EFFECT OF DROP JUMPING AND KNEE VALGUS ON FEMORAL CARTILAGE THICKNESS

by

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Abstract

Background: The incidence of anterior cruciate ligament (ACL) ruptures is 30-78 per 100,000 people a year. While the main treatment for an ACL rupture is surgery, only 61- 89% of athletes return to sports after surgery. Females are at a 3-5X higher risk for ACL injuries than males. In a prospective study, knee abduction angle, also known as valgus angle, of women who later suffered an ACL injury was ~8° greater vs women who did not tear their ACLs. When landing with high knee valgus angles, it is theorized that the knee joint compresses the lateral femoral cartilage (FC) more vs. the medial FC. Due to this unequal distribution of compression across the knee joint, the lateral FC is hypothesized to be thinner compared to the medial FC after experiencing jumping and landing loads experienced in sports.

Purpose: The purpose is to investigate the effect of frontal plane landing technique on FCT in healthy, recreationally active females performing drop jumping activities.

Methods: After completing the informed consent process, all subjects had both knees imaged using ultrasound and then performed two series of 10 drop jumping activities from a 30-cm box. Ultrasound images were be taken before and after each drop jump series. Knee FCT were measured in Horos software. Based on recorded videos, subjects were placed into one of two groups based on whether they naturally landed in knee valgus vs those who did not.

Results: All 11 subjects were considered to use a valgus landing technique due to the position of their knee to ankle at ground impact as defined by the landing error scoring system. There was no significant difference in any of the compartments throughout the jumps except for the left

knee's lateral femoral cartilage, which decreased by an estimated .104mm or 5.89% (p=0.032). The observed power for the left lateral FCT was 0.658.

Significance: With appropriately powered future studies, should the results show that females landing with more knee valgus experience greater lateral FC changes in thickness after the drop jumping tasks, this would support the need for further research investigating 1) whether or not landing technique is indeed a risk factor for FC injury and 2) whether changing landing technique to reduce knee valgus would result in relatively more equal cartilage deformations comparing medial vs lateral FC. Because of the low observed power of the current study, results should be interpreted with caution.

Background

ACL Injuries are a Problem

ACL injuries are a problem in recreationally active individuals. The incidence of ACL ruptures is between 30 to 78 per 100,000 people a year. The main treatment for an ACL rupture is reconstructive surgery with a hamstring tendon graft or a patellar tendon graft (Thaunat, 2019). Only 61% to 89% of athletes were able to return to sports after their ACL reconstruction (Gans, 2018). Hootman (2007) and colleagues analyzed 16 years of National Collegiate Athletic Association injury surveillance data. The data reported that the sports with the highest rates of ACL ruptures were women's soccer, women's gymnastics, women's basketball, and men's football. One of the main concerns after surgery is the chance of injuring the ACL reconstructed knee again.

Second ACL injuries are the short-term burden after reconstruction. The ACL injury incidence rate after reconstruction is 15 times greater in subjects on both contralateral and ipsilateral knees (Paterno, 2012). Recurrent ACL injuries may occur due to traumatic reinjuries, graft failure, or surgical errors. The estimated re-rupture rate after ACL reconstruction is between 1% and 11%. Ahmed et al. looked at 200 patients who had primary reconstruction for an ACL rupture and watched them over 20 years to see the outcome of their surgeries. They found that 36 sustained another rupture and 29 needed a revision surgery. ACL injuries do not just lead to immediate burdens, but also to ones that the patient will endure over the course of their life.

Long-term Burden of ACL Injury

After an ACL injury, the individual's health is affected for the rest of their life. Lohmander and colleagues (2004) looked at 67 women who suffered an ACL injury 12 years before their study. The average age of the women in the study was 31 years old, therefore, the average age at injury was 19 years old. 75% of female soccer players reported having issues with quality of life due to their knee 12 years after an ACL rupture. At the 12-year mark, 51% of the soccer players had fulfilled the criterion for radiographic knee osteoarthritis. The development of osteoarthritis is the long-term burden after reconstruction.

Osteoarthritis is a major illness that damages and affects the health of the articular cartilage (Bedewi, 2020). The chance of developing post-traumatic osteoarthritis after ACL reconstruction increased over time. At the 5-, 10-, and 20-year mark post-surgery, the chances of developing post-traumatic osteoarthritis was 11.3%, 20.6%, and 51.6% (Cinque, 2018). The average age for women to tear their ACL is 33.9 but is made of two peaks- one in their teens and one in their forties- resulting in a higher average (Nicholls, 2018). In comparison to healthy individuals, only around 9.29% of the individuals in the United States will have symptomatic osteoarthritis by the time they are 60 years old (Losina, 2013). Individuals who have an ACL injury are not just put through a physical burden, but an economical one too.

ACL injuries cause an economical burden, especially when including the development of osteoarthritis. Mather et al. (2013) looked at the societal and economic impact of ACL tears to show the substantial cost associated with the injury. The prices collected were from data in 2012, therefore, the data is likely underestimating the economic burden of current day. The average total cost for an ACL reconstruction in the United States was $27,452 in 2012. However, if the surgery occurred between the ages of 20-25, the long-term cost jumps to the mid-$40,000 range. Society is also affected by patients' ACL reconstructions and pays around $38,121 over the person's life. The development of osteoarthritis costs annually around $2.78 billion in 2012 for patients who chose the ACL reconstruction route. The identification of risk factors for ACL injuries is critically important to prevent the occurrence of long-term economic and health burdens associated with this devastating injury.

ACL Injury Risk Factors

The main risk factor for experiencing an ACL injury is being female. Female athletes are at a 3-5 times higher risk for ACL injuries than their male counterparts (Lohmander, 2007). This difference is suspected to be due to a difference in the quadriceps angle- Q angle. The Q angle is an anatomical measurement that is formed by a line from the anterior superior iliac spine to the center of the patella and then a second line from the center of the patella to the tibial tuberosity. The Q angle in females is 3.4 to 4.9 degrees greater than in males when standing and 2.7 to 5.8 degrees greater when in supine. This anatomical difference is hypothesized by researchers to place a greater lateral pull of the quadriceps at the knee in females, which may place the ACL at risk (Sutton, 2013).

Knee abduction, also known as valgus, angle of women who suffer ACL injuries is greater than the angle in uninjured women (Hewett, 2005). Hewett and colleagues prospectively studied 205 female athletes in sports related to ACL injuries such as soccer and basketball. The athletes performed three drop jumps from a 31 cm tall box with 25 markers on specific anatomical locations. Through the use of a motion capture system, the athletes knee abduction angles were measured at initial and peak contact when landing from the box. The athletes were then tracked through 2 fall and 1 winter sports season. The female athletes that had an ACL injury had a 8.4 degree greater knee abduction angle at initial contact and a 7.6 degree greater angle at peak contact. Valgus loading might not only be a risk factor for ACL injury but could also be a risk factor for poor tibiofemoral cartilage health. When loading in valgus, the knee joint compresses the lateral femoral cartilage and places the medial femoral cartilage under tension. Due to the compression, the lateral condyle is hypothesized to be smaller and overall, less healthy.

Effect of Knee Loading on Cartilage Health

Femoral articular cartilage is an elastic connective tissue found on the distal end of the femur. The cartilage has two main functions for the human body: provide lubricant for smoother movement and absorb the shock of weight-bearing movement.

Acute deformation of the tibiofemoral cartilage is normal and occurs diurnally- over the course of the day. A research study measured healthy subject's femoral cartilage thickness using ultrasound at 8-9 am and again at 4-5 pm on the same day to quantify diurnal change. The women’s average right lateral femoral cartilage changed from 1.83 mm to 1.65 mm, which is a 9.9% decrease. The women’s average right medial femoral cartilage changed from 1.77 mm to 1.62 mm, which is an 8.5% decrease. When these two measurements are combined with the intercondylar area deformation, the right femoral articular cartilage decreases diurnally overall around 8% in women (Kilic, 2015). This acute change was noticed in healthy participants who just went about activities of daily living such as walking.

There is significantly more acute cartilage deformation in individuals who walk and run compared to those who are at rest. Each participant in this study (Harkey, 2017) performed all three conditions: walking, running, control/rest. The walking group went from a pre-FCT of 2.23 mm to a post-FCT of 2.08 mm, which was a 6.72% decrease. The running group went from a pre-FCT of 2.23 mm to a post-FCT of 2.04 mm, which was a 8.93% decrease. The control/rest group went from a pre-FCT of 2.21 mm to a post-FCT of 2.28 mm, which was a 3.39% increase. There was no major difference between the walking and running group, which starts the question on load response.

The previous Harkey study led to a follow-up about the response and recovery of femoral articular cartilage after walking and drop-landing. This study (Harkey, 2018) was done to see the changes from a low (walking) and high (drop-landing) stress load on femoral cartilage thickness. The drop landing took the high loading conditions to the extreme with 120 drop landings from a 62 cm platform. The study showed that the walking and drop-landings both had impacts of cartilage deformation. The immediate overall femoral cartilage deformation was -7.11% after walking and -10.05% after drop-landing. The control group's average overall cartilage only immediately deformed by -0.95%. The drop-landing group took longer than expected to recover and still showed -2.57% deformation after 45 minutes. The walking group was only at 0.07% deformation after 45 minutes. One area that research does not cover is whether valgus landing technique might alter medial vs lateral cartilage thickness. The compression of the lateral cartilage during valgus landing leads one to suspect that it will deform at a higher rate than the medial cartilage due to the knee angle at landing.

Purpose and Hypothesis

The females who land in knee valgus are expected to have a smaller lateral femoral cartilage thickness than those who land normally. A smaller lateral femoral cartilage thickness is expected due to a greater compression at impact because of the landing angle on the knee joint. This repeated compression would lead the female to be susceptible to developing osteoarthritis. The purpose of the project is to investigate the effect of clinically relevant loads and landing techniques on femoral cartilage thickness in healthy, recreationally active females. If a smaller lateral femoral cartilage thickness is shown, then the next step in the research would be to study the participants long-term to see if valgus landing and relevant loads are risk factors for osteoarthritis.

Methods

In November of 2022, an IRB study (UMCIRB 22-001815) was approved for this project to allow the use of human participants. There were 11 total subjects collected for the project. All subjects in the study are female, between the ages 18-25, recreationally active, have no known history of knee injuries or surgeries, and have no current injuries to the lower extremity that would prevent them from performing common jumping and landing activities. All the data collection for this project occurred in the Performance Optimization Lab of the Ward Sports Medicine Building.

When subjects came into the lab, there were pre-image tasks they had to complete. All subjects completed the informed consent process and then completed 2 surveys: Knee Injury and Osteoarthritis Outcome Score (KOOS) and Tegner Activity Score Sheet (Tegner). The KOOS quantifies the health of the subject's knee in the past week. The Tegner quantifies the activity level of the subject on a 1-10 scale. A 1 on the Tegner means the subject lives a sedentary lifestyle and a 10 means the subject is a professional athlete.

The participants were then taken to the ultrasound machine in the lab to obtain control images of both knees. Subjects laid supine on an examination table and performed a hip bridge to align the legs for proper imaging. The subjects then laid down their legs and would flex their left knee to roughly 140-degrees, which was checked with a goniometer (Figure 1). 2 images of the left knee were taken superior to the patella and then the leg was repositioned, which was followed by 2 more images. The images provide a clear view of all compartments of the femoral articular cartilage: medial condyle, intercondylar notch, lateral condyle (Figure 1). The reposition occurred to create a control, since no weight bearing happened between pictures means the images should be the same. The subject then turned 180-degrees on the table to allow the ultrasound user to not have to move the machine around the table. The same procedure was taken for the control images of the right leg.

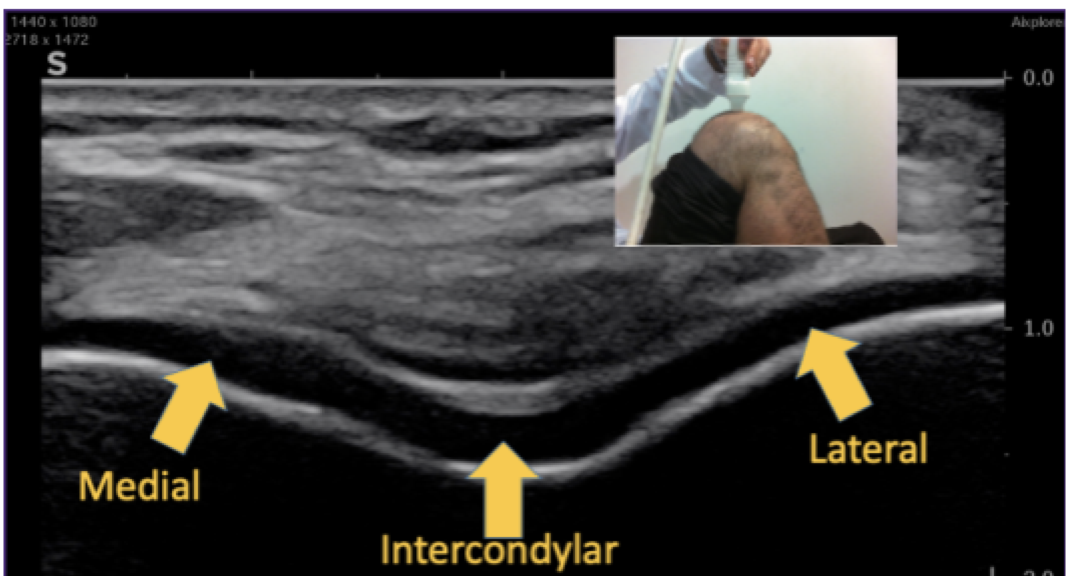

Figure 1. Pre-analysis ultrasound image of femoral cartilage and location of probe.

At the completion of the control images, the subjects were taken to a 30-cm platform for the drop jumps. Video cameras were set up in the frontal and sagittal plane of where the subject would land to catch the landing technique used. A software, called Noraxon, was used to quantify the force applied during landing on the force plate and to collect the videos in the sagittal plane. A research team member would talk the subjects through the process required for the drop jumps and would demonstrate the jump for the participants. The participants were not allowed to have a practice jump due to the extra impact on their cartilage that would cause, and the study is testing their “normal” landing technique. The subjects would then perform 10 drop jumps.

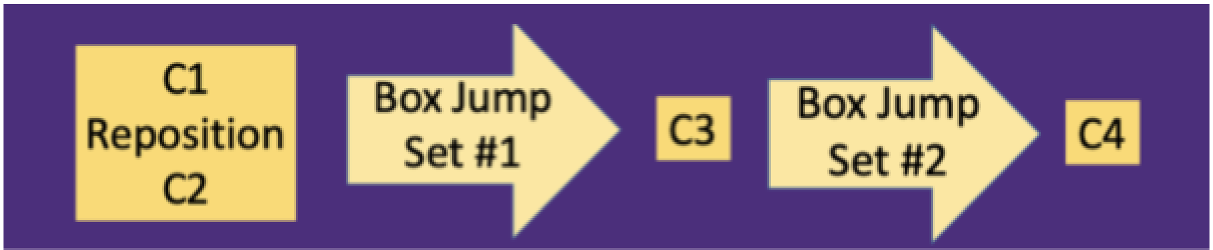

Figure 2. Experimental Procedures: C1-C4 represent 4 ultrasound imaging timepoints: Two control conditions & two conditions post 10 drop jumps from a 30cm box. C1 & C2 averaged due to high similarity (ICCs ~.93-0.99).

After set #1 of box jumps, the subjects were taken back to the ultrasound machine to obtain 2 images of both knees. No reposition occurred during C3 and C4 due to not needing an extra control, which is already incorporated in taking multiple images. The same procedure as C1 and C2 was followed to ensure accuracy and reliability between images. The subjects would then repeat the previous jump and image procedure for set #2 of box jumps and C4 (Figure 2). The images from C4 would conclude the subject's time in the lab and the total time for the procedure is around 45 minutes.

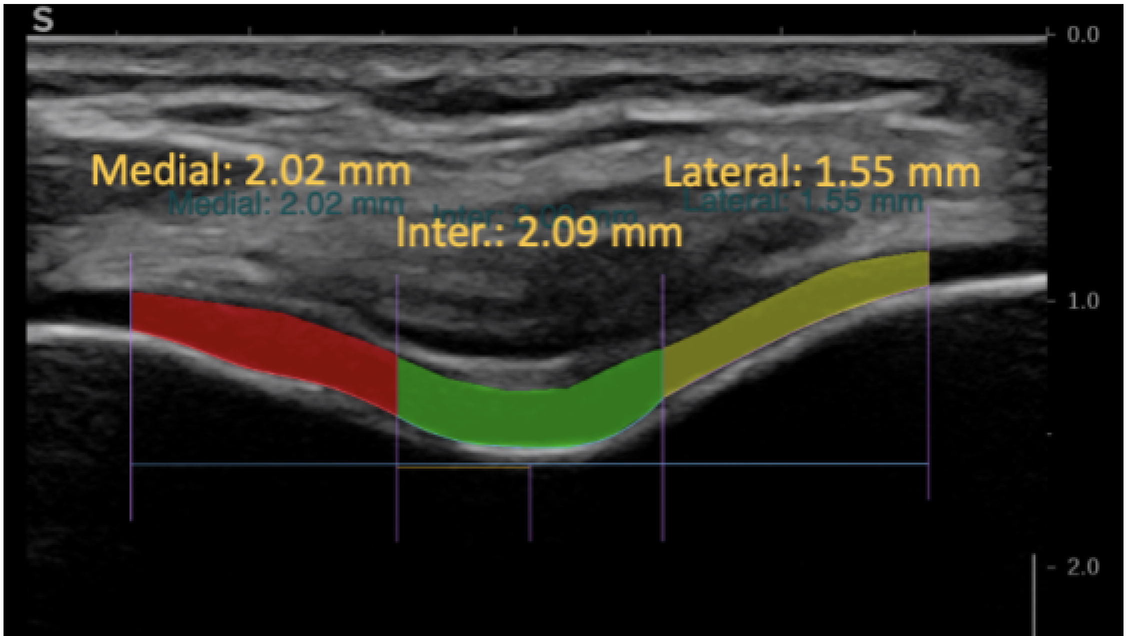

Figure 3. Representative ultrasound image analysis of femoral cartilage thickness across 3 femoral cartilage regions.

After the completion of data collection, the images from the ultrasound machine were uploaded into an analysis software, Horos. A scaffolding was created to separate the 3 compartments: medial, intercondylar, lateral (Figure 3). The scaffolding split each compartment into 1-cm boxes to evenly distribute the cartilage. A separate spline was drawn on the femoral side of the cartilage for each compartment. An area was then created for each of the compartments. The area was divided by the spline to create the femoral articular cartilage thickness. The first image of each condition was analyzed for both limbs, therefore, 8 images were used for analysis. The collection of additional images was collected in case of a need for additional reliability analysis or if there were visible issues with the primary image.

Results

Height	63.64±2.91
Weight	125.38±14.97
Tegner	5.73±.90

Table 1. Participant characteristics, mean ± SD, 11 total subjects.

The 11 subjects had an average Tegner score of 5.73 (Table 1), which means most worked out at least 3-5 times per week. Our subjects ranged from individuals who jogged twice a week to some that play intramural volleyball 5 times a week. Once the surveys were completed, the subjects were taken to a scale to obtain their height and weight. The average height of our subjects was 63.64 inches, and the average weight was 125.38 pounds (Table 1).

The frontal and sagittal plane videos from the drop jumps were analyzed after by a separate sub-investigator. This separation was in place to minimize bias when knowing the landing technique of the subjects while analyzing the ultrasound images. The landing error scoring system (LESS) tool was used as a tool to determine if the subjects in knee valgus or not. All 11 subjects were considered to use a valgus landing technique due to the position of their knee to big toe at ground impact. The sub-investigator in charge of LESS compared three similar landing videos from the 20-drop jump trials to determine the landing technique used by the participant. Since all the subjects in the study landed in valgus based on the LESS, we could not compare those who landed in valgus to those who did not. Therefore, all analyses focused on the effect of drop jumping on femoral cartilage thickness in individuals who land in knee valgus.

Left Knee Analysis					Right Knee Analysis			
Compartment	Trial	FCT mean	ST Dev		Compartment	Trial	FCT Mean	ST Dev
Medial	C	1.91	0.23		Medial	C	1.92	0.27
Medial	C3	1.89	0.21		Medial	C3	1.91	0.28
Medial	C4	1.90	0.26		Medial	C4	1.90	0.29
Intercondylar	C	2.07	0.30		Intercondylar	C	2.05	0.27
Intercondylar	C3	2.05	0.29		Intercondylar	C3	2.11	0.28
Intercondylar	C4	2.04	0.26		Intercondylar	C4	2.12	0.30
Lateral*	C	1.77	0.21		Lateral	C	1.79	0.29
Lateral	C3	1.74	0.31		Lateral	C3	1.79	0.24
Lateral*	C4	1.66	0.19		Lateral	C4	1.80	0.24

Table 2. FCT data, mean (mm) and standard deviation. *= significant difference

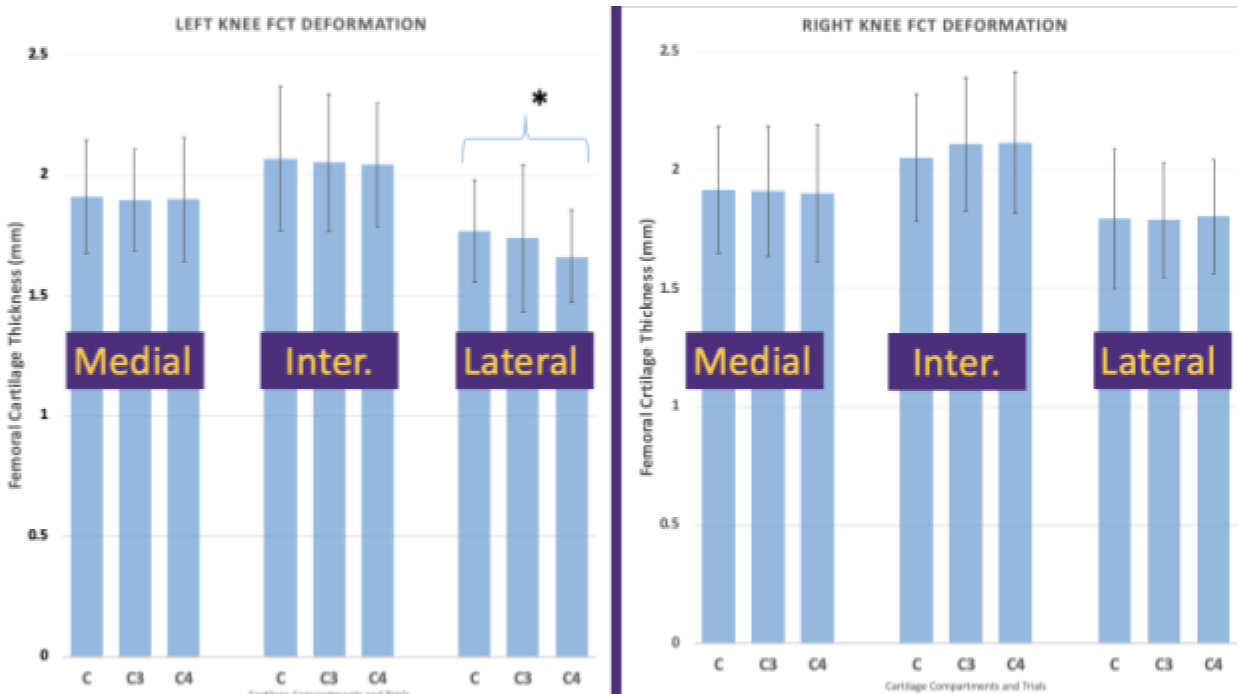

Figure 4. Mean FCT. Error bars represent standard deviation. Percentages represent deformation. * = significant difference.

The data collected in Table 2 was then inputted into Statistical Package for the Social Sciences (SPSS). There were 6 separate ANOVAs ran on the image analysis data from Horos to produce a report on the three compartments of the cartilage for both limbs. The C1 and C2 image timepoints were averaged together to create the "control" defined as (C) in Table 2. The averaging of C1 and C2 was performed due to a high similarity between the two conditions with ICCS between 0.93-0.99. C3 and C4 in Figure 3 still represented the trials after set #1 and set #2 of drop jumps respectively. There was no significant difference in any of the compartments throughout the drop jumps except for the left knee's lateral femoral cartilage, which decreased thickness by an average of 0.104mm (Standard error= 0.024) or 5.89% (p=0.032) when comparing the control condition C to C4. The significant difference of the left knee's lateral femoral cartilage is shown in Figure 4 with a distinction from an asterisk. The observed power for the left lateral FCT was 0.66. The observed power for the other 5 analyses were between .062-.657.

Discussion

Overall Findings

All 11 subjects were considered to use a valgus landing technique due to the position of their knee to big toe at ground impact based on LESS. There was no significant difference in any of the compartments throughout the drop jumps except for the left knee's lateral femoral cartilage, which decreased thickness by an average of 0.104mm (Standard error= 0.024) or 5.89% (p=0.032). The findings support the hypothesis that landing in valgus would cause a decrease in the thickness of the lateral condyle due to a greater compression at ground impact.

Why were cartilage changes in the left knee but not the right?

This study was only able to produce a decrease in thickness for the left knee's lateral condyle and not for the right limb. Other studies have not investigated inter-limb cartilage thickness variation directly, however, the diurnal study by Kilic (2015) was able to see a decrease in thickness for both limbs. In the diurnal study, the left limb lateral femoral cartilage decreased by 8.1% and the right limb lateral femoral cartilage decreased by 9.84%. Therefore, not seeing a significant difference in this study's right limb raises the question about asymmetrical landing and leg dominance. Diurnal changes in both limbs make sense due to the equal nature of impact when moving throughout the day. In this study, the repeated activity of landing could create an uneven impact on one leg over the other. It is possible that subjects could land on one leg more than another subconsciously by choosing their "dominant" leg. Future research should investigate the possibility of asymmetrical landing impact to see if this data is apparent in a wider population.

Current results compared to the literature

With current literature, the findings of this project portray that deformation might not be a linear path. Using 20-drop jumps from a 30-cm box, this study was able to produce an average decrease of 5.89% in the left knee's lateral femoral cartilage. This percent of decrease is like that seen from diurnal and higher load studies. In the diurnal study by Kilic (2015), there was a 8.1% decrease in the left knee's lateral femoral cartilage for the female subjects. In the higher-load study by Harkey (2018), there was a 6.8% decrease in the left knee's lateral femoral cartilage in male and female subjects combined.

The higher-load study from Harkey (2018) had subjects perform 120 drop jumps from a 60-cm box. The varying loads across all studies and in comparison, to the current study all produced similar decreases in thickness, which raise the question even more regarding landing technique being a predominant factor in determining the extent of cartilage thickness changes in comparison to the magnitude of the load itself. The diurnal and higher-load studies did not investigate landing technique, which is suspected to play a part in landing impact and changes in thickness. The results produced by the clinically relevant load in the current study and higher load studies are also not to be taken as negative towards the human body. The diurnal study shows that the cartilage naturally thins throughout the day and rejuvenates when subjects are resting.

The studies use varying demographics in relation to their subjects and means the comparison of results with caution. The diurnal study used “everyday men and women” with an average age around 30-32 and a BMI around 24-26. The higher-load study used men and women around the same age, 21-22, and Tegner score, 5.91, as this present study. The diurnal and higher-load study were able to see decreases in thickness in the medial and intercondylar area, which brings in the question of increased load in relation to wider impact on cartilage thickness. The decreased thickness seen in this study might be the start of the impact seen in the other studies, but we only 20 total repetitions of drop jumps from 30cm high where the other studies used many more repetitions to produce their results.

Limitations

The main limitation related to this research project has to do with the amount of data collected. Only 11 subjects were analyzed for this project, and this restriction of data was apparent with low observed powers. The observed power for the left lateral femoral cartilage thickness was 0.658, which is lower than the 0.8 which is a commonly accepted statistical power. The interpretation of the results should be taken with caution until the statistical power is higher. The observed power is low due to not having enough data to analyze and the effect size difference between conditions being moderate. The recommendation to alter this would be increasing the sample size by collecting 20 total subjects.

The other limitations have to do with the restrictions of the LESS in relation to the degrees of knee valgus and all subjects landing with the same technique. The LESS was used as a “checkbox” to determine if the subjects landed in knee valgus or not. The scoring system is used to classify valgus, but the tool was never intended to measure the severity of valgus. The subjects who seem to have “knock knees” and those with a slight knee valgus are both just considered valgus landers. The main recommendation to fix the LESS issue would be to use motion capture along with it to collect data on the degrees and severity of valgus. All 11 subjects in the project land in knee valgus, which prevents comparison of normal landing technique and valgus. The main recommendation to overcome this issue is to get a higher sample pool and to possibly introduce male subjects. Females are more likely to land in knee valgus than their male counterparts, and allowing men to enter the study would allow this issue to diminish but also potentially add a confounding factor of sex as the biomechanical literature is clear in that sex differences in human movement exist in the population targeted in the current study.

Conclusion

The results partially support the hypothesis that landing in knee valgus deforms the lateral femoral articular cartilage. While results show significant deformation is present in the left knee lateral femoral cartilage, we speculate that this is only shown in one leg due to possible asymmetrical ground impact forces on the lower limbs. The current analysis is statistically underpowered so results for this study should be cautioned. Analysis of a larger sample of subjects (n=20) will support or refute these findings.

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