition, the ankle exhibited increased peak dorsiflexion, and decreased peak plantarflexion and eversion angles.

A stiffer midsole is thought to reduce the overall sagittal plane bending of the shoe during dynamic activities, potentially reducing the bending motion and forces that occur at the MTPJ inside the shoe. While it

Figure 3. Comparisons of biomechanical measures between task and shoe for: (A) kinematics, (B) peak force, and (C) relative load. (+ significant difference between tasks, # significant difference between shoes) (AnkPF- ankle plantarflexion, AnkDF- ankle dorsiflexion, AnkEV- ankle eversion, AnkINV- ankle inversion, M1- medial hindfoot, M2- lateral hindfoot, M3- medial mid-foot, M4-lateral midfoot, M5- medial forefoot, M6- middle forefoot, M7- lateral forefoot, M8- hallux, M9- lesser toes).

is possible there were differences in the longitudinal bending motion of the shoe between footwear conditions, the kinematics reported were true measures of anatomical motion, as all electromagnetic sensors

were placed directly on the foot. A previous study comparing kinematics with anatomical and footwear placements of electromagnetic sensors on football cleats with different midsole stiffness levels resulted

in significant differences between shoes in footwear referenced kinematics but not in anatomically referenced kinematics.²⁰ Although the mechanical properties of the shoe may limit shoe motion, this does not necessarily translate to what happens to the foot inside the shoe. In the current study, the stiffer shoe elicited no kinematic differences at the foot, instead it promoted a relatively more dorsiflexed ankle. It is possible that participants' heels slipped superiorly in the shoe in order to overcome the stiffness of the shoe, which is consistent with other studies that show compensatory changes at joints proximal or distal to a restricted joint.^{20,23} These unintended consequences are important and may put the athlete at risk of a different or concomitant injury. For example, greater dorsiflexion during landing may simulate a greater eccentric loading of the Achilles tendon or may increase patellofemoral joint compression forces leading to patellofemoral pain.^{24,25} Additionally, although increasing midsole stiffness predominantly affects the sagittal plane, significant reductions of ankle eversion were identified in the stiffer shoe. Any modifications to mechanical properties of footwear should account for subsequent compensatory changes that may result in other planes or at other local and regional joints.

Modifying midsole stiffness also altered the distribution of plantar forces. Specifically, a stiffer midsole resulted in a reduction of force under the lesser toes. The stiffer midsole did not bend as readily during the landing task, shifting the center of pressure posteriorly from the toe region to the midfoot and hindfoot. This shift in center of pressure caused a corresponding shift in forces posteriorly instead of dispersing through the toes and forefoot. Considering these results, a stiffer shoe may be advantageous for an athlete at risk for or rehabilitating from a lesser toe injury. Interestingly, this pattern was not evident at the great toe. A statistically insignificant increase in force was observed under the hallux in the stiffer shoe. This may be because of the time points chosen for analysis in this study included both the landing and jumping phase of both tasks. The hallux endures 40% greater forces during jumping than landing and may be driving these results.²⁶ During jumping, a stiffer shoe may promote a quicker anterior shift of the center of pressure to the great hallux. These data

complement results from the kinematic analysis in that a stiffer basketball shoe may not provide biomechanical benefits for an athlete with 1st MTPJ injury.

The tasks used in this study were novel and relevant to the basketball athlete. Basketball is characterized by significant jumping demands and frontal plane movements, with constant vertical and horizontal accelerations and decelerations.² When done on a single-leg, forces significantly increase, potentially placing an athlete at greater risk for injury.^{27,28} Both the SDJ and CDJ were frontal plane, single-leg landings that incorporated a maximal vertical hop, simulating a basketball game situation. Not surprisingly, there were significant biomechanical differences between the two tasks. The SDJ, which consisted of a movement towards the lateral aspect of the landing foot, elicited greater plantarflexion angles and loading of the medial forefoot and lesser toes. The CDJ, which consisted of a movement towards the medial aspect of the landing foot, elicited greater dorsiflexion and eversion angles and loading of the lateral midfoot and hallux. This movement profile that occurs during the CDJ may be of further concern because the combination of high forces under the base of the fifth metatarsal and greater ankle dorsiflexion motion can lead to corresponding increases in forefoot dorsiflexion and a bending moment across the fifth metatarsal. This has been proposed as a mechanism for Jones fracture.²⁹

Considering the data presented in this and other studies that measure true anatomical foot and ankle range of motion,²⁰ clinicians should be cautious when prescribing midsole modifications to athletes with biomechanical or pathological concerns for the metatarsals and rest of the foot. A stiffer midsole may not produce the intended outcome of reduced motion at the MTPJ, as attempts to reduce motion of the shoe do not necessarily translate to reduced anatomical motion of the foot. Furthermore, if a modification to stiffness is implemented, it is crucial that the clinician be aware of and observe potential biomechanical changes at nearby and similarly vulnerable joints. Changing the mechanical properties of the shoe might not be the only possible intervention for athletes with foot pathology. The strength and activation of the foot "core", or intrinsic foot muscles, might play an important role in foot function.³⁰

There were some limitations involved with this study. First, this study included a relatively small participant pool that represented a homogenous population. However, the goal was to study the effects of changing midsole stiffness in basketball shoes on competitive basketball players, which was deemed successful (average playing experience = 10.3 years). While the use of in-shoe electromagnetic motion analysis sensors was novel and provided more valid information than footwear measures of motion, there are drawbacks with using a tethered motion analysis system. These include a limitation to the natural athletic environment and a small capture volume within which to perform dynamic movements.

CONCLUSIONS

Altering midsole stiffness in basketball shoes results in differences in ankle kinematics and plantar forces. This modification is often used to reduce MTPJ motion; however, this was not observed. Instead, footwear with higher midsole stiffness caused compensatory changes at the ankle and not at the MTP joint. Furthermore, medially-directed single leg landings may elicit biomechanical strategies that are potentially adverse to the 5th metatarsal. Continued investigation of foot injuries and the effect of basketball-specific footwear and tasks are warranted.

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