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Effects of synthetic turf and shockpads on impact attenuation related biomechanics during drop landing

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I am submitting herewith a thesis written by Hang Qu entitled "Effects of synthetic turf and shockpads on impact attenuation related biomechanics during drop landing." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Kinesiology.

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Effects of synthetic turf and shockpads on impact attenuation related biomechanics during drop landing

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ABSTRACT

Synthetic turf has been widely utilized in sports since 1964. Discrepancies, however, in injury incidence on synthetic turf and natural grass have been reported throughout studies. Adding a shock pad under synthetic turf carpet is claimed to aid in energy absorption and decrease impact loading. Although some studies have conducted materials tests and compared mechanical characteristics of synthetic turf with different shock pads, no studies have examined biomechanical characteristics of impact related human movements on an infilled synthetic turf system with different underlying shock pads. The purpose of this research was to investigate effects of an infilled synthetic turf with three shock pads of different energy absorption characteristics on impact attenuation related biomechanics of lower extremity during drop landing. Wearing running shoes, twelve active and healthy recreational male athletes performed five trials of drop landing from 60 cm with a controlled landing style (maximum knee flexion) on five surface conditions: a regular surface (force platform), an infilled synthetic turf, turf plus foam shock pad, turf plus a lower density shock pad, and turf plus a high density shock pad. A motion analysis system and force platform were utilized to collect kinematic and kinetic data. Furthermore, a mechanical test was conducted based on ASTM F355 standard. The turf plus shock pad systems resulted in lower 1st vertical peak ground reaction force (GRF) and its loading rates compared to synthetic turf without a shock pad. However, no differences in 2nd vertical GRF and joint kinematics and kinetics across surfaces were found. These results suggest that landing from 60 cm may cause a plateau effect in energy attenuation for the examined turf and turf plus shock pad systems. Future studies may be needed to explore the shock attenuation capacities of landing surfaces in landing activities from a lower height (< 60 cm).

Keyword: drop landing, synthetic turf, shock pad, impact attenuation, landing styles, landing height

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CHAPTER I

INTRODUCTION

Anterior cruciate ligament (ACL) injuries that commonly occur in sports (15, 55), are expensive to treat, and take a long time to heal (45, 82). Based on data from the National Collegiate Athletic Association (NCAA) Injury Surveillance System (ISS), Hootman et al. (36) documented that over 5,000 ACL injuries represented 2.6% of all injuries with an injury rate of 0.15 per 1000 athlete-exposures. Over a period of 16 years for 15 NCAA sports, ACL injuries have increased by average of 1.3%. Agel et al. (2) reported 1,268 cases of ACL injuries in basketball and soccer over a span of 13 years. *In vitro* studies suggest that ACL injuries may be the result of high loading to the knee, and tibiofemoral displacements caused by compressive forces on the posterior tibial slope (10, 52, 53). Lack of attenuation of ground reaction forces (GRF) in lower extremities could generate these compressive forces in the knee.

Synthetic turf has been widely utilized in sports for almost 50 years (60). For sports at all level (30), the use of synthetic turf has caused increased concerns regarding the safety in elite and recreational athletes (9). The disagreements in injury rates on synthetic turf have been reported in the literature. Some studies have reported that the injuries of lower extremities were significantly higher on synthetic turf compared to natural grass (23, 27, 59, 63, 66). On the contrary, other studies have documented no difference in injury incidences of acute lower extremities between synthetic and natural turf (11, 26, 31, 63, 77). In addition, it was reported that training injuries were more frequent on natural grass compared to synthetic turf (32, 62). Landing movements are frequently involved in various sports, such as football, soccer, basketball, and volleyball. The rapid movement not only requires eccentric muscle action of the quadriceps to counteract knee flexion during the weight acceptance phase (52, 53), but also generates excessive impact force to lower extremities. Landing styles and jump techniques, landing and jumps heights, and landing surfaces are often considered as factors related to injuries and sport performances (8, 25, 33, 41, 43, 44, 54, 59, 64, 86, 88, 90).

Landing styles are determined by the maximum knee flexion angle during landing. A soft landing has a greater maximum knee flexion and a stiff landing has a smaller knee flexion angle; while, a normal landing has a maximum knee flexion angle between the soft and stiff landing styles. By comparing the three landing styles, Zhang et al. (93) reported that the 1st and 2nd peak vertical GRFs, the peak extensor moments and powers in hip, knee and ankle, and energy absorption significantly increased with increased landing stiffness. Knee and hip extensor were the primary sources of energy absorption in soft landing, while ankle plantarflexor played the major role for stiff landing. DeVita and Skelly (19) reported that the peak vertical GRFs, the peak ankle plantarflexor moments, and muscle work done by the hip and knee significantly increased in a stiff landing compared to a soft landing. As a result, the increased landing stiffness actually reduced the capacity of the muscles for energy absorption in loading. Similar results in vertical GRFs were also found in other studies (58, 65, 91).

When landing from a higher height, greater peak vertical GRFs occur because increased contact velocity is generated (71). Zhang et al. (93) documented that the peak vertical GRFs, peak joint moments and powers, and energy absorption in ankle, knee and hip extensor significantly increased with increased landing heights. McNitt- Gray (50) reported similar results in the peak vertical GRFs, extensor moments and energy absorption in three lower extremity joints, and that changes in landing height could result in adjustments of landing styles.

Landing surfaces affected sport performance and injury (81, 85). A stiff surface can reduce energy loss and provide sufficient GRFs, while a more compliant surface is able to absorb more energy and prevent potential injuries (20). Severn et al. (74) suggested that loading during sport movements, footwear, playing surfaces, and environmental conditions were four primary factors associated with player-surface interactions or injuries. Jones et al. (37) reported that athletes showed larger variability in knee kinematics on synthetic turf compared to natural grass in single-leg landing from a jump for heading movements. Shorten and Himmelsbach (75) showed that peak tibial acceleration in drop landing on synthetic turf were significantly higher than natural grass. Brock et al. (16) found that the peak medial GRF in running shoes were significantly higher compared to studded shoes, and the time to reach peak vertical GRF in studs shoes was longer compared to running shoes on synthetic turf for cutting movements.

To improve energy absorption and reduce the impact loading (38), some turf companies have begun to include a shock pad (a cushioning layer) under synthetic turf carpet to better mimic natural grass behaviors. Material tests have indicated that the material’s type, density, and thickness were important properties that directly affected mechanical performance of shock pad and turf systems (with a combination of turf and shock pad) (4, 29 128, 84). Wang et al. (84) compared two synthetic hockey turf systems with a thick shredded rubber pad and a thin polyurethane foam pad. They reported that the thick rubber shock pad system showed less strain under the greater loading rate, and higher peak pressure compared to the thin foam shock pad, suggesting that the thick rubber shock pad turf system was less viscoelastic and stiffer compared to the ones with thin foam shock pad under the same loading rates. Alleguer et al. (4) reported that stress, energy return, and cyclic loading endurance increased as shock pad density increased under the same impact loading.

STATEMENT OF PROBLEM

Although some studies have conducted material tests and compared mechanical characteristics of synthetic turf with different shock pads, according to the literature, a limited number of studies have examined landing, and cutting movements on synthetic turf. There is no published data for the biomechanical characteristics of impact related human movements on an infilled synthetic turf system with different underlying shock pads.

Therefore, the purpose of this research was to investigate the energy absorption characteristics on impact attenuation related biomechanics of lower extremity during drop landing for three shock pads as an underlayment on an infilled synthetic turf shock pad. A third-generation infilled synthetic turf system was used in the study with a combination of three shock pads: a foam shock pad (SP1), a lower density shock pad (SP2) and a higher density shock pad (SP3). Five surface conditions were tested: a regular surface (force platform), an infilled synthetic turf, turf plus SP1, turf plus SP2, and turf plus SP3.

SIGNIFICANCE OF STUDY

This study aimed to provide much needed information on lower extremities kinematics and kinetics differences during drop landing on the infilled synthetic turf surface using three different shock pads.

Drop landing is one of the most common high impact and/or explosive movements in sports. This movement generates high loading and demonstrate rapid deceleration. Landing style, landing height, and footwear were controlled to provide the testing conditions and environments for better understanding of surface-related factors associated with impact and energy attenuation as well as generation during the tested movements.

Three shock pads with different material properties were tested with the infilled synthetic turf in this study. The results from the tests of the dynamic movements on these surface conditions would provide important information about interactions of human movements with different surface characteristics related to the materials and structures of the surface and related shock pads. These results would potentially provide valuable knowledge of surface-related factors associated with sport injuries and enhancements.

HYPOTHESIS

1. Peak vertical GRF and its loading rate, peak joints moment and power, and work done by lower extremities would be smaller on the turf and turf systems with shock pads compared to the regular surface and turf only surface during drop landing.
2. The turf systems with higher density and thicker shock pad would have smaller GRF and loading rates, peak joints moment and power, work of lower extremities during landing compared to the turf systems with lower density and thin shock pad during drop landing.

DELIMITATIONS

1. Participants were men aged from 18 to 30 years old.
2. Participants were healthy and free from major injuries (e.g. bone fracture, ligament tear, which need orthopedic surgery) of lower extremity and lower back, and free of injuries in past six months and free of pain on the day of testing.

3. Participants were playing football, soccer, basketball and/or volleyball, and were experienced and skilled in landing and jumping movements.
4. Each participant performed five successful trials in each of the ten test conditions with enough warm-up and rest times.
5. The testing area on top of the force platforms is large enough and covered with synthetic turf and/or shock pads, and the turf is infilled with the sand and rubber particles evenly to ensure consistent impact attenuation characteristics across the testing surface area.
6. Kinematics were collected at 240 Hz utilizing a 3D motion analysis system (Vicon Motion Analysis Inc., UK) and GRFs were collected at 1200 Hz utilizing two force platforms (Advanced Mechanical Technologies, Inc., Watertown, MA).

LIMITATIONS

1. All the participants were recruited from a convenient sample of the students on the campus of The University of Tennessee, Knoxville.
2. Participants may perform drop landing activities with different techniques in the lab environment compared with in real games or trainings.
3. The accuracy of kinematics results was limited by manual placements of the anatomical markers. However, every effort was made to ensure that the markers were placed at the accurate bony landmarks and consistently.
4. Only one type of synthetic turf and three types of shock pad were tested.

CHAPTER II

LITERATURE REVIEW

The purpose of this research is to investigate effects of infilled synthetic turf and shock pad on impact attenuation in lower extremity biomechanics during drop landing and drop jump. This chapter includes literature review in four sections: research background documenting the reason of conducting this study, review on mechanism of non-contact anterior cruciate ligament injuries, biomechanical characteristics of drop landing and drop jump, and surface-related factors associated with human movement studies on synthetics surfaces.

BACKGROUND

Anterior cruciate ligament (ACL) injuries have been considered as one of the most common knee injuries in sports (15). There are an estimated 80,000 to 100,000 ACL repairs in the United States per year (17). In U.S, the costs for ACL reconstruction in a lifetime averaged $38,121 to society, while rehabilitation costs averaged $88,538 (45). Long recovery and rehabilitation times were normally required for patients and often followed by secondary injury or osteoarthritis (82).

Sports surfaces during athletic movements play an important role not only in performance enhancement (85) but also in injury prevention (81). As an alternative to natural grass, synthetic turf has been used in many sports in the past 50 years and even at the highest-level of international professional competitions (30). Compared to natural grass, synthetic turf requires lower maintenance costs, is suitable for more weather conditions, lasts longer, and has improved consistency in playing conditions(29). It has been demonstrated that athletes performed faster in sprints on synthetic turf rather than natural grass (78). In 2015, for the very first time, all of the games for Women’s World Cup were played on synthetic turf. However, the widespread adoption of synthetic turf has caused increasing concerns in both elite and recreational athletes about the safety of the surface (9).

Numerous studies have suggested that the injury rates differ in different sports on synthetic turf compared to natural grass (3, 7, 21, 67). Generally, it has been reported that incidences of severe lower extremity injuries such as knee and ankle sprains (27, 63, 68), ACL injury (23), and overuse injury (59) were higher on synthetic turf compared with natural grass. However, it was also reported that no difference was observed in acute injury incidence in games or training between synthetic turf and natural grass (63).

To enhance the safety of synthetic turf, companies have started to add a cushioning layer called the shock pad under the turf, which is usually made from foam, composite plastics, or shredded rubber (4). The purpose of the shock pad is to increase shock and energy absorption to a synthetic turf system. Apart from improved cushioning capacity, a shock pad is also useful in maintaining consistent performance of synthetic turf (4).

MECHANISMS OF NON-CONTACT ACL INJURIES

Injuries frequently occur during landing related activities due to high vertical impact force applied to the human body. Particularly, ACL injuries can result from a direct contact (with another player or an object) or indirect contact mechanisms. McNair et al. (47) reported that approximately 70% of ACL injuries occurred during non-contact situations. This result was supported by the findings of Boden et al. (14), who found that 81% of 89 ACL injury among 100 knee injury cases were due to non-contact mechanisms during foot strike with the knee near full extension. In the second part of their study, they reviewed videotapes of 27 ACL tear cases and, the results confirmed their findings mentioned above. They concluded that maximum eccentric muscle actions occur when the knee in a position where the extensor muscles cause strain on the ACL.

Non-contact ACL injuries are results of high loading applied to their knees. The mechanisms of non-contact ACL injuries include the valgus collapse of the knee (34), a rapid deceleration, a change of direction, and landing with a small knee flexion angle (14). Some *in vitro* studies were conducted to explore the loading on ACL by a combination of forces and moments. Berns et al. (10) measured strain in the ACL utilizing a load application system on cadaver specimens to quantify effects of both single and combined loads on ACL. They found that the anteromedial bundle of the ACL was mainly strained by anterior force, which up to 200 N during early flexion phases. Higher strain also occurred with the knee joint in a position of 30 degrees of flexion. Significantly larger strain resulted from both of valgus moment and internal axial moment in combination with anterior force compared to that of an anterior force alone. Therefore, these results suggested that the combination of anterior force with valgus or internal moments may result in an ACL injury when the knee joint is in a flexion angle between 15 to 30 degrees. Furthermore, Meyer et al. (52, 53) hypothesized that excessive joint compressive loads could result in ACL tear. The results showed that ACL tore in 21 of 23 knee cadavers under repeatedly compressive loads, ranged from 2.9 kN to 7.8 kN, at flexion angles from 30 degrees to 120 degrees. Relative tibiofemoral displacements when the ACL ruptured ranged from 1.6 to 9.2 mm in anteroposterior displacement, and 2.7 to 5.5 mm in mediolateral displacement. In addition, internal rotation was observed ranging from 0.8 to 14.8 degrees. The authors suggested that the ACL ruptures caused by tibiofemoral displacements due to compressive forces on posterior tibial slope. In reality, insufficient ground reaction forces (GRF) absorption in lower extremities could generate these compressive forces on knee joints when people perform landing and jumping.

BIOMECHANICS OF DROP LANDING AND DROP JUMP

Sport involves rapid movements, such as landing and jumping movements, which require eccentric muscle action of the quadriceps to resist knee flexion during the weight acceptance phase. Many studies have been conducted to explore biomechanical factors related to injury and its prevention for drop landing (DL) and drop jump (DJ). For instance, landing/jumping techniques, landing/jump height and landing surfaces were considered to be associated with landing and DJ performance (8, 25, 33, 41, 44, 54, 64, 86, 90). Nigg and Ekstrand (59) suggested that excessive impact force could cause both acute and repetitive injuries on human collagen tissues, including ligaments.

Drop Landing

Landing is a common occurrence in many sports, such as football, basketball, soccer, and volleyball. Landing techniques have been examined extensively in areas of sports performance and injury prevention (28). Landing is regarded as a complicated movement, that requires people to coordinate dynamic muscle control maintain joint stability of the lower limb and absorb GRF (42).

Landing Styles

Landing style, defined as maximum knee flexion, is often associated with ACL injuries (43). Yu and Garrett (91) investigated how different landing styles could cause an increase of ACL loading. They suggested that the patella tendon-tibia shaft angle would increase with decreased knee flexion angle, which would lead to augmented anterior shear force at the proximal end of the tibia. This in turn would generate knee internal rotation and abduction moments which may cause an increase of ACL loading. They also noted that by increasing elevation and deviation angles of ACL, which were defined as the angle between the tibial plateau and the ACL and the angle between the projection of the ACL on the tibial plateau and the anterior-posterior tibial line (39), smaller knee flexion angle resulted in increased ACL loading. Increased peak posterior GRFs were reported for increasing ACL loading through the generation of knee flexion moments.

With regard to landing styles, a soft landing style has a greater maximal knee flexion angle and a normal landing has a smaller knee flexion angle. In contrast, a stiff landing has the smallest knee flexion angle. Zhang et al. (93) examined effects of three different landing techniques on lower limb joints. Nine healthy subjects performed a soft landing, normal landing, and stiff landing from three different heights: 32 cm, 62 cm, and 103 cm. Maximum knee flexion angles were monitored by an electrogoniometer. Significant differences were observed in peak vertical GRFs, joint moments and powers, and energy absorption among three different landing styles. The 1st (at forefoot contact) and 2nd (at heel contact) peak GRFs increased as landing stiffness increased. The results showed that knee joint extensors consistently contributed in energy absorption in soft, normal and stiff landing conditions while the ankle joint plantarflexors played a more important role in stiff landing. No difference was found in the 1st peak ankle plantarflexor moment, and the peak hip extensor moment in soft landing compared with normal landing. However, the 1st and 2nd peak ankle plantarflexor and knee extensor moment, and the peak hip extensor moment significantly increased with increased landing stiffness. Additionally, the knee and hip extensor dissipated more energy in the soft landing.

DeVita and Skelly (19) defined the soft landing and stiff landing as maximum knee flexion angles greater or less than 90 degrees, respectively. Eight healthy female athletes performed DL from 59 cm height with the soft and stiff landing styles. Their average maximal knee flexion angles were 117 and 77 degrees, respectively. They demonstrated that the stiff landing increased peak vertical GRFs by 2 to 3 times bodyweight (BW) compared to the soft landing. However, the anterior-posterior GRFs were similar for the two landing conditions. No differences were found in peak hip and knee extensor moments between the soft and stiff landings. The peak ankle plantarflexor moments were significantly greater in the stiff landing compared to the soft landing. Significant differences were found in muscle work performed by hip and knee between the soft and stiff landings. The authors also showed that more energy was absorbed by hip and knee muscles in the soft landing compared to the stiff landing. Therefore, the stiff landing leads to less knee joint work, which reduces the muscles' ability in loading dissipation. Primary energy dissipation was contributed by knee and ankle (37% and 37%, respectively) in soft landing, whereas ankle plantarflexors absorbed the major part of the energy in the stiff landing (50%).

It has been found that greater peak vertical GRFs were found to be related to more extended knee angle during landing (65). Myer et al. (58) hypothesized that a significant increase of anterior tibiofemoral translation would be generated by a stiff landing compared with a soft landing. In order to test their hypothesis, biplane fluoroscopy was utilized to measure tibiofemoral kinematics of soft and stiff landing from a 40 cm height. This test was performed by sixteen healthy subjects. Significantly greater peak vertical GRFs, peak knee extensor moment, and a smaller range of motion (ROM) were found for the stiff landing compared to the soft landing. There was no significant difference in peak anterior-posterior GRFs between the two landing styles. The kinematics results also demonstrated that the stiff landing caused significantly greater average and maximum absolute internal rotation than the soft landing. However, the data collected by the biplane fluoroscopy failed to support the hypothesis since no significant differences were observed in the average and maximum anterior tibiofemoral translation, internal/external rotation and adduction/abduction in the knee between soft and stiff landing conditions.

Landing Heights

Landing heights have been reported as another important factor associated with injury and performance during landing (25). Landing from a greater height has been shown to cause greater maximal vertical GRFs than landing from a lower height due to the increased contact velocity, which increases risks of injury (24). Drop heights were also investigated in a study conducted by Zhang et al. (93), where subjects performed drop-landing from 32 cm, 62 cm, and 103 cm. A positive correlation between landing heights and the peak GRFs was found. The peak joint moments and powers in ankle, knee and hip also significantly increased with increases in landing height. The results also showed that knee ROM was significantly increased with increased landing heights. Furthermore, knee ROM showed significant interactions between landing height and style. Energy absorbed by ankle, knee and hip extensor increased with increases of landing heights. Knee joint muscles were the major source of energy absorption (over 40%) among all conditions except for the stiff landing from 103 cm height, in which hip extensors dissipated a majority of the energy (45.3%).

McNitt-Gray (49, 50) studied kinematics, and kinetics of lower extremities during drop landing, performed by six healthy gymnasts and six healthy recreational athletes from three different heights: 32 cm, 72 cm, and 128 cm. The peak vertical GRFs increased from 4 to 11 BW across three different landing heights. The hip and knee joint flexion significantly increased with increased landing heights, suggesting that landing heights may trigger adjustments and adaptions in landing styles. In addition, an increase in peak joint angular velocities was observed. Kinetic results revealed that maximum extensor moments and work achieved by the ankle plantarflexor, knee and hip extensor muscles increased significantly with the increased heights. Gymnasts demonstrated significantly greater peak extensor moments in ankle and hip joints compared to recreational athletes, showing a greater ability of gymnasts to adapt to the increased impact loading; recreational athletes flexed their hip joint more to dissipate increased impact loading as landing height increased (50).

Seegmiller and McCaw (71) tested their hypothesis that gymnasts showed significantly greater loading at toe contact and heel contact by comparing 1st and 2nd peak vertical GRF in drop landing when barefoot from three different heights: 30 cm, 60 cm, and 90 cm. No difference was found in 1st and 2nd peak vertical GRFs from a 30 cm height between gymnasts and recreational athletes. Significantly higher 1st and 2nd vertical GRFs (31% and 33%, respectively) were found at 60 cm height in gymnasts compared to recreational athletes. At 90 cm height, gymnasts showed higher 1st and 2nd peak vertical GRFs (27% and 34%, respectively) compared to recreational athletes. Additionally, both gymnasts and recreational athletes exhibited a significant increase in 2nd peak GRF from 2 to 6 BW as the landing height increased.

The lack of difference in peak GRFs between the groups at 30 cm suggested that 30 cm height was too low for drop landing, compared to other studies (48, 72).

Yeow et al. (88) have examined the relationship of landing heights and GRF, knee flexion angles, angular velocities, and joint powers by performing landing from 7 equidistant heights ranging from 0.15 m to 1.05 m. The results suggest that the peak vertical GRF, peak GRF slope and peak GRF impulse increased exponentially as landing heights increased, while knee flexion angle at contact, peak GRF, and peak knee flexion velocity increased as landing height increased logarithmically, while joint power increased linearly with increased landing heights. Therefore, the knee variables increased less while GRF increased as landing heights increased, indicating that the impact attenuation ability of the knee joint was limited when landing from a higher height. In other studies (87, 89), they have also compared the effects of landing from 30 and 60 cm height on kinematics, kinetics and energy dissipations of lower extremity joints. In the sagittal plane (89), they reported that the knee flexion angles at the peak GRF, maximum knee flexion angle, times to maximum peak knee flexion angle, maximum knee flexion velocity, and knee extensor power were greater in landing from 60 cm than 30 cm. Knee eccentric work at 60 cm were 1.9 times greater than 30 cm. In the frontal plane (87), greater peak hip internal abduction moments compared to those in the knee and ankle joints. Furthermore, eccentric work done by hip joint during landing increased significantly with increased height. The hip and knee contributed the most to the total energy absorption in landing while the ankle played the smallest role in absorbing energy.

Drop Jump

Drop jump (DJ) is a popular exercise for plyometric training to improve jump performance of athletes by gaining mechanical output of knee extensors and ankle plantarflexors (12). Previous studies have suggested that DJ training has increased the jump height and agility of athletes by allowing eccentric contraction of muscles and more exertion of stored up energy during the concentric contraction during the movement (33, 44, 54, 86).

Jumping Techniques

By utilizing DJ as a training intervention program, Hewett et al. (35) evaluated effects of plyometric training on jump techniques of 11 female volleyball athletes for six weeks. The goal of the training program was to decrease landing forces and improve jump height. The athletes who showed higher peak adduction moments during landing were grouped as the adduction-dominant group, otherwise they were in the abduction-dominant group. The results showed that after plyometric training, 91% of the athletes deceased their peak GRF in landing by about 23.5%. Seven adduction-dominant athletes had a 62% decrease in peak knee adduction moment and four abduction-dominant athletes showed 110% decrease in peak knee abduction moments, which were highly correlated to the peak GRF during landing. The vertical jump height was significantly increased by about 10% after the training.

Bobbert et al. (12) examined effects of jumping techniques on lower extremity joints by utilizing DJ and countermovement drop jump from 20 cm height. Instead of bouncing upward as quick as possible after initial ground contact, countermovement drop jump allows subjects to land softly and gradually toe-to-heel with knee flexion before taking off. By monitoring displacement of the center of mass (COM) from the upright standing to its highest position, the jump heights for DJ was about 4 cm lower than countermovement drop jump, with smaller ROM of hip and knee joints in DJ compared to countermovement drop jump. The peak vertical GRF for DJ were 40% higher than countermovement drop jump during takeoff. No significant differences were observed in the vertical velocity of COM at the moment of takeoff between two jump techniques. However, during the take-off phase, average vertical acceleration in DJ was higher than in countermovement drop jump due to a shorter time in DJ. This resulted from higher joint moments generated in DJ compared with countermovement drop jump. In both jump techniques, the peak net joint moments occurred around take-off. The peak extensor moments of hip, knee, and ankle in DJ were all significantly higher than in countermovement drop jump. At take-off, the peak knee extensor moment and ankle plantarflexor moment in DJ were significantly higher than those in countermovement drop jump. Furthermore, the peak knee and ankle powers in DJ were significantly larger compared with countermovement drop jump. Hence, the authors suggested that DJ training may efficiently improve performance of knee extensors and ankle plantarflexors of athletes.

Drop Heights

Bobbert et al. (13) conducted a study to explore the effect of three different drop heights on kinematics and kinetics of lower extremities in DJ. They hypothesized that maximum velocity of eccentric muscle contractions would increase as the drop height increased. Six healthy athletes dropped with barefoot from 20 cm, 40 cm and 60 cm heights. The net vertical impulse and takeoff time significantly increased as drop height increased. Eccentric work is achieved during the downward movement of the body and increased with increased drop height. The peak vertical GRF increased as drop height increased and was 31% greater at 40 cm compared to 20 cm, and 28% larger at 60cm compared to 40 cm. During the landing phase, no differences were found in the peak hip joint moments among three conditions. However, the peak knee extensor moments were significantly higher at 40 cm compared to 20cm, and the peak ankle plantarflexor moments were significantly higher in 60 cm compared to 20 cm. The peak hip power at 60 cm was significantly higher than 20 cm and 40 cm, and the peak knee and ankle powers were significantly increased at 40 cm compared 20 cm, and also at 60 compared with 40 cm. Eccentric knee joint work was larger in 60 cm compared to 20 cm and 40 cm. Ankle eccentric work significantly increased at 40 cm compared to 20 cm, and also at 60 cm compared to 40 cm. During the takeoff phase, the knee takeoff angle, peak ankle plantarflexor moment and peak power were significantly larger at 60 cm compared with the two lower heights. The data obtained failed to support their hypothesis due to no differences observed in vertical jumping performance among different drop heights. However, at 60cm height, a sharp peak of net joint reaction force occurred at the moment when the heel touched the ground, which again suggests that drop height needs to be limited when investigating DJ.

In the study conducted by Walsh et al. (83), different combinations of drop heights and duration of initial ground contact were examined. Fifteen male decathletes performed five trials of DJ from 20, 40 and 60 cm heights. At each height, the athletes performed a maximum jump in the 1st DJ trial, and then four DJ trials with progressively shorter contact time than the previous one. Therefore, the contact time of the 1st trials of all subjects were the longest, and the contact time of the 5th trials of all subjects were the shortest. The athletes with the moderate contact time (3rd trials) achieved the largest peak and mean mechanical power of COM regardless of drop heights. Moreover, the maximum vertical GRF increased with a shorter contact time and greater drop height. No difference was found in vertical take-off velocity of COM for the first three longest contact time groups (1st, 2nd and 3rd trials of all subjects) at all three drop heights. Additionally, the vertical velocity of the three groups was significantly greater than the ones in last two shortest contact time groups (4th and 5th trials of all subjects). The maximum knee extensor moments increased with increased drop heights, in all contact time conditions. The positive work by the knee joint with moderate and 4th shorter contact time was significantly larger at 20 cm compared with the other two height conditions. The authors concluded that landing strategy preceding the takeoff played a more important role in the effect of jump rather than drop height in DJ performance.

SURFACE-RELATED FACTORS

Injury Incidence on Synthetic and Natural Turfs

Numerous studies have focused on the comparison of lower extremity injury incidence playing on synthetic turf and natural grass. An earlier study showed that the injury rate of knee sprains on synthetic turf was significantly higher compared then with natural grass in American football (68). An epidemiology study (23) based on NCAA injury surveillance system data (ISS) showed that in football seasons from 2004-2005 to 2008-2009, 46.23% of 318 ACL injuries occurred on synthetic turf, whereas the ACL injury incidence per 10,000 athlete-exposures on synthetic turf were 1.4 times greater than natural grass (23). Further research has shown that the incidences of overuse injury and foot and ankle sprains were higher on synthetic turf (27, 59, 63). In contrast, conflicting results have been reported that there is no significant difference in acute injuries between the third generation synthetic turf and natural turf (11, 26, 31, 63, 77). However, it has also been reported that training injuries increased on natural grass (32, 62).

Higher injury rates are also perceived by athletes, as one study on soccer injury rates using subjective evaluation showed that athletes felt that the likelihood of injury on synthetic turf is greater than on natural grass (66).

With regard to injury types, injury incidences for soccer athletes during games (31) and training (32) have been compared between synthetic turf and natural grass. Based on the NCAA ISS results from 2005-2006 to 2006-2007 seasons, it was found that during games (31), lower extremity injuries were most commonly reported on synthetic turf and natural grass for both male (67.2% vs. 67.5%) and female (70.2% vs. 67.7%) athletes (31). Among lower extremities injuries occurring on synthetic turf compared to natural turf, male athletes reported that thigh (27.7% and 24.3%, respectively) and ankle (26.8% and 28.4%, respectively) as the most common injury locations, whereas the most common injury sites for females were knee (36.2% and 33.5%, respectively) and ankle (22.3% and 28.5%, respectively). The injury rates of lower extremities on synthetic turf were not significantly higher than those on natural grass for male or female athletes. In training (32), a similar pattern of overall injury incidences in the lower extremities were observed. The most common injury locations reported by male athletes remained in thigh and ankle, while female athletes reported that thigh and ankle were the most common injured sites on synthetic turf, and the thigh and knee were mostly injured on natural grass. Similarly, Ekstrand et al. (27) found that there is no significant difference in soccer injury incidence between synthetic turf and natural grass.

Effects of Materials, Stiffness and Thickness of Landing Surfaces

Landing surface is another extrinsic factor related to injury incidence in lower limbs during sports performance of athletes (21, 25). Synthetic surfaces have been used in many sports

(60). The mechanical properties were determined by the structure properties of the landing surfaces.

It has been demonstrated that playing on synthetic turf is one of the risk factors that has resulted in an increase in the incidence of lower extremity injuries (22, 23, 56). Steele et al. (79) tested vertical GRF of netball athletes of landing on 12 different synthetic surfaces (bitumen, concrete, 3 types of synthetic turf and 7 types of rubber surfaces). The results showed that athletes needed significantly longer time to reach the initial peak vertical GRF on synthetic turf compared with other surface conditions, which indicated that synthetic turf increased time duration to dampen impact forces to the body. They also reported that, on synthetic turf, nine of 10 athletes showed different foot contact strategies in each trial of heel-strike, flatfoot to forefoot-strike, while only one subject consistently used forefoot-strike landing style. This variation suggested that subjects tended to change their landing styles in response to alteration in landing surfaces. The authors noted that these changes in landing strategies may cause changes in loading to the body during landing, which may potentially increase risk of injuries.

A stiff surface helps improve performance by minimizing energy loss. In contrast, a compliant surface plays a role in energy absorption (20) and subjects tend to change their movement patterns on different sport surfaces (60). McNitt-Gray et al. (51) examined gymnasts' adjustments of landing strategies under three different surface conditions: a regular surface (force platform), a soft mat, and a stiff mat. The contact velocity was controlled by landing from a 69 cm height. All subjects showed significantly greater hip and knee flexion on mat surfaces than the regualr surface. On the soft mat, significantly smaller maximum knee flexion angles were observed in 10 of the 14 subjects as compared to the stiff mat. Additionally, smaller peak knee angular velocities on the soft mat were found compared to the stiff mat and regular surface. Subjects showed shorter time to reach the peak knee angular velocity on the regular surface and stiff mat compared to the soft mat. In addition, less vertical GRFs were noted on the regular surface than the soft and stiff mats. Subjects demonstrated longer time to reach the peak vertical GRF on the soft mat than the other mats. The results showed subjects adjusted their landing strategies and body stiffness to cope with various surfaces. Less joint flexions were observed when landing on mats. This may allow them to adapt to unexpected situations more effictively.

In addition to the stiffness of mat, the thickness of mat was considered to be related to landing performance. Skelly et al. (76) compared physiological, biomechanical and perceptive responses of step aerobics on three different surfaces: force platform, force platform covered with a thin pad, and force platform covered with a thick pad. A subjective survey was also conducted. It has been hypothesized that landing on the compliant surface would decrease the impact loading whereas insufficiently stiff surface would have increased energetic cost to achieve performance. The results of the physiological test showed that there was no significant difference in energy cost among the three surface conditions. From the biomechanical aspects, no significant differences were observed in the peak vertical GRF, joint ROMs, or time of foot contact on three surfaces. Nevertheless, the results of the subjective survey demonstrated that the subjects felt mostly unsafe to land on the surface covered with a thin pad and felt most stress on their lower extremity under force platform only condition. On the thick pad surface, subjects reported that they felt more stable compared to the other conditions.

Human Movements on Synthetic Turf and Natural Grass

Synthetic turf is a common synthetic surface. A qualified synthetic turf system for soccer normally consists of several layers: a concentrate or asphalt base, or a crushed stone/gravel base, and synthetic turf with sand/rubber infill (29). The third generation of synthetic turf has gained popularity in recent years, and its fibers normally range from 40 to 70 mm in length made from nylon, polyethylene or polypropylene. The two most common fiber construction types are monofilament and slit-film (73).

It has been reported that the loading during sport movements, footwear, playing surfaces and environmental conditions were major factors related to play-surface interaction (74). Jones et al. (37) examined effects of natural grass and synthetic turf on knee kinematics during single-leg landing from a jump of a heading movement. They reported that by comparing percentage of root mean squared differences during landing phase on synthetic turf with those on natural grass, the knee angle difference in frontal plane (13%) was the greatest compared to those in transverse plane (11%) and sagittal plane (5%) angles of knee. No differences were observed in knee ROM in all three planes. The difference of standard deviation of knee angles in frontal plane (37%), sagittal plane (34%) and transverse plane (53%) were larger on synthetic turf than on natural grass. The results suggested that medial-lateral movements (e.g. cutting movement, etc.) may have potential effects on injury and performance on synthetic turf due to large differences observed in knee adduction/abduction angles.

Shortern and Himmelsbach (75) have compared 1.0 m drop landing on synthetic turf and natural grass. A single peak tibial acceleration was observed during landing. Peak acceleration on synthetic turf (-30.1 ± 8.5 g) were significantly greater compared to natural grass (-25.7 ± 6.6

g). Mean acceleration power was dissipated significantly more on natural turf compared to synthetic turf. The results suggested that landing strategies adaptations may not always play the primary role in shock dissipation of lower extremities on different surfaces, and surface effects were also important.

Brock et al. (16) have investigated single-leg 90° land-cut and 180° cutting movements on synthetic turf with wearing running shoes and football cleats with natural turf or synthetic turf studs. The results showed that time to reach peak vertical GRF in the running shoes were shorter than other stud conditions. No difference in peak vertical GRF and its loading rates were found among shoe conditions. Peak medial GRF in running shoes was significantly higher compared to natural turf and synthetic turf studs in 180° cut.

Thoms et al. (80) have developed the Tennessee Athletic Field Tester (TAFT) to mimic athlete response to surface on synthetic turf compared to natural turf. The TAFT was designed to apply foot strike with compression and shear force. The test results showed that the peak vertical reaction forces measured by TAFT seemed to be consistent with what were reported for running of human, suggesting that it is possible to compare the results of vertical impact loading generated by athletes and those measured by this mobile materials test system.

By using a game-simulator to test different shoe and surface combinations, it has been shown that natural grass induced lowest peak torques while synthetic turf developed the highest peak torques under same loading (40). The results of this study might, to a certain extent, explain the reason why non-contact knee injuries frequently occurred among athletes on synthetic turf since high peak torque increased risk of injury.

Synthetic Turf with Shock pad

As mentioned earlier, to make synthetic turf surfaces to behave more like natural grass, some turf companies have begun to add a shock pad under synthetic turf to improve energy absorption and decrease the impact loading (38). Shock pads are made from different materials with different properties. Material test results indicated that a turf system with a shock pad made from shredded rubber showed stiffer properties than a shock pad made from foam under compression loading (84). Density and thickness are two important parameters to be considered for the shock pad (4, 29). FIFA has a minimum requirement of density and thickness in addition to the synthetic turf in order to maintain consistent mechanical performance accounting for infill deformations caused by athlete-turf interactions (29).

Wang et al. (84) have conducted materials tests to examine the synthetic hockey turf system with different thickness shock pad made of different materials. A 12 mm thin shock pad made of polyurethane foam, and a 15 mm thick shock pad was made of shredded polyurethane rubber. To mimic walking and running, controlled cyclic compression loading with two loading rates (0.9 Hz for walking and 3.3 Hz for running) were applied to the turf systems, respectively. By manipulating loading rates, the results of stress-strain relationships indicated that the increased loading rates caused increased stiffness response on both of turf systems. For the thick rubber shock pad system, less strain was generated by the greater loading rate. The thick rubber shock pad system showed higher peak pressure than the thin foam shock pad system. These results illustrated that a thick rubber shock pad turf system demonstrated less viscoelastic properties and was stiffer than the thin shock pad turf under the same loading rate.

Allgeuer et al. (4) studied effects of a series of shock pads with different density and thickness on energy absorption. The FIFA Quality Concept Test Methods were utilized in this study. A 20 kg mass was dropped vertically from a 55 mm height to the testing turfs. The results showed that stress increased with the shock pads with increased density, as well as energy return and cyclic loading endurance, suggesting the importance of the density of shock pad in energy absorption. They also concluded that low density of shock pad did not meet the requirement according to FIFA Quality Concept.

McGhie and Ettema (46) reported that while performing sprint stop, the maximum impact force was lower on the turf with an underlying shock pad. Furthermore, a synthetic turf coupled with a cushioning layer is perceived to be more pleasant to play on a hard and rigid surface by athletes (69).

CHAPTER III

METHODS

PARTICIPANTS

Ten to twelve healthy and active male recreational athletes between the ages of 18 to 30 years who had a minimum of three years playing football, soccer, basketball or volleyball and played these sports two to three times per week, were recruited to participate in the study from the University campus. The inclusion criteria include that the participants had never had orthopedic surgery and did not have injuries of lower extremities or the back within the previous 6 months, they were supposed to be free from pain on the test day, and they answered “No” to all the questions on the Physical Activity Readiness Questionnaire (PAR-Q – see appendices). Flyers were posted in the buildings on UT campus, and announcements were made in Physical Education Activity Program classes to recruit participants. Participants were asked to provide a written informed consent and the experimental protocol was approved by the University Review Board prior to data collection.

INSTRUMENTATION

Shoe

Participants wore a pair of standard lab running shoes (Noveto, Adidas).

Synthetic Turf Carpets and Shock Pads

A monofilament synthetic turf (Astro Turf® Gameday 360, AstroTurf, Dalton, GA) and three types of shock pad were used in this study. The first type of shock pad (PB2000YSR, Brock International, CO) was made from expanded polypropylene, its thickness is 23 mm and density is 56.1 kg/ cubic m. The second and third types of shock pad (Recticel Flexible Foams, Belgium) were mainly made of open-cell flexible polyurethane trim foam boned with isocyanate binder, the thicknesses were 10 mm and 12 mm, the densities were 200 kg/cubic m and 250 kg/cubic m, respectively.

A total of five surface conditions were tested in this study: force platform only, a monofilament synthetic turf, and three turf systems including turf plus foam shock pad (PB2000YSR, Brock International), turf plus lower density shock pad (Recticel Flexible Foams, Belgium), and turf plus higher density shock pad (Recticel Flexible Foams, Belgium). The turf and shock pad pieces were all cut as 60 cm ×60 cm square pieces to match the dimensions of the force platforms. For the turf only condition, the turf pieces were mounted directly to the force platform with double-sided tape (Model 442063, Duck Brand In.). For the other turf related surface conditions, each type of shock pads was mounted to the force platform firstly with the double-sided tape, then the turf piece was mounted on the top of the shock pad layer with the double-sided tape. The sand and rubber were infilled into the turf piece according to the manufacturer specifications. Specifically, each turf piece was infilled with sand (2 lbs.), then crumb rubber (3.6 lbs.). The sand and rubber were then brushed into the synthetic turf canopy using a stiff brush. Consistency and height of infilling distributions of the turf surface were measured at a minimum of nine locations (Figure 1) using a 3-prong surface depth gauge (Canadian Playground Advisory Inc., Canada). If infill height at any of the testing locations was not in range of 30 to 32 mm, the infills were brushed again using the same procedure described above.

Figure 1. Locations for infill height measurements of the testing turf piece.

Overhead Bar

A Motorized over-head bar was used to raise the subject to the desired landing height, which is 60 cm in this study (19, 89, 93), measured from the mid-heel to the landing surfaces and initiate the drop landing (DL) activities. The height of the bar can be controlled by an electrical hoist.

Three-Dimensional High-speed Motion Capture System

A 12-camera motion capture system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was utilized to collect kinematics data. Reflective anatomical markers were bilaterally placed on the acromion processes, iliac crests, greater trochanters, anterior and posterior superior iliac spines medial and lateral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and 2nd toes. A set of four tracking markers mounted on a thermoplastic shell was attached on the trunk, pelvis, thigh, and shank. Three discrete tracking markers were placed on the posterior and lateral heel counter of the shoes. All the anatomical markers were removed after a static trail.

Force Platforms

Two force platforms (1200 Hz, Advanced Mechanical Technologies, Inc., Watertown, MA) were used to measure the GRF data.

EXPERIMENTAL PROTOCOL

Participants were asked to attend one testing session in the Biomechanics/Sport Medicine Lab at the University of Tennessee, Knoxville. At beginning of the test session, participants were asked to fill out an information sheet, including subject demographic information, sport and physical activity history and level, and injury history.

Participants first warmed up by running for five minutes on the treadmill and two minutes self-stretching of major muscle groups. Then participants were asked to perform five trails in each of 5 testing conditions. These testing conditions included DL from a 60 cm height (19, 89, 93) for each of the five surfaces conditions: force platform only, turf, and three turf systems include turf plus foam shock pad, turf plus low density shock pad, and turf plus high density shock pad. Participants were asked to perform in a normal landing style, with the maximum knee flexion angle between 91 to 109 degrees, which was monitored by real-time streaming function in Nexus software, and land symmetrically in a balance fashion. All participants had opportunities to practice till they became familiar with the testing protocols. To minimize systematic errors, the testing conditions were firstly randomized between the force platform only and turf conditions. The testing order of the turf only and turf systems was then randomized. The three turf systems were further randomized. A successful trial for the DL was a trial in which participants landed symmetrically, within the knee flexion range, and were able to maintain balance after landing.

A mechanical test was conducted on the turf surface, and the three turf plus shock pad surfaces following the Standard Test Method for Impact Attenuation of Playing Surface Systems and Material (6). A standard mass (9.1 ± 0.050 kg) was dropped from 60 cm height for 3 trials on five different spots (Figure 2) on each surface. The maximum decelerations in the time-deceleration history were recorded for further analyses.

Figure 2. Locations for mechanical test.

DATA AND STATISTICAL ANALYSIS

Marker trajectories and GRF data were smoothed using a 4th order Butterworth low-pass filter at cutoff frequencies of 12 Hz (8), respectively, for joint kinematics and moment calculations. The GRF data were filtered separately using a 4th order Butterworth low-pass filter at a cutoff frequency of 100 Hz (8) for GRF related calculations. The GRF, kinematic and kinetic data were analyzed during the landing phase, which is defined as the time from initial ground contact to the maximum knee flexion.

All GRF, kinematics and kinetics variables were processed and computed in Visual3D biomechanics software suite (5.0, C-Motion, Inc., Germantown, MD). An X-y-z (X-axis: anteroposterior direction; y-axis: medial-lateral direction; z-axis: vertical direction) Cardan sequence was used in three-dimensional kinematics computations and a right-handed rule was used to determine positive and negative signs for angular kinematic and kinetic variables. GRFs were normalized to body weight (BW) and joint moments and powers were normalized to body mass (Nm/kg and W/kg, respectively). The dependent variables included peak vertical GRFs, vertical GRF loading rate, flexion ROMs of hip, knee and ankle, peak extensor moments of hip, knee and ankle, and only negative work during the landing phase of hip, knee and ankle.

A one-way (Surface) repeated measures analysis of variance (ANOVA) was performed to determine effects of five surface conditions on the variables of interest for each of the two movements separately (23, IBM SPSS Statistics, Chicago, IL). An alpha level was set at 0.05 *a priori*. When a main effect was significant, post hoc comparisons using a paired-sample *t*-test with Bonferroni adjustments were conducted to determine differences across surface conditions at different movements or across surface conditions. Therefore, the significance level for the paired-sample *t*-test was set at 0.005.

CHAPTER IV

EFFECTS OF SYNTHETIC TURF AND SHOCKPADS ON IMPACT ATTENUATION RELATED BIOMECHANICS DURING DROP LANDING

ABSTRACT

Synthetic turf has been widely utilized in sports since 1964. Discrepancies, however, in injury incidence on synthetic turf and natural grass have been reported throughout studies. Adding a shock pad under synthetic turf carpet is claimed to aid in energy absorption and decrease impact loading. Although some studies have conducted materials tests and compared mechanical characteristics of synthetic turf with different shock pads, no studies have examined biomechanical characteristics of impact related human movements on an infilled synthetic turf system with different underlying shock pads. The purpose of this research was to investigate effects of an infilled synthetic turf with three shock pads of different energy absorption characteristics on impact attenuation related biomechanics of lower extremity during drop landing. Wearing running shoes, twelve active and healthy recreational male athletes performed five trials of drop landing from 60 cm with a controlled landing style (maximum knee flexion) on five surface conditions: a regular surface (force platform), an infilled synthetic turf, turf plus foam shock pad, turf plus a lower density shock pad, and turf plus a high density shock pad. A motion analysis system and force platform were utilized to collect kinematic and kinetic data. Furthermore, a mechanical test was conducted based on ASTM F355 standard. The turf plus shock pad systems resulted in lower 1st vertical peak ground reaction force (GRF) and its loading rates compared to synthetic turf without a shock pad. However, no differences in 2nd vertical GRF and joint kinematics and kinetics across surfaces were found. These results suggest that landing from 60 cm may cause a plateau effect in energy attenuation for the examined turf and turf plus shock pad systems. Future studies may be needed to explore the shock attenuation capacities of landing surfaces in landing activities from a lower height (< 60 cm).

Keyword: drop landing, synthetic turf, shock pad, impact attenuation, landing styles, landing height

INTRODUCTION

Synthetic turf has been widely utilized in sports since 1964 (38, 60). For sports at all level (30), the use of synthetic turf has caused increased concerns regarding the safety in elite and recreational athletes (9). However, disagreements in injury rates on synthetic turf and natural grass have been reported in the literature. Some studies have reported that injuries of lower extremities were significantly higher on synthetic turf compared to natural grass (23, 27, 59, 63, 66). On the contrary, other studies have documented no difference in acute lower extremity injury incidences between synthetic and natural turfs (11, 26, 31, 63, 77). In addition, it was reported that injuries in practice were more frequent on natural grass compared to synthetic turf (32, 62).

To improve energy absorption and reduce the impact loading, some turf companies have begun to add a shock pad (a cushioning layer) under synthetic turf carpet (38). Materials tests have indicated that material type, density and thickness directly affected mechanical performance of shock pads and turf systems (with a combination of turf and shock pad) (4, 29, 84). Previous studies reported that a thick rubber shock pad turf system was less viscoelastic and stiffer compared to those with thin foam shock pad under the same loading rates (84), and stress and energy return increased as shock pad density increased under the same impact loading condition (4).

Landing movements are frequently involved in various sports, such as football, soccer, basketball, and volleyball. This rapid movement not only requires eccentric quadriceps muscle action to counteract knee flexion during the weight acceptance phase (52, 53), but also generates excessive impact force to lower extremities. Landing styles, as a related factor, are determined by the maximum knee flexion angle during landing (19, 93). Landing with small knee flexion angle may cause increased anterior cruciate ligament (ACL) loading by increasing the patella tendon-tibia shaft angle, which leads to augmented anterior shear force at the proximal end of the tibia and generates knee internal rotation and abduction moments (91). When landing from a higher height, greater peak vertical GRFs occur due to an increased contact velocity (71). With an increased landing height, GRF increased more rapidly and the knee variables, including knee flexion angles, angular velocities, and joint power, increased less, indicating that the impact attenuation ability of knee joint was limited, when landing height increased (88). Similarly, peak vertical GRF, as well as hip, knee and ankle extensor moments and energy absorption significantly increased with increased landing heights (50, 93), suggesting that changes in landing height could result in adjustments of landing styles.

Aiming to provide adequate impact attenuation properties, landing surfaces affected sport performance and impact shock attenuation of athletes (81, 85). A stiff surface can reduce energy loss and provide sufficient GRFs, while a more compliant surface may absorb more energy and reduce impact related injuries (20). Steele and Mulburne (79) reported that synthetic turf generated lower 1st peak vertical GRF compared to other synthetic surfaces (bitumen, concrete, and rubber surfaces) when landing from a typical netball attacking movements. However, no difference was observed in 2nd peak vertical GRF. Jones et al. (37) reported that athletes exhibited greater knee kinematic variability on synthetic turf compared to natural grass when performing single-leg landings from a jump heading movement. Shorten and Himmelsbach (75) showed that peak tibial accelerations in drop landing on synthetic turf were significantly higher than natural grass. Brock et al. (16) found that peak medial GRF in running shoes was higher compared to football cleats, and time to reach peak vertical GRF in football cleats was longer compared to running shoes in cutting movements on a 3rd generation infilled synthetic turf. However, a regression study suggested that surface stiffness did not affect the peak vertical GRF of double-leg landing from controlled heights (61).

Although a limited number of studies have examined landing movements on synthetic turf, no studies have examined biomechanical characteristics of impact related biomechanics on an infilled synthetic turf system with different underlying shock pads. Therefore, the purpose of this research was to investigate effects of an infilled synthetic turf with a combination of three shock pads on impact attenuation related biomechanics characteristics of lower extremity during drop landing. Five surface conditions were tested: a regular surface (force platform), an infilled third-generation synthetic turf, the turf plus a foam shock pad, turf plus a lower density shock pad, and turf plus a higher density shock pad. We hypothesized that 1) the peak vertical GRFs and their loading rates, peak joints moment and power, and work done by lower extremities would be reduced on the turf plus shock pad systems compared to the regular surface and turf only surface; 2) these variables would be reduced during landing on the turf systems with higher density and thicker shock pad, compared to the turf system with lower density and thin shock pad.

METHODS

Participants

Twelve healthy and recreationally active male athletes (mean ± SD age: 24.33 ± 4.08 years, height: 1.78 ± 0.05 m, mass: 76.33 ± 7.04 kg, BMI: 24.02 ± 1.56) who had a minimum of three years playing football, soccer, basketball or volleyball and played these sports two to three times per week, were recruited to participate in the study from the University campus. The inclusion criteria include that the participants had never had orthopedic surgery and did not have lower extremities or back injuries within the previous 6 months, they were free from pain on the test day, and they answered “No” to all the questions on the Physical Activity Readiness Questionnaire (PAR-Q – see appendices). Flyers were posted in the buildings on UT campus, and announcements were made in Physical Education Activity Program classes to recruit participants. Participants were asked to provide a written informed consent and the experimental protocol was approved by the University Review Board prior to data collection.

Instrumentation

Participants wore a pair of standard lab running shoes (Noveto, Adidas). A monofilament synthetic turf (Astro Turf® Gameday 3D 60, Astro Turf, Dalton, GA) and three types of shock pad were used in this study. The first shock pad (PB2000YSR, Brock International, CO) was made from expanded polypropylene with a thickness of 23 mm and density of 56.1 kg/m^3. The second (uni F 81.84, Recticel Flexible Foams, Belgium) and third shock pad (uni 82.16, Recticel Flexible Foams, Belgium) were mainly made of open-cell flexible polyurethane trim foam boned with isocyanate binder. Their thicknesses were 10 mm and 12 mm and the densities were 200 kg/m^3 and 250 kg/m^3, respectively. A total of five surface conditions were tested in this study: regular surface (force platform), a monofilament synthetic turf, and three turf systems including turf plus foam shock pad, turf plus lower density shock pad, and turf plus higher density shock pad. The turf and shock pad pieces were all cut into two 60 cm × 60 cm square pieces to match the dimensions of the two force platforms. For the turf only condition, the turf pieces were mounted directly to the force platform with double-sided tape (Model 442063, Duck Brand In.).

For the other turf related surface conditions, shock pad was first mounted to the force platform and the turf piece was mounted on the shock pad layer with the double-sided tape. The sand and rubber were infilled into the turf piece according to the specifications of the manufacturer. Specifically, each turf piece was infilled first with sand (2 lbs.) and then rubber (3.6 lbs.). The sand and rubber were then brushed evenly using a stiff brush. Consistency and height of infilling distributions of the turf surface were measured at a minimum of nine locations (Figure 1) using a 3-prong surface depth gauge (Canadian Playground Advisory Inc., Canada). If infill height at any of the testing locations was not in range of 30 to 32 mm, the infills were brushed again using the same procedure described above.

A 12-camera motion capture system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was utilized to collect three-dimensional kinematic data. Reflective anatomical markers were bilaterally placed on the acromion processes, iliac crests, greater trochanters, anterior and posterior superior iliac spines medial and lateral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads, and 2nd toes. A set of four tracking markers mounted on a thermoplastic shell was attached on the trunk, pelvis, thigh, and shank. Three discrete tracking markers were placed on the posterior and lateral heel counter of the shoes. All the anatomical markers were removed after a static trail. In addition, two force platforms (1200 Hz, Advanced Mechanical Technologies, Inc., Watertown, MA) were used to measure the GRF data. The force data were collected simultaneously using Nexus of the Vicon system.

Experimental Protocol

Participants first warmed up by running for five minutes on the treadmill and two minutes self-stretching of major muscle groups. Then participants were asked to perform five trails in each of 5 testing conditions. These testing conditions included drop landing from a 60 cm height (19, 89, 93) for each of the five surfaces conditions: force platform only, turf, and three turf systems include turf plus foam shock pad, turf plus low density shock pad, and turf plus high density shock pad. Participants were asked to perform the drop landing from a height of 60 cm on a motorized over-head bar (19, 89, 93), measured from the mid-heel to the landing in a normal landing style, with the maximum knee flexion angle between 91 to 109 degrees. The maximum knee flexion was checked using Visual3D software for each trial. All participants had opportunities to practice till they became familiar with the testing protocols. To minimize systematic errors, the testing conditions were firstly randomized between the force platform only and turf conditions. The testing order of the turf only and turf systems was then randomized. The three turf systems were further randomized. A successful trial for the DL was a trial in which participants landed symmetrically, within the knee flexion range, and were able to maintain balance after landing.

A mechanical test was conducted on the turf surface, and the three turf plus shock pad surfaces following the Standard Test Method for Impact Attenuation of Playing Surface Systems and Material (6). A standard mass (9.1 ± 0.050 kg) was dropped from 60 cm height for 3 trials on five different spots (Figure 2) on each surface. The maximum decelerations in the time-deceleration history were recorded for further analyses.

Data and Statistical Analysis

Marker trajectories and GRF data were smoothed using a 4th order Butterworth low-pass filter at cutoff frequencies of 12 Hz (8), respectively, for joint kinematics and moment calculations. The GRF data were filtered separately using a 4th order Butterworth low-pass filter at a cutoff frequency of 100 Hz (8) for GRF related calculations. The GRF, kinematic and kinetic data were analyzed during the landing phase, which was defined as the time from initial ground contact to the maximum knee flexion.

All GRF, kinematics and kinetics variables were processed and computed in Visual3D biomechanics software suite (5.0, C-Motion, Inc., Germantown, MD). An X-y-z (X-axis: anteroposterior direction; y-axis: medial-lateral direction; z-axis: vertical direction) Cardan sequence was used in three-dimensional kinematics computations and a right-handed rule was used to determine positive and negative signs for angular kinematic and kinetic variables. Internal moment was utilized for joint moment calculation. In addition, GRFs were normalized to body weight (BW) and joint moments and powers were normalized to body mass (Nm/kg and W/kg, respectively). The dependent variables included 1st and 2nd vertical GRF peaks and loading rates, time to 1st peak vertical GRF, flexion ROMs of trunk, hip, knee and ankle, peak extensor moments of trunk, hip, knee and ankle, and only negative work during the landing phase of hip, knee and ankle.

A one-way (Surface) repeated measures analysis of variance (ANOVA) was performed to determine effects of five surface conditions on the variables of interest for each of the two movements separately (23, IBM SPSS Statistics, Chicago, IL). An alpha level was set at 0.05 *a priori*. When a main effect was significant, post hoc comparisons using a paired-sample *t*-test with Bonferroni adjustments were conducted to determine differences across surface conditions at different movements or across surface conditions. Therefore, the adjusted significance level was 0.005.

RESULTS

All participants utilized forefoot to rearfoot landing strategies. The 1st peak vertical GRF was higher on regular surface compared with the conditions of turf plus foam shock pad (p=0.003), turf plus low density shock pad (p=0.002), and turf plus high density shock pad (p=0.022, Table 1). Time to 1st peak vertical GRF occurred earlier on regular surface than on the conditions of turf only (p=0.032, table 1), and turf plus low density shock pad (p=0.022). The loading rate for 1st peak GRF was higher in regular surface compared to the conditions of turf only (p=0.004, table 1), turf plus foam shock pad (p=0.001), turf plus low density shock pad (p=0.001), and turf plus high density shock pad (p=0.002). No differences were found in 2nd GRF and its loading rate across the surface conditions.

For joint kinematic variables, no differences were found in the contact angle of ankle, knee and hip (Table 2). No differences were found in ankle dorsiflexion ROM, knee flexion ROM, and Trunk flexion ROM. However, hip flexion ROM during the impact phase was greater on regular surface than on turf surface (p=0.041, Table 2).

No differences were noticed in the peak ankle plantarflexion moment and knee extension moment across surfaces (Table 3). Nevertheless, the pairwise comparison results showed that the peak hip extension moment was higher on turf plus low density shock pad compared with regular surface (p=0.05) and turf plus foam shock pad (p=0.05). Meanwhile, the peak trunk extension moment was greater on the turf plus low density shock pad compared with the regular surface (p=0.04) and turf surface (p=0.007). Furthermore, no differences were found in the peak ankle plantarflexion power, knee extension power, and hip extension power across surfaces. The eccentric work performed by ankle, knee and hip joints showed no differences across surfaces (Table 3).

The mean G_{max}, the maximum deceleration in the time-deceleration history, was 187.5 g for the synthetic turf surface only, 90.5 g for the turf plus foam shock pad, 124.9 g for the turf plus low density shock pad, and 119.0 G for turf plus high density shock pad, respectively (Figure 3). The 187.5 g for the synthetic turf only treatment exceeds the acceptable 165 G_{max} level recommended by the Synthetic Turf Council (1). These results suggest the shock pads can reduce G_{max} for synthetic turf.

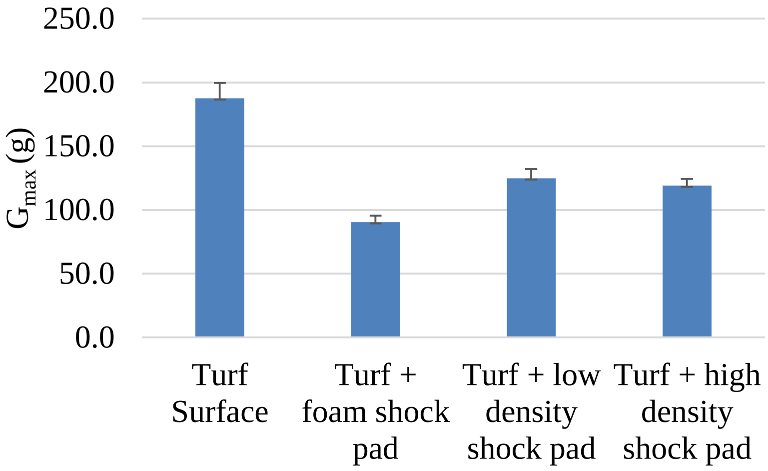

Figure 3. G_{max} on turf surface, turf plus foam shock pad, turf plus low density shock pad, and turf plus high density shock pad

DISCUSSION

The purpose of this research was to investigate effects of an infilled synthetic turf with three shock pads on impact attenuation related biomechanics characteristics of lower extremity during drop landing. The hypothesis that the turf and turf systems would result in lower peak vertical GRFs and their loading rate, peak joints moment and power, and work done by lower extremities compared to the regular surface was only partially supported.

A lower 1st peak vertical GRF and its loading rate were observed for the turf and three turf plus shock pad systems compared to the regular surface. The loading rates for 1st and 2nd peak GRFs on regular surface were similar compared to previous studies (18, 71). The 1st peak vertical GRF loading rates were also lower on the three turf plus shock pad conditions and turf surface compared to regular surface. However, no difference was noticed between regular surface and turf only surface. Additionally, no differences were noticed in the 2nd peak vertical GRF and its loading rates across surfaces. Our results are supported by findings by Steele et al. (79), who tested vertical GRFs of netball athletes of landing from a typical netball attacking movement on 12 different synthetic surface conditions (bitumen, concrete, 3 types of synthetic turf with sand and rubber granuale fillings and 7 types of rubber surfaces). The authors reported no differences in 1st peak vertical GRF across surfaces. Other studies documented that, by comparing landing on a soft and a stiff mat, surface stiffness was not a crutial factor related to the 1st peak vertical GRF (5, 61). Arampatzis et al. (5) conducted a simulation study, in which they reported the 1st peak vertical GRF in landing from 80 cm were 1.51, 1.61, and 1.62 BW on soft, medium, and hard mats, respectively. The synthetic surfaces used in these studies (5, 61, 79), whether synthetic turf or mats with different stiffnesses, were all single layer with a single type surface. In our study, three different types of shock pad and one type of synthetic turf carpet were used. While we did not find any difference between regular surface and turf only surface conditions., reductions in 1st peak vertical GRF of 13.3%, 12.7% and 12.7% on the three turf shock pad systems compared to regular surface were observed. Although no differences were noted in the 1st peak vertical GRF between regualr surface and turf only surface, the longer time to the 1st peak vertical GRF on turf surface resulted in lower loading rate compared to regular surface. We found that the loading rates for the 1st peak vertical GRF on turf with either shock padshock pad treatment and theturf only surface were reduced compared to regular surface by 20.5%, 20.4%, 25.4%, and 21.1% respectively. Lower loading rate could decrease the risks of injury. Due to the time to 1st peak vertical GRF occurred only about 11 ms after the initial ground contact, human body was not quick enough to be actively involved in impact dissapation. These results indicate that adding shock pad to a synthetic turf system had effects on attenuating more impact forces.

Our results showed that the 2nd peak vertical GRFs, the greater peak compared to the 1st peak GRFs and associated with heel-contact, were not different across the tested surface conditionss. This result is supported by previous studies (references?). Niu et al. (61) developed a regression model based upon 26 selected studies to evaluate the relashionship between the 2nd peak GRF and surface stiffness and other influential factors during double-leg landing from specific landing heights, and found that surfaces stiffness did not affect the 2nd peak vertical GRF. However, McGhie and Ettema (46) reported that while performing sprint stop, the maximum impact force was lower on the turf with an underlying shock pad. The sprint stop was a straight sprint with a rapid deceleration, primarily an anteroposterior movement. On the other hand, the landing movements in the current study was a pure vertical task, hence the vertical impact in our study was much higher than the sprint stop. McNitt-Gray et al. (51), who examined gymnasts’ adjustments of landing strategies under three different surface conditions (a regular surface (force platform), a soft mat, and a stiff mat) from a 69 cm height, found lower peak vertical GRFs on the regular surface than the soft and stiff mats. While these results are contrary to the results of the current study, it is important to note that McNitt-Gray et al. (50) did not control landing strategy and that participants varied their landing strategies as compensation for the regular surface. However, in the current study, landing strategy was controlled which may explain the lack of differences in 2nd peak vertical GRF. The lack of differences in 2nd peak vertical GRF across the surfaces may also be a result of the 60 cm landing height (18, 19, 70, 71, 89, 92). Since we have controlled the landing stiffness (strategy) by limiting the maximum knee flexion to fall within (100 ± 9 º), the landing height may play an important role in affecting the peak vertical GRFs' results. The results suggest that the turf systems may be "bottomed out" and insufficient to attenuate the heel contact impact force during landing. . Therefore, the impact force generated from landing of 60 cm may be too high for any of the turf surfaces to show any additional attenuation effects. In addition, the previous surface related landing studies (5, 61, 79) allowed their participants to land with a self-selected landing strategy and these authors all pointed out those participants adjusted their landing strategies and body stiffness to cope with impacts on the difference surface conditions.

The joint kinetic results showed no differences in peak ankle plantarflexion and knee extension moments across the surfaces. Both occurred after the 2nd peak GRF (50 ms after the initial ground contact), at around 65 ms and 87 ms, respectively. The lack of difference in 2nd peak GRF explains the non-significant differences in joint moments. These kinetic results are also supported by the lack of difference in ankle and knee ROM. However, hip extension moment on turf plus low density shock pad was greater compared to regular surface (16.9%) and turf plus foam shock pad (15.6%), and occurred before the 2nd peak GRF (42 ms). The peak trunk extension moment on turf plus low density shock pad was greater compared to the turf only surface (21.2%) and turf plus foam shock pad (13.0%), occurring even earlier (32 ms). The trunk extension moments seemed to contribute the greatest impact attenuation compared to lower extremity joints across surfaces yielding higher peaks; while, the hip extension moments the was the lowest across surfaces. No differences were observed in peak extensor power and eccentric work done by the ankle, knee, and hip across surfaces. Surprisingly, the peak hip extensor power was the lowest across all surfaces, while the eccentric ankle work contributed the least among three joints. Even though the results seemed to suggest that no adjustments were made in ankle and knee joints in landing across different surfaces, the participants may have accommodated the surface conditions by increasing hip and trunk peak extension moments to maintain overall body posture and stiffness across the surfaces. Our second hypothesis was partially confirmed by greater hip extension moment and trunk extension moment occurred on turf plus low density shock pad compared to turf plus foam shock pad.

Adding a shock pad under synthetic turf is aimed at improving energy absorption and decreasing impact loading (38). The material test results indicated that turf system with underlying shock pad made from shredded rubber showed stiffer properties than shock pad made from foam under compression loading (84). Density and thickness are two important parameters to be considered for the shock pad (4, 29). FIFA has a minimum requirement of density and thickness, in addition to the synthetic turf, in order to maintain consistent mechanical performance accounting for infill deformations caused by athlete-turf interactions (29). The “on-field” material test results from this study suggested that the foam shock pad, the thickest and made of a denser material compared to the two flexible shock pads, has the best impact attenuation capacity compared with the other two shock pads. The turf plus foam shock pad showed the highest impact acceleration attenuation with 51.7% reduction of the peak impact acceleration while the turfs plus low and high density shock pad showed lower attenuation with 33.4% and 36.5% reductions of the peak acceleration, respectively compared to the turf only surface. These test results were in agreement with results previously reported (4, 29, 84). However, these results were contrary on some performance of the results in current human test.

In order to minimize potential effects of variability in landing styles on impact related variables, we controlled maximum knee flexion and landing height. Not surprisingly, there were no differences in the ankle, knee and hip contact angles, or ankle and knee ROM across the surfaces. Multiple studies have demonstrated that landing with decreased maximum knee flexion angles (i.e. increased landing stiffness) caused increases in the 1st and 2nd peak vertical GRFs, the peak extensor moments and powers of hip, knee and ankle, and reduced energy attenuation by these joints (19, 57, 65, 93). Participants tended to flex knees more when landed on stiffer surface, and generated less GRF compared to a compliant surface (51).

The limitations for this study included, participants may perform drop landings in athletic participation with different techniques than within the lab environment. Additionally, we only tested one type of synthetic turf and three types of shock pad. Finally, the 60 cm landing height may have yielded plateau effects on the vertical GRF. Future studies should identify a more suitable and lower landing height.

CONCLUSION

The results from this study suggest that the three turf plus shock pad systems reduced the initial vertical GRF and its loading rate compared to the regular surface during vertical drop landing. However, no differences were detected in the 2^{nd} peak vertical GRF and its loading rates. No differences were found in joint ROM, extensor moments, and peak extension power of ankle and knee, nor in work done by the lower extremity joints. On the other hand, turf plus low density shock pad resulted in greater hip extension moments compared to regular surface and turf plus foam shock pad, and greater trunk extension moments compared to turf surface and turf plus foam shock pad. Overall, the turf plus shock pad systems seem to provide improved impact attenuation for landing activities from heights of 60 cm or lower.

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APPENDICES

APPENDIX A: TABLE IN CHAPTER IV

Table 1: Peak vertical ground reaction forces and related loading rates: mean ± SD.

	Regular surface	Turf	Turf + Foam shock pad	Turf + Low density shock pad	Turf + High density shock pad	F Test
1st peak vertical GRF (BW)	1.58±0.30	1.44±0.24	1.37±0.25[a]	1.37±0.27[a]	1.38±0.27[a]	F=8.3, p=0.006
Time_1st peak vertical GRF (s)	0.011±0.002	0.013±0.002[a]	0.012±0.002	0.013±0.002[a]	0.012±0.002	F=3.7, 9=0.046
Loading rate_1st vertical GRF (BW/s)	146.4±34.9	116.4±28.1[a]	116.5±26.9 [a]	109.2±22.4[a]	115.5±23.5[a]	F=20.1, p<0.001
2nd peak vertical GRF (BW)	3.05±0.96	2.89±0.77	2.88±0.72	2.89±0.89	2.91±0.71	F=0.3, p=0.850
Loading rate_2nd vertical GRF (BW/s)	67.2±31.5	61.0±27.5	62.7±25.2	61.6±28.6	63.0±22.0	F=0.5, p=0.737

a: Significantly different from regular surface.
b: Significantly different from turf surface.
c: Significantly different from turf + foam shock pad.
d: Significantly different from turf + low density shock pad.

Table 2: Joint kinematic variables: mean ± SD.

	Regular surface	Turf	Turf + Foam shock pad	Turf + Low density shock pad	Turf + High density shock pad	F Test
Ankle Contact Angle (º)	-27.0±5.4	-27.1±3.8	-26.6±4.6	-26.7±4.9	-26.3±5.0	F=0.2, p=0.922
Ankle Dorsiflexion ROM (º)	51.1±6.0	51.9±6.1	50.5±6.1	50.0±6.8	50.7±6.2	F=1.3, p=0.273
Knee Contact Angle (º)	-19.7±4.0	-21.4±4.4	-20.5±5.3	-21.0±5.3	-20.7±5.2	F=1.6, p=0.261
Knee Flexion ROM (º)	-80.6±4.2	-80.2±6.2	-79.9±5.9	-79.2±5.7	-80.5±3.6	F=0.3, p=0.841
Hip Contact Angle (º)	20.1±7.2	20.3±7.2	19.7±7.1	20.0±5.6	19.5±7.0	F=0.2, p=0.922
Hip Flexion ROM (º)	70.9±12.6	66.6±10.9 [a]	68.2±14.0	67.5±13.0	67.7±14.3	F=4.3, p=0.038
Trunk Flexion ROM (º)	-31.5±10.0	-27.8±9.6	-28.3±7.7	-28.5±9.1	-30.0±6.9	F=2.8, p=0.094

a: Significantly different from regular surface.
b: Significantly different from turf surface.
c: Significantly different from turf + foam shock pad surface.
d: Significantly different from turf + low density shock pad surface.
Negative values indicate plantarflexion, knee flexion, and trunk flexion.

Table 3: Peak joint moment and power, and work: mean ± SD.

	Regular surface	Turf	Turf + Foam shock pad	Turf + Low density shock pad	Turf + High density shock pad	F Test
Ankle plantarflexion moment (Nm/Kg)	-1.23±0.19	-1.25±0.21	-1.25±0.24	-1.25±0.22	-1.26±0.21	F=0.1, p=0.971
Knee extension moment (Nm/Kg)	2.59±0.34	2.59±0.35	2.58±0.34	2.61±0.41	2.65±0.39	F=1.0, p=0.472
Hip extension moment (Nm/Kg)	0.89±0.29	0.96±0.23	0.90±0.26	1.04±0.24 [a, c]	0.99±0.26	F=2.8, p=0.098
Trunk extension moment (Nm/Kg)	5.73±1.41	5.15±1.25	5.57±1.36	6.24±1.47 [b, c]	5.96±1.60	F=5.6, p=0.008
Ankle plantarflexion power (W/Kg)	-17.2±8.0	-17.3±3.4	-17.1±3.7	-16.5±3.8	-17.9±3.9	F=0.6, p=0.682
Knee extension power (W/Kg)	-32.1±8.0	-31.4±8.2	-32.0±6.4	-31.9±8.9	-32.9±7.2	F=0.6, p=0.656
Hip extension power (W/Kg)	-15.6±6.4	-15.3±6.5	-15.5±5.3	-16.3. ±6.4	-15.1±4.1	F=0.5, p=0.734
Ankle eccentric work (J/Kg)	-0.71±0.17	-0.77±0.16	-0.75±0.18	-0.75±0.18	-0.77±0.19	F=0.4, p=0.782
Knee eccentric work (J/Kg)	-2.52±0.33	-2.47±0.41	-2.42±0.37	-2.45±0.40	-2.54±0.40	F=1.8, p=0.215
Hip eccentric work(J/Kg)	-1.51±0.55	-1.35±0.37	-1.40±0.44	-1.45±0.37	-1.48±0.43	F=1.5, p=0.297

a: Significantly different from regular surface.
b: Significantly different from turf surface.
c: Significantly different from turf + foam shock pad surface.
d: Significantly different from turf + low density shock pad surface.
Negative values indicate extension moment and power, and eccentric work performed.

APPENDIX B: INDIVIDUAL PARTICIPANT CHARATERISTICS

Table 4: Individual participant characteristics.

Subject	Age (Years)	Gender	Height (m)	Weight (Kg)	BMI (Kg/m^2)	Sports involvement (≥ 3 years)	Exercise frequency (Times/Week)
1	21	Male	1.80	73.6	22.7	Basketball	5
2	20	Male	1.85	87.8	25.7	Football	3
3	19	Male	1.78	66.6	21.0	Soccer	7
4	26	Male	1.71	73.2	25.0	Soccer, volleyball	3
5	24	Male	1.78	69.8	22.0	Basketball	5
6	25	Male	1.86	83.4	24.1	Football, basketball	5
7	25	Male	1.80	86.1	26.6	Soccer	5
8	30	Male	1.86	83.9	24.3	Soccer	7
9	30	Male	1.74	70.9	23.4	Basketball	5
10	20	Male	1.76	73.7	23.8	Basketball, soccer	4
11	22	Male	1.73	74.9	25.0	Basketball, volleyball	5
12	30	Male	1.71	72.1	24.7	Basketball	5
Mean±SD	24.3±4.1	-	1.78±0.05	76.3±7.0	24.0±1.6	-	4.9±1.2

APPENDIX C: INFORMED CONSENT FORM

INFORMED CONSENT FORM

Effects of synthetic turf and shock pads on impact attenuation related biomechanics during drop landing and drop jump

Principal Investigator:	Hang Qu, B.S.	Faculty Advisor:	Songning Zhang, PhD
Address:	144 HPER 1914 Andy Holt Avenue Knoxville, TN 37996 Phone: (865) 974-8768	Address:	340 HPER 1914 Andy Holt Avenue Knoxville, TN 37996 Phone: (865) 974-2091

Introduction

You are invited to participate in this research study because you are an adult between 18 and 30 years old. This research investigates the force absorption in lower limbs of drop landing and drop jump on an artificial turf and shock pads. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to participate in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol

If you agree to participate, you will attend one study session at the Biomechanics/Sports Medicine Lab on the UT campus. You will need to complete the demographic questionnaire and Physical Activity Readiness Questionnaire (PAR-Q), which will be used for this study. The study visit will take approximately 2½ – 3 hours. You will need to wear clothing appropriate for exercise which includes spandex shorts and t-shirt. If you do not have spandex type of clothing, spandex short or laboratory paper short will be provided.

We will measure your weight and height. We will place reflective markers on your feet, ankles, legs, knees, thighs, pelvis and trunk. This will allow motion cameras to capture your body movements when performing the exercises. The motion cameras will not record images of you. If you have any questions, interests, or concerns about any equipment to be used in this test, please feel free to ask the investigator or other research personnel.

You will perform the following movements.

- Perform maximum vertical jump 3 times.
- Perform drop landing from a height of 23.6 inches 5 times on floor.
- Perform drop landing from a height of 23.6 inches 5 times on artificial turf.
- Perform drop landing from a height of 23.6 inches 5 times on artificial turf with one type of shock pad.
- Perform drop landing from a height of 23.6 inches 5 times on artificial turf with second type shock pad.
- Perform drop landing from a height of 23.6 inches 5 times on artificial turf with third type of shock pad.
- Perform drop jump from a height of 15.7 inches 5 times on floor.
- Perform drop jump from a height of 15.7 inches 5 times on artificial turf.

- Perform drop jump from a height of 15.7 inches 5 times on turf with one type shock pad.
- Perform drop jump from a height of 15.7 inches 5 times on turf with second type shock pad.
- Perform drop jump from a height of 15.7 inches 5 times on turf with third type shock pad.

Trials need to be completed with a normal landing style, with the maximum knee flexion between 81 to 99 degrees only on the drop landing trials. If you are within 81 to 99 degrees, you will be asked to repeat the trial. You will have opportunity to practice trials to become familiar with the testing procedures. It is anticipated that you will not be required to perform more than eight trials of each test condition. You can take breaks as needed. You can end any exercise early and do not have to complete the study visit.

Potential Risks

Risks associated with this study are minimal. There is a small risk of an ankle sprain but it is no greater than the risk you would experience when playing your sports. In order to prevent potential muscle strains and ligament sprains, you will be asked to perform a standardized warm-up and stretching prior to the actual testing. The turf surface is infilled with the sand and rubber particles evenly to prevent any possibility of ankle sprains. You are asked to practice the movements before the testing and take breaks as needed. In the unlikely event you are injured during the study, we will provide standard first aid. However, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation and you will be responsible for any medical expenses. If you are injured, please notify Hang Qu or her advisor, Dr. Songning Zhang (974-2091).

Every research study involves some risk to your confidentiality. It is possible that other people could find out you were in the study or see your study information. But we will do our best to keep your information confidential to minimize this risk.

Benefits of Participation

You may not benefit from participation in this study directly. However, the potential benefits for you include the knowledge of jump height and control of landing techniques and experience of landing on the different surfaces. You can receive an individual report of your landing and jumping biomechanics to share with your athletic trainer and coaches in case it might be helpful to your sport performance and injury prevention. Results from this study may help society to better understand which turf and shock pad combination is the best option in force absorption for human jump and landing performance.

Confidentiality

Your information will be kept confidential. Your research data and records will be stored securely and will be made available only to researchers who work on this study. The motion cameras will not record images of you. Your name will not be in any research data. Instead, a code number will replace your name on your data. Your name will not appear with the study results that will be presented at conferences and published in journals. Your data will be stored using password protected hard drives. Your data may be used for future research purposes after the completion of this study. If you decide to withdraw from the study, data collected up to that point may be used for research purposes, unless you request that it be destroyed.

Contact Information

If you have any questions about the study at any time or if you experience any problems as a result of participating in this study you can contact Hang Qu or Dr. Songning Zhang at 1914 Andy Holt Ave. 136 HPER Bldg., the University of Tennessee and/or (865) 974-2091. Questions about your rights as a participant can be addressed to Compliance Officer in the Office of Research at the University of Tennessee at (865) 974-7697.

Voluntary Participation and Withdrawal

Your participation is entirely voluntary and your refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You may withdraw from the study at any time without penalty or loss of benefits to which you are otherwise entitled. Your participation in this study may be stopped by if you fail to follow the study procedures or if the principal investigator believes it is in your best interest to stop participation.

Consent Statement

I have read the above information. I agree to participate in this study. I have received a copy of this form.

Subject's Name: _______________ Subject's Signature: _______________ Date: ___________

Investigator's Signature: _____________________________ Date: ________________________

APPENDIX D: FLYER

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Kinesiology, Recreation, and Sport Studies
COLLEGE OF EDUCATION, HEALTH & HUMAN SCIENCES

If you:

- male, are healthy and between the ages of 18 and 30
- are free from leg, foot and back injuries within last 6 months
- have never accepted orthopedic surgery
- have played or are playing football, soccer, basketball or volleyball
- work out ≥ 3 times per week

Please consider being our subjects!

Good Jumpers Wanted

In our lab, you can:

- experience the advanced motion capture and other technology
- know how the synthetic turf systems affect your jump performance

For participation or more information:

Please contact **Hang Qu (Frankie)** at the UT Biomechanics/Sports Medicine Lab:

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APPENDIX E: PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age and you are not used to being very active, check with your doctor.

No	Yes	
☐	☐	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2. Do you feel pain in your chest when you do physical activity?
☐	☐	3. In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6. Is your doctor currently prescribing drugs (for example water pills) for your blood pressure of heart condition?
☐	☐	7. Do you know of <u>any other reason</u> why you should not do physical activity?

Please note: If your health changes so that you then answer YES to any of these questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

If you answered YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active of BEFORE you have a fitness appraisal. Tell you doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want as long as you start slowly and build up gradually. Or you may need to restrict your activities to those which are safe for you. Talk to your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

If you answered NO to all questions

If you have answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physical active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part if a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active if:

- You are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better, or If you are or may be pregnant – talk to your doctor before you start becoming more active.

I understand that my signature signifies that I have read and understand all the information on the questionnaire, that I have truthfully answered all the questions, and that any question/concerns I may have had have been addressed to my complete satisfaction.

Name (please print)

Signature

Date

APPENDIX F: INDIVIDUAL RESULTS FOR SELECTED VARIABLE

Table 5: 1st Peak Vertical GRF (BW)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	2.092±0.072	1.920±0.221	1.691±0.008	1.828±0.159	1.767±0.198
2	1.159±0.087	1.327±0.094	0.935±0.074	0.893±0.058	0.970±0.156
3	1.591±0.054	1.570±0.070	1.437±0.063	1.415±0.073	1.397±0.114
4	1.482±0.067	1.616±0.134	1.509±0.039	1.340±0.040	1.408±0.082
5	1.285±0.068	1.124±0.102	1.071±0.101	1.112±0.079	1.039±0.019
6	1.584±0.099	1.389±0.161	1.358±0.138	1.329±0.070	1.269±0.159
7	1.410±0.061	1.463±0.137	1.283±0.048	1.251±0.066	1.257±0.088
8	1.370±0.063	1.208±0.061	1.242±0.064	1.303±0.087	1.296±0.063
9	2.016±0.128	1.802±0.141	1.833±0.148	1.801±0.076	1.915±0.106
10	1.737±0.103	1.291±0.197	1.358±0.034	1.198±0.197	1.353±0.113
11	1.892±0.146	1.308±0.067	1.479±0.153	1.643±0.095	1.468±0.091
12	1.283±0.031	1.314±0.122	1.219±0.114	1.293±0.135	1.470±0.123
Mean±SD	1.575±0.303	1.444±0.240	1.368±0.249	1.367±0.274	1.384±0.265

Table 6: 2nd Peak Vertical GRF (BW)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	3.698±0.331	2.804±0.074	2.770±0.170	2.778±0.102	3.451±0.218
2	2.632±0.169	2.374±0.173	2.635±0.062	2.680±0.112	2.704±0.247
3	2.097±0.295	2.316±0.232	2.476±0.187	2.215±0.139	2.421±0.241
4	2.280±0.161	2.422±0.175	2.496±0.228	2.376±0.152	2.833±0.050
5	3.639±0.099	2.875±0.239	2.814±0.248	2.821±0.257	2.823±0.230
6	1.934±0.200	2.554±0.073	2.077±0.144	2.115±0.068	2.168±0.115
7	2.478±0.218	2.211±0.204	2.217±0.215	2.012±0.154	2.221±0.081
8	4.066±0.254	4.252±0.156	4.210±0.117	4.221±0.065	3.993±0.229
9	4.603±0.114	4.196±0.298	4.363±0.196	4.347±0.189	4.367±0.084
10	2.892±0.289	2.500±0.366	2.848±0.226	2.332±0.295	2.646±0.164
11	4.285±0.279	3.870±0.341	3.224±0.209	4.318±0.175	3.178±0.186
12	1.964±0.267	2.252±0.278	2.454±0.165	2.408±0.164	2.161±0.196
Mean±SD	3.047±0.962	2.885±0.767	2.882±0.722	2.885±0.886	2.914±0.714

Table 7: Time to 1st Peak Vertical GRF (BW)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	0.012±0.001	0.015±0.002	0.013±0.000	0.015±0.001	0.015±0.001
2	0.011±0.001	0.013±0.001	0.010±0.001	0.009±0.002	0.010±0.003
3	0.013±0.001	0.014±0.001	0.012±0.001	0.015±0.001	0.012±0.001
4	0.011±0.001	0.013±0.001	0.013±0.000	0.014±0.002	0.012±0.001
5	0.008±0.000	0.011±0.002	0.010±0.001	0.011±0.001	0.009±0.002
6	0.013±0.000	0.012±0.000	0.014±0.001	0.014±0.001	0.015±0.002
7	0.009±0.001	0.012±0.001	0.011±0.001	0.012±0.002	0.012±0.002
8	0.010±0.001	0.010±0.003	0.010±0.002	0.010±0.001	0.010±0.001
9	0.009±0.001	0.009±0.000	0.010±0.000	0.011±0.001	0.011±0.001
10	0.013±0.001	0.014±0.001	0.014±0.001	0.014±0.002	0.013±0.002
11	0.010±0.001	0.011±0.000	0.012±0.001	0.014±0.001	0.012±0.001
12	0.013±0.001	0.016±0.002	0.013±0.000	0.016±0.002	0.016±0.002
Mean±SD	0.011±0.002	0.013±0.002	0.012±0.002	0.013±0.002	0.012±0.002

Table 8: Time to 2nd Peak Vertical GRF (BW)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	0.044±0.002	0.050±0.003	0.047±0.002	0.051±0.003	0.049±0.004
2	0.050±0.002	0.058±0.003	0.045±0.004	0.040±0.002	0.046±0.005
3	0.057±0.003	0.054±0.003	0.048±0.002	0.053±0.003	0.049±0.002
4	0.063±0.005	0.059±0.003	0.059±0.003	0.061±0.004	0.051±0.002
5	0.039±0.001	0.047±0.004	0.048±0.003	0.046±0.002	0.042±0.003
6	0.059±0.005	0.048±0.001	0.056±0.004	0.054±0.001	0.056±0.004
7	0.050±0.003	0.055±0.006	0.054±0.002	0.058±0.006	0.054±0.006
8	0.038±0.002	0.038±0.002	0.038±0.002	0.036±0.000	0.038±0.003
9	0.038±0.002	0.039±0.002	0.038±0.000	0.039±0.001	0.042±0.002
10	0.053±0.003	0.059±0.004	0.054±0.003	0.058±0.001	0.054±0.005
11	0.044±0.003	0.044±0.002	0.049±0.001	0.050±0.001	0.050±0.003
12	0.054±0.002	0.054±0.001	0.048±0.001	0.053±0.004	0.057±0.009
Mean±SD	0.049±0.008	0.050±0.007	0.049±0.007	0.050±0.008	0.049±0.006

Table 9: Ankle Contact Angle (º)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-27.323±2.282	-27.662±2.739	-25.657±3.210	-28.134±1.503	-28.369±3.235
2	-20.270±4.475	-24.924±2.045	-20.850±1.549	-20.166±4.165	-21.439±3.787
3	-28.162±0.540	-27.816±0.933	-25.161±1.115	-26.295±2.106	-24.519±0.850
4	-32.195±1.067	-32.855±1.491	-31.970±2.443	-32.565±1.453	-26.828±0.805
5	-20.774±2.265	-21.743±3.254	-20.579±2.373	-20.227±2.845	-16.060±2.955
6	-29.199±2.737	-28.194±2.169	-28.737±1.742	-29.932±1.017	-29.238±1.131
7	-27.705±1.529	-26.152±0.781	-26.148±1.250	-27.186±2.184	-27.007±1.455
8	-20.030±1.059	-20.532±1.510	-21.230±0.572	-20.418±0.330	-21.134±0.709
9	-26.863±2.235	-28.159±2.336	-26.470±1.275	-26.729±1.178	-28.432±1.100
10	-35.587±1.310	-31.965±1.222	-33.893±0.563	-30.837±1.044	-33.551±0.831
11	-33.913±1.221	-30.687±1.754	-33.457±1.205	-34.868±1.775	-33.391±0.553
12	-21.661±2.437	-24.161±1.396	-25.559±2.611	-23.587±1.831	-25.327±0.931
Mean±SD	-26.974±5.364	-27.071±3.801	-26.643±4.632	-26.745±4.907	-26.275±5.049

Table 10: Ankle Dorsiflexion ROM (°)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	52.457±2.696	53.718±1.973	52.459±3.209	53.956±2.677	55.378±3.283
2	44.684±2.770	49.159±3.226	42.967±1.650	37.705±1.442	43.857±5.490
3	54.496±2.493	53.647±1.163	48.406±0.917	48.703±2.101	48.151±2.356
4	60.441±1.932	65.009±1.270	62.735±1.663	61.411±2.552	57.424±1.615
5	42.176±1.880	45.173±2.258	45.076±2.431	45.269±4.053	41.239±3.778
6	52.431±1.724	50.592±3.161	50.672±1.405	49.925±0.622	52.134±1.251
7	49.295±1.486	47.023±2.360	48.038±1.228	49.258±2.898	47.789±2.205
8	41.391±1.323	41.922±1.757	41.367±2.196	41.381±1.481	41.918±3.069
9	48.210±3.336	50.442±4.753	47.927±3.245	46.791±3.349	49.444±2.186
10	55.729±2.058	57.754±2.183	55.867±2.558	52.266±2.790	55.526±3.053
11	55.978±2.274	51.771±2.956	53.937±2.009	57.722±1.921	56.848±3.081
12	55.988±1.692	56.570±1.447	55.973±3.024	55.994±3.555	58.471±3.999
Mean±SD	51.107±6.017	51.898±6.137	50.452±6.111	50.032±6.788	50.682±6.184

Table 11: Knee Contact Angle (º)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-19.422±0.898	-19.617±2.024	-18.642±3.428	-19.098±2.293	-20.301±3.062
2	-24.302±2.178	-24.648±2.424	-24.563±3.242	-26.216±4.553	-25.200±1.047
3	-14.331±2.136	-14.439±1.648	-14.086±0.572	-12.948±3.195	-13.808±1.169
4	-24.202±1.167	-24.635±1.718	-22.932±1.082	-22.938±1.365	-22.290±2.003
5	-25.060±4.025	-29.639±3.462	-29.741±3.889	-30.488±1.951	-30.795±3.526
6	-19.980±3.116	-22.281±1.664	-23.017±2.096	-20.497±1.137	-22.697±2.631
7	-21.014±3.965	-25.448±2.277	-26.714±1.415	-27.463±2.507	-24.590±1.360
8	-23.486±0.664	-22.814±1.090	-23.573±0.702	-24.151±2.181	-24.185±2.475
9	-15.868±1.579	-15.060±0.809	-13.266±2.086	-15.612±1.541	-13.082±0.750
10	-14.885±2.067	-20.753±2.605	-16.480±1.259	-17.473±1.434	-16.714±2.626
11	-18.351±1.346	-18.439±2.262	-17.210±0.911	-17.397±0.802	-17.669±0.910
12	-15.058±2.835	-18.540±1.926	-15.602±3.418	-17.221±3.319	-16.849±3.108
Mean±SD	-19.663±4.005	-21.359±4.444	-20.485±5.310	-20.958±5.310	-20.681±5.236

Table 12: Knee Flexion ROM (º)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-80.165±4.465	-82.073±3.264	-79.712±0.883	-86.882±3.218	-79.162±2.714
2	-73.235±3.667	-72.611±2.660	-74.431±2.349	-72.237±2.964	-76.896±2.142
3	-82.791±3.868	-84.041±2.214	-83.622±3.665	-86.649±4.675	-82.178±4.640
4	-74.986±2.915	-80.809±3.380	-73.267±2.900	-73.343±1.550	-80.508±4.732
5	-77.374±2.896	-71.672±3.450	-76.870±1.784	-71.557±4.405	-74.060±3.740
6	-81.069±4.455	-78.593±3.640	-77.588±2.531	-78.532±2.254	-77.791±5.195
7	-78.209±3.176	-70.813±7.144	-73.298±6.321	-74.222±2.164	-77.645±4.760
8	-79.678±4.213	-78.756±5.349	-75.175±0.821	-79.025±1.504	-79.625±4.886
9	-81.620±1.868	-91.498±0.244	-91.411±2.720	-79.857±0.814	-84.152±3.127
10	-86.176±4.135	-81.060±4.602	-85.146±1.246	-85.772±3.588	-84.213±2.691
11	-85.306±3.134	-85.020±3.611	-80.541±1.543	-77.898±1.539	-83.940±6.271
12	-86.451±5.653	-85.250±1.754	-87.397±2.702	-84.249±4.370	-85.755±1.654
Mean±SD	-80.588±4.226	-80.183±6.171	-79.871±5.915	-79.185±5.655	-80.494±3.592

Table 13: Hip Contact Angle (°)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	25.764±1.582	23.731±2.518	22.745±3.415	24.260±1.862	25.670±5.295
2	12.511±1.286	9.601±6.606	13.481±2.623	15.931±4.180	12.480±1.260
3	9.802±1.795	10.826±0.822	9.538±1.300	14.203±2.172	12.015±3.288
4	24.670±3.466	23.522±1.674	19.154±1.942	22.533±1.637	18.154±1.669
5	26.506±3.398	28.761±2.606	27.757±4.342	28.365±2.175	28.000±3.468
6	28.646±4.177	30.237±2.273	33.264±2.679	26.742±2.513	32.324±2.765
7	12.627±7.275	15.317±2.221	14.669±2.117	13.118±3.902	13.981±3.372
8	15.331±0.806	15.209±1.002	12.498±0.830	15.755±1.317	13.167±2.251
9	28.778±2.045	26.827±1.680	26.229±1.352	26.692±1.887	26.657±0.757
10	16.282±3.787	16.440±3.337	16.530±2.644	14.860±2.623	16.392±2.074
11	25.957±4.388	26.996±7.068	23.549±4.686	21.011±3.937	20.060±4.923
12	14.441±5.227	16.206±3.710	17.325±4.094	16.251±2.589	14.609±3.003
Mean±SD	20.110±7.170	20.306±7.177	19.728±7.076	19.977±5.574	19.459±6.991

Table 14: Hip Flexion ROM (º)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	59.394±5.518	57.325±3.059	54.047±2.665	57.447±2.071	55.266±2.731
2	60.486±1.778	52.886±3.388	58.384±2.263	57.488±4.696	57.043±3.176
3	65.158±5.498	63.418±1.557	60.250±2.920	65.150±2.942	58.753±3.789
4	50.866±2.232	50.279±3.040	44.214±0.684	46.523±2.114	44.617±7.821
5	68.720±2.559	61.343±1.438	66.127±1.707	60.079±1.590	63.696±2.655
6	78.728±5.845	80.665±5.487	73.486±0.944	79.111±2.749	69.453±5.070
7	89.092±4.277	81.487±5.007	92.688±5.511	89.340±4.568	91.170±7.327
8	71.774±2.732	68.603±5.068	75.798±3.511	73.575±1.050	76.421±3.777
9	65.612±3.153	62.732±4.174	72.075±0.494	63.688±1.758	66.855±2.669
10	94.020±3.363	82.868±2.693	88.549±1.356	87.741±4.662	94.182±4.858
11	66.730±3.181	66.601±4.403	58.923±6.543	59.174±4.009	64.672±10.758
12	80.202±2.913	70.984±3.727	73.703±0.387	70.775±3.734	70.752±4.726
Mean±SD	70.898±12.575	66.599±10.873	68.187±14.046	67.508±12.985	67.740±14.294

Table 15: Trunk Flexion ROM (°)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-27.797±2.900	-31.987±3.739	-22.616±0.440	-22.332±2.776	-25.083±3.213
2	-37.669±8.987	-22.323±4.255	-34.133±1.777	-36.327±2.555	-34.434±4.938
3	-45.725±3.911	-45.668±1.399	-43.371±1.714	-51.357±0.320	-42.595±1.057
4	-20.761±1.640	-22.028±1.541	-22.085±1.161	-23.769±1.525	-30.143±2.828
5	-38.282±1.204	-31.380±1.383	-31.195±0.712	-32.345±1.164	-35.776±1.436
6	-18.735±3.319	-16.005±2.700	-21.665±1.357	-20.392±2.251	-23.565±2.666
7	-16.235±3.648	-12.907±1.199	-18.838±2.250	-17.598±2.763	-19.554±3.743
8	-47.051±1.948	-42.406±3.670	-34.710±1.572	-31.699±1.069	-32.008±1.194
9	-32.676±2.512	-29.267±1.478	-34.517±1.019	-27.912±2.454	-30.477±1.939
10	-35.446±4.383	-27.664±2.800	-31.559±0.521	-29.320±1.337	-36.716±3.966
11	-25.801±0.991	-24.029±1.490	-18.946±1.334	-20.404±1.186	-20.628±1.967
12	-32.259±1.283	-28.427±1.143	-25.990±1.059	-28.970±1.753	-28.779±1.782
Mean±SD	-31.536±10.015	-27.841±9.553	-28.302±7.730	-28.535±9.148	-29.980±6.909

Table 16: Ankle Plantarflexion Moment (Nm/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-0.965±0.153	-1.376±0.233	-1.683±0.360	-1.379±0.110	-1.184±0.303
2	-1.254±0.189	-1.660±0.165	-0.979±0.148	-0.940±0.279	-0.995±0.230
3	-1.323±0.161	-1.281±0.089	-1.504±0.084	-1.423±0.017	-1.399±0.063
4	-1.243±0.161	-1.219±0.128	-1.104±0.120	-1.121±0.175	-1.249±0.146
5	-0.839±0.071	-0.989±0.087	-0.980±0.149	-1.003±0.174	-1.201±0.135
6	-1.499±0.145	-1.166±0.061	-1.304±0.174	-1.596±0.111	-1.257±0.043
7	-1.266±0.060	-1.471±0.193	-1.306±0.065	-1.488±0.290	-0.986±0.286
8	-1.040±0.074	-0.900±0.082	-1.006±0.058	-0.925±0.095	-1.087±0.094
9	-1.426±0.131	-1.385±0.169	-1.352±0.114	-1.225±0.108	-1.495±0.104
10	-1.413±0.073	-1.226±0.153	-1.221±0.074	-1.391±0.180	-1.226±0.270
11	-1.226±0.105	-1.213±0.035	-1.548±0.032	-1.317±0.070	-1.742±0.065
12	-1.237±0.119	-1.070±0.158	-1.045±0.174	-1.202±0.236	-1.300±0.247
Mean±SD	-1.228±0.194	-1.246±0.210	-1.253±0.239	-1.251±0.219	-1.260±0.212

Table 17: Knee Extension Moment (Nm/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	2.174±0.131	2.111±0.073	2.269±0.080	2.428±0.079	2.341±0.148
2	2.889±0.057	2.966±0.056	2.869±0.226	2.637±0.169	2.903±0.232
3	2.422±0.134	2.309±0.079	2.004±0.045	2.101±0.139	2.065±0.095
4	2.471±0.176	2.529±0.087	2.658±0.078	2.596±0.145	2.683±0.093
5	2.587±0.205	2.441±0.096	2.598±0.124	2.663±0.106	2.566±0.337
6	2.236±0.052	2.443±0.152	2.335±0.032	2.435±0.109	2.544±0.116
7	2.679±0.161	2.776±0.181	2.633±0.119	2.667±0.145	2.684±0.177
8	2.437±0.099	2.466±0.197	2.731±0.073	2.504±0.077	2.466±0.193
9	3.028±0.155	2.882±0.109	2.783±0.150	2.727±0.280	2.940±0.239
10	2.561±0.172	2.487±0.207	2.423±0.255	2.417±0.091	2.596±0.211
11	3.316±0.292	3.392±0.373	3.313±0.103	3.800±0.105	3.619±0.059
12	2.284±0.231	2.314±0.056	2.313±0.277	2.323±0.297	2.378±0.166
Mean±SD	2.590±0.340	2.593±0.352	2.577±0.341	2.608±0.414	2.649±0.388

Table 18: Hip Extension Moment (Nm/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	1.346±0.283	0.923±0.176	1.160±0.241	1.133±0.140	1.019±0.197
2	0.984±0.054	0.904±0.143	1.071±0.133	1.303±0.140	1.277±0.246
3	0.789±0.104	0.957±0.126	0.775±0.081	0.989±0.147	0.872±0.195
4	0.604±0.079	0.861±0.121	0.639±0.191	0.953±0.163	0.915±0.046
5	1.000±0.073	1.121±0.174	0.991±0.065	1.000±0.192	1.040±0.267
6	0.584±0.050	1.004±0.089	0.723±0.085	0.823±0.075	0.638±0.077
7	0.461±0.022	0.557±0.132	0.638±0.097	0.647±0.051	0.825±0.181
8	1.389±0.138	1.500±0.223	1.387±0.029	1.572±0.102	1.358±0.127
9	0.974±0.097	0.910±0.139	1.023±0.049	1.141±0.193	0.957±0.131
10	0.917±0.046	1.118±0.180	0.806±0.042	0.962±0.095	1.467±0.389
11	0.706±0.095	0.767±0.230	0.491±0.142	0.909±0.094	0.780±0.052
12	0.872±0.177	0.946±0.272	1.051±0.063	1.014±0.067	0.718±0.094
Mean±SD	0.885±0.285	0.964±0.226	0.896±0.259	1.037±0.235	0.989±0.259

Table 19: Trunk Extension Moment (Nm/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	7.166±0.908	6.806±0.562	7.072±0.581	7.686±0.818	6.620±0.922
2	4.489±0.438	4.997±0.899	4.232±0.280	6.031±0.752	4.984±1.591
3	6.528±0.276	7.216±0.381	6.939±0.476	7.063±0.478	7.500±0.933
4	4.170±0.718	4.874±0.576	5.157±0.897	5.308±0.186	5.888±0.359
5	5.991±0.357	4.480±0.372	5.270±0.561	6.297±0.717	6.399±0.388
6	5.266±0.211	5.404±0.409	4.544±0.154	5.268±0.764	4.263±0.476
7	3.916±0.652	4.457±0.580	4.301±0.275	4.665±0.627	5.175±0.766
8	7.998±0.817	6.151±0.214	8.057±0.505	9.192±0.298	8.954±0.797
9	6.864±0.898	6.043±0.269	6.858±0.232	7.414±0.963	7.777±0.256
10	6.237±0.519	3.294±0.624	5.213±0.350	6.080±0.244	5.540±0.402
11	6.454±0.919	4.870±0.679	5.523±0.522	6.213±0.261	5.191±0.298
12	3.635±0.189	3.213±0.533	3.679±0.141	3.712±0.260	3.217±0.381
Mean±SD	5.726±1.409	5.150±1.250	5.570±1.362	6.244±1.465	5.959±1.596

Table 20: Ankle Plantarflexion Power (W/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-15.701±2.211	-20.418±2.675	-20.629±0.934	-20.792±1.123	-20.775±3.870
2	-14.858±2.167	-19.962±1.594	-12.605±1.343	-10.227±2.816	-13.928±0.222
3	-18.123±1.429	-18.751±1.537	-20.758±1.287	-19.205±0.405	-19.027±1.133
4	-17.228±1.498	-14.918±0.565	-15.864±0.252	-14.678±0.274	-19.927±2.247
5	-11.633±1.458	-12.454±1.639	-12.709±2.016	-12.879±0.860	-14.060±1.620
6	-21.055±1.572	-18.095±1.869	-16.790±0.655	-21.687±1.269	-16.969±0.422
7	-16.693±1.906	-19.267±1.012	-16.083±1.240	-16.393±1.180	-13.893±3.333
8	-12.534±0.754	-10.100±1.073	-11.615±0.320	-10.553±1.245	-12.750±0.991
9	-21.026±0.940	-21.489±3.733	-20.274±2.350	-17.171±2.121	-21.282±0.555
10	-19.390±1.143	-15.646±0.976	-15.837±0.994	-16.594±2.650	-15.814±2.834
11	-18.856±0.777	-17.480±0.341	-23.423±0.873	-19.714±1.033	-25.465±1.018
12	-18.920±1.142	-18.756±1.640	-18.727±2.187	-17.583±1.050	-20.812±2.333
Mean±SD	-17.168±3.039	-17.278±3.396	-17.110±3.722	-16.456±3.763	-17.892±3.921

Table 21: Knee Extension Power (W/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-28.345±2.720	-24.623±1.919	-29.491±1.612	-29.925±5.503	-29.749±2.879
2	-32.164±1.619	-26.922±2.639	-31.478±1.424	-29.506±2.525	-36.267±2.203
3	-23.722±2.290	-24.508±2.206	-22.999±0.741	-20.996±1.984	-23.375±1.621
4	-27.100±1.747	-31.400±0.979	-29.200±3.294	-29.231±2.593	-32.781±2.502
5	-33.159±1.728	-28.205±1.154	-33.163±0.838	-30.468±2.070	-33.126±0.665
6	-23.418±2.100	-27.776±3.400	-24.493±0.761	-26.006±0.943	-25.970±1.784
7	-32.006±1.728	-29.757±1.961	-27.991±1.610	-27.878±2.286	-30.053±1.790
8	-35.583±2.188	-35.490±2.013	-38.580±0.502	-6.775±0.997	-35.828±2.420
9	-43.441±2.605	-41.840±3.733	-42.965±1.623	-38.338±3.007	-44.417±0.578
10	-30.999±0.912	-26.592±2.373	-30.402±1.820	-27.832±2.918	-30.330±1.826
11	-50.055±4.260	-52.323±3.508	-42.564±2.003	-56.154±1.309	-47.268±1.201
12	-24.710±4.280	-27.316±1.021	-30.253±3.397	-29.544±2.718	-25.726±1.905
Mean±SD	-32.058±8.004	-31.396±8.217	-31.965±6.396	-29.388±11.265	-32.907±7.223

Table 22: Hip Extension Power (W/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-16.428±1.546	-11.149±2.834	-12.269±0.456	-12.143±3.253	-10.516±1.543
2	-10.028±1.332	-8.865±0.382	-11.714±1.399	-14.735±2.125	-13.936±0.970
3	-9.965±1.631	-11.604±2.573	-14.275±2.865	-13.298±0.822	-17.390±0.859
4	-10.307±2.743	-7.709±0.870	-8.736±0.680	-8.920±0.663	-11.276±1.564
5	-14.311±1.261	-14.365±2.920	-12.709±0.941	-11.499±0.592	-13.328±2.768
6	-12.180±1.414	-16.103±2.120	-16.771±1.903	-13.875±0.511	-14.213±1.817
7	-13.946±3.925	-11.536±0.732	-13.179±1.657	-11.984±1.196	-11.745±1.130
8	-10.767±0.801	-14.918±1.437	-13.651±1.045	-18.493±5.260	-15.394±1.474
9	-25.992±2.327	-27.148±5.165	-23.508±0.642	-26.739±4.388	-25.508±0.684
10	-13.781±0.309	-12.425±1.505	-11.025±3.500	-12.441±0.252	-13.289±1.520
11	-29.450±1.204	-27.535±2.325	-22.998±1.225	-26.995±1.544	-18.780±1.435
12	-19.613±2.741	-20.010±1.977	-24.578±3.331	-24.877±2.591	-15.335±2.362
Mean±SD	-15.564±6.397	-15.281±6.511	-15.451±5.334	-16.333±6.377	-15.059±4.075

Table 23: Ankle Eccentric Work (J/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-0.584±0.148	-1.061±0.445	-0.877±0.310	-0.779±0.153	-0.863±0.161
2	-0.525±0.234	-969±0.341	-0.472±0.147	-0.446±0.251	-0.458±0.162
3	-0.859±0.088	-0.810±0.059	-0.897±0.068	-0.931±0.185	-0.756±0.122
4	-0.791±0.079	-0.696±0.079	-0.900±0.290	-0.679±0.102	-0.758±0.099
5	-0.431±0.109	-0.534±0.072	-0.542±0.087	-0.639±0.299	-0.672±0.340
6	-0.871±0.210	-0.733±0.113	-0.703±0.190	-0.894±0.064	-0.810±0.110
7	-0.707±0.038	-0.721±0.136	-0.646±0.108	-0.895±0.276	-0.563±0.205
8	-0.489±0.121	-0.559±0.298	-0.473±0.090	-0.432±0.051	-0.529±0.070
9	-0.932±0.161	-0.945±0.123	-0.921±0.178	-0.725±0.353	-0.905±0.132
10	-0.766±0.129	-0.753±0.096	-0.816±0.135	-0.662±0.315	-0.976±0.819
11	-0.748±0.220	-0.601±0.154	-0.963±0.110	-0.879±0.139	-1.052±0.160
12	-0.826±0.181	-0.811±0.098	-0.774±0.116	-0.979±0.320	-0.898±0.220
Mean±SD	-0.711±0.165	-0.766±0.164	-0.749±0.178	-0.745±0.182	-0.770±0.185

Table 24: Knee Eccentric Work (J/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-2.304±0.309	-1.915±0.451	-1.852±0.457	-2.225±0.354	-2.226±0.127
2	-2.897±0.447	-2.780±0.620	-2.837±0.116	-2.935±0.484	-3.150±0.266
3	-2.221±0.181	-2.216±0.167	-2.061±0.339	-1.993±0.056	-1.958±0.177
4	-2.248±0.176	-2.401±0.086	-2.177±0.177	-2.345±0.316	-2.692±0.155
5	-2.629±0.342	-2.335±0.117	-2.519±0.171	-2.151±0.617	-2.302±0.375
6	-2.098±0.169	-2.205±0.159	-2.220±0.286	-2.126±0.102	-2.142±0.096
7	-2.318±0.099	-2.279±0.185	-2.160±0.140	-2.002±0.437	-2.432±0.199
8	-2.428±0.268	-2.251±0.570	-2.535±0.175	-2.581±0.066	-2.484±0.095
9	-2.814±0.137	-2.810±0.484	-3.023±0.228	-2.585±0.344	-2.862±0.143
10	-2.720±0.214	-2.452±0.048	-2.325±0.411	-2.693±0.457	-2.350±0.669
11	-3.220±0.332	-3.504±0.656	-2.961±0.177	-3.310±0.164	-3.301±0.273
12	-2.422±0.404	-2.481±0.235	-2.331±0.315	-2.429±0.257	-2.570±0.229
Mean±SD	-2.527±0.33	-2.469±0.40	-2.417±0.36	-2.448±0.39	-2.539±0.40

Table 25: Hip Eccentric Work (J/Kg)

Subject	Regular surface	Turf surface	Turf + foam shock pad	Turf + low density shock pad	Turf + high density shock pad
1	-0.844±0.277	-0.945±0.326	-0.818±0.276	-0.860±0.343	-0.797±0.089
2	-1.693±0.440	-1.368±0.740	-1.570±0.177	-1.765±0.466	-1.800±0.380
3	-1.116±0.130	-1.151±0.113	-1.165±0.190	-1.365±0.225	-1.281±0.132
4	-0.793±0.176	-0.689±0.086	-0.652±0.177	-0.833±0.316	-0.792±0.155
5	-1.158±0.194	-1.025±0.151	-0.982±0.071	-1.086±0.266	-1.246±0.123
6	-1.526±0.142	-1.528±0.291	-1.515±0.199	-1.447±0.263	-1.453±0.237
7	-1.346±0.290	-1.357±0.259	-1.430±0.195	-1.566±0.352	-1.641±0.396
8	-1.250±0.230	-1.188±0.167	-1.294±0.075	-1.431±0.235	-1.331±0.075
9	-1.636±0.348	-1.766±0.435	-1.873±0.251	-1.714±0.290	-1.706±0.092
10	-2.203±0.206	-1.456±0.322	-1.819±0.343	-1.771±0.235	-2.296±0.444
11	-1.833±0.345	-1.628±0.437	-1.543±0.179	-1.551±0.298	-1.634±0.205
12	-2.695±0.568	-2.038±0.280	-2.111±0.402	-2.037±0.300	-1.807±0.127
Mean±SD	-1.508±0.554	-1.345±0.374	-1.398±0.438	-1.452±0.370	-1.482±0.430

VITA

Hang Qu (Frankie) was born in Hefei, China, to the parents of Ronghong Zhao and Changlong Qu. She grew up and attended primary school through high school in Hefei city. After she graduated from Hefei No.8 High School, she was admitted to Shanghai University of Sport in 2010 and received her Bachelor of Science degree in Kinesiology with a concentration in Biomechanics in 2014. To pursue a Master degree, she was admitted by the University of Tennessee, Knoxville and was offered a graduate teaching assistantship in 2014. After graduating with a concentration in Biomechanics/Sports Medicine in 2016, she will head to the University of Oregon for a PhD in Human Physiology.