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Abstract #1

The Relationship of Anterior Cruciate Ligament Volume and T2* Relaxation Times to Anterior Knee Laxity

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Context: Greater anterior knee laxity (AKL) has been reported as a prospective anterior cruciate ligament (ACL) injury risk factor and could be indicative of a weaker ligament. Given that ACL morphometry and structural composition have the potential to influence ligamentous strength, understanding the combined contributions of morphometry and structural composition is warranted.

Objective: To determine the extent of normalized ACL volume and T2* relaxation times to predict AKL in active males and females.

Design: Cross-sectional study.

Setting: Controlled laboratory.

Patients or Other Participants: Twenty active healthy males (1.80 ± 0.07 m, 84.0 ± 10.9 kg, 23.3 ± 2.9 years) and twenty active healthy females (1.67 ± 0.08 m, 61.9 ± 7.2 kg, 21.3 ± 2.3 years) were recruited.

Intervention(s): ACL volume was obtained with T2 weighted magnetic resonance (MR) scans. ACL structural composition was assessed by T2* relaxation times. AKL was measured via a commercial knee arthrometer.

Main Outcome Measure(s): The ACL was manually segmented from each sagittal image to calculate ACL volume. Normalized ACL volume was ACL volume divided by height and weight. T2* relaxation times were calculated using the signal intensity (SI) relationship from all twelve echo times of the T2* relaxation imaging sequence. AKL was defined as the anterior displacement of the tibia relative to the femur at 130 N loads. Stepwise linear regressions with normalized ACL volume and T2* relaxation times as independent variables and AKL as the dependent variable were performed.

Results: In males, mean normalized ACL volume = 37.1 ± 7.8 $mm^3/(kg*m)^{-1}$; mean T2* = 19.1 ± 2.5 ms; mean AKL = 6.3 ± 1.9 mm. In females, mean normalized ACL volume = 32.6 ± 8.9 $mm^3/(kg*m)^{-1}$; mean T2* = 18.5 ± 2.2 ms; mean AKL = 8.1 ± 2.7 mm. In males, smaller normalized ACL volume combined with higher T2* relaxation times significantly predicted greater AKL ($R^2 = 0.39$, $P = .015$; $R^2\Delta = 24\%$, $P\Delta = .020$). In females, normalized ACL volume was significantly associated with AKL ($R^2 = 0.43$, $P = .002$), but T2* relaxation times could not explain additional variance ($R^2\Delta = 0\%$, $P\Delta = .928$).

Conclusions: Smaller normalized ACL volume combined with greater T2* relaxation times predicted larger AKL in active males. The findings that ACL morphometry and structural composition features individually and collectively contribute AKL in males enhance the knowledge on how to define the weaker ACL and how these intrinsic factors impact ligamentous function in males. Future work should continue to investigate other non-invasive measurements representing structural composition in females and how chronic loading may influence ACL size and structural composition.

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Abstract #2

Relationships Between Anterior Cruciate Ligament Structural Properties and Inter-Subject Variability in Anteroposterior Knee Laxity Across the Menstrual Cycle and During Exercise in Physically Active Females

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Context: Females vary substantially in the magnitude of change in anteroposterior knee laxity (APL) across the menstrual cycle and during exercise. Whether structural properties of the anterior cruciate ligament (ACL) influence the magnitude of laxity change, or whether menstrual cycle and exercise related laxity changes are related to one another is unknown.

Objective: To initially examine relationships between ACL structural properties, APL changes during exercise and APL changes across the menstrual cycle in physically active females. We hypothesized a smaller and structurally weaker ligament would be associated with greater APL changes, and that females with greater APL changes during the menstrual cycle would have greater APL changes during exercise.

Design: Descriptive, longitudinal study.

Setting: Research laboratory.

Patients or Other Participants: 8 eumenorrheic females who were physically active ≥4 days/week (21.1 ± 3.1 years, 162.6 ± 9.8 cm, 62.8 ± 7.3 kg).

Intervention(s): APL was acquired each morning (prior to activity) across one complete menstrual cycle, and before and after a 27 minute intermittent exercise protocol on days of the menstrual cycle when knee laxity was expected near nadir (EX1; 3–5 days post onset of menses) and when elevated in the early to mid-luteal phase (EX2). Magnetic resonance scans (3T) of the knee were obtained on the same leg (dominant stance limb).

Main Outcome Measure(s): APL (mm) was obtained from –89 to 130 N using the KT2000 knee arthrometer. Absolute change in APL across the menstrual cycle (APLΔ_MC), and during exercise (APLΔ_EX1; APLΔ_EX2) were computed. ACL volumes (ACL_V = mm^3) were obtained from the T2 weighted images. T2* relaxation times (T2* = ms) were measured with gradient echo data sets (greater T2* indicative of less organized extracellular matrix). Relationships were examined via bivariate Pearson correlations.

Results: Baseline APL increased 0.6 ± 0.5 mm from EX1 to EX2 (P = .006), but there was no difference in APL changes during EX1 vs. EX2 (0.3 ± 0.7 mm; P = .216). ACL_V (954.8 ± 165.6 mm^3) was moderately and positively correlated with APLΔ_MC (3.2 ± 0.9 mm)($r = 0.60$; $P = .059$), APLΔ_EX1 (0.8 ± 0.4 mm)($r = .49$; $P = .108$), and APLΔ_EX2 (1.1 ± 0.9 mm)($r = .39$; $P = .169$), but did not reach significance due to small sample size. Similar moderate, but negative correlations were observed between T2*(21.8 ± 4.5 ms) and APLΔ_MC ($r = –0.62$; $P = .051$), APLΔ_EX1 ($r = –0.56$; $P = .145$), and APLΔ_EX2 ($r = –0.42$; $P = .150$). Strong positive associations were observed between APLΔ_MC and both APLΔ_EX1 ($r = 0.89$; $P = .003$) and APLΔ_EX2 ($r = 0.68$; $P = .032$). APLΔ_EX1 and APLΔ_EX2 were also positively correlated ($r = .79$; $P = .019$).

Conclusions: Females who had greater APL changes across the menstrual cycle also had greater APL changes during both exercise sessions. Thus, APL changes during a single exercise bout may provide insights into APL changes across the menstrual cycle (which currently requires daily sampling to determine). Contrary to our hypothesis, smaller APL changes were associated with a smaller and less organized ACL. Replication of these findings in a larger sample is needed to confirm these associations. Further research is needed to clarify associations between ACL structural properties and the magnitude of these acute laxity changes.

Abstract #3

Simulated Landing Neural Correlates of Anterior Cruciate Ligament Injury Risk Biomechanics

Criss CR†, Grooms DR†, Diekfuss JA*, Ellis JD*‡, Thomas S*, DiCesare C*, Bonnette S*, Yuan W*‡, Dudley J*, Schneider DK*§, Berz K*, Riley M‡, Myer GD*‡: †Ohio University, Athens; *Cincinnati Children's Hospital Medical Center, OH; ‡University of Cincinnati College of Medicine, OH; §Riverside Methodist Hospital, Columbus, OH

Context: Anterior cruciate ligament (ACL) injuries predominantly occur via non-contact mechanisms, secondary to motor coordination errors that result in knee abduction that in turn increases load on the ligament. However, the nervous system processing that underlies high injury risk motor coordination errors are unknown, limiting current intervention efforts.

Objective: The purpose of this study was to determine brain neural activity differences between individuals with high injury risk mechanics (elevated knee abduction moment during landing) and those at low risk during a simulated landing task.

Design: Case-control study.

Patient or Other Participants: Thirty female high school soccer players (16.10 ± 0.87 years, 165.10 ± 4.64 cm, 63.43 ± 8.80 kg) were evaluated with 3D biomechanics during a standardized drop vertical jump from a 30 cm box for group determination: 9 fit the high-risk classification (≥21.74 Nm knee abduction moment) and 11 fit low-risk classification (≤10.6 Nm knee abduction moment). Five participants in each group were pair-wise matched on age, sport, body mass index and leg dominance and completed the neuroimaging protocol.

Intervention(s): A fMRI motor task was performed to simulate landing (bilateral, loaded ankle-knee-hip movement, similar to a leg press) and engage brain activity for "landing" neuromuscular control using a 3 Tesla MR scanner with a 32-channel, phased array head coil. Participants were asked to engage in metronome timed bilateral ankle-knee-hip flexion/extension while secured to a leg press apparatus that provided ~20% body mass resistance.

Main Outcome Measure(s): Brain activity was contrasted between the two groups with an a priori significance level of $P <$ .05 (multiple comparisons corrected) mixed effects analysis; Correction was performed with the Gaussian random field cluster approach with the threshold set at $z > 3.1$.

Results: Those with high injury risk biomechanics had increased neural activity in two clusters: 1) the primary motor, sensory and premotor cortices (peak z-score: 5.32, $P =$ .04, 339 voxels) and 2) the lingual gyrus, intracalcarine cortex, and precuneus (peak z-score: 4.94, $P <$ .01, 3219 voxels). There were no activation decreases in the high-risk group relative to the low-risk group.

Conclusions: The increased sensorimotor neural activity in the high-risk group during simulated landing may provoke a more rapid saturation of motor coordination capacity during high-demand sports activity leading to the breakdown in neuromuscular control that results in high knee abduction moments. Similarly, the high-risk group's relative increased activity in regions that integrate sensory, visual-spatial, and motor planning information may impair their ability to maintain a safe knee position during more dynamic maneuvers with environmental navigation and\or high visual processing demand. These data may indicate that high-risk knee injury biomechanics is, in part, a manifestation of maladapted spatial awareness and attention to knee motor control that contributes to increased abduction loading during more demanding activity.

Abstract #4

Sensorimotor Neural Correlates of Anterior Cruciate Ligament Injury Risk Biomechanics

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Context: The most common anterior cruciate ligament (ACL) injury mechanism is a non-contact motor coordination error that results in excessive knee abduction loading (medial collapse) during athletic movements. Preventing motor coordination errors requires optimal neural integration of joint position (proprioception) and force control, but the neural mechanisms that propagate injury risk coordination are not well understood.

Objective: The purpose of this study was to determine the brain activity differences for knee position and force control between athletes with high injury risk mechanics relative to those with low injury risk landing biomechanics.

Design: Case-control study.

Patients or Other Participants: Thirty female high school soccer players (16.10 ± 0.87 years, 165.10 ± 4.64 cm, 63.43 ± 8.80 kg) were evaluated with 3D biomechanics during a standardized drop vertical jump from a 30 cm box for group determination: 9 fit the high-risk classification (≥21.74 Nm knee abduction moment) and 11 fit low-risk (≤10.6 Nm knee abduction moment). Five participants in each group were pair-wise matched on age, sport, body mass index and leg dominance and completed neuroimaging.

Intervention(s): Participants completed two fMRI motor tasks 1) a unilateral open chain knee positioning task and 2) a unilateral closed chain knee force attenuation task. MR scanning was conducted on a 3 Tesla scanner using a 32-channel, phased array head coil. Participants were asked to engage in a metronome-timed unilateral knee flexion/extension task followed by a unilateral leg press (~20% body mass resistance) ankle-knee-hip flexion/extension task.

Main Outcome Measure(s): Brain activity was contrasted between the two groups with an a priori significance level of $P <$ .05 mixed effects analysis, Gaussian random field cluster corrected for multiple comparisons and the threshold at $z > 3.1$.

Results: Athletes with high injury risk biomechanics had decreased neural activity in one cluster for knee positioning (cingulate gyrus and parietal cortex; peak z-score: 4.14, $P \leq$ .01, 788 voxels) and increased brain activity for knee force control in two clusters: 1) frontal cortex (peak z-score: 4.71, $P <$ .01, 1602 voxels) and 2) posterior cingulate and precuneus (peak z-score: 4.43, $P <$ .01, 725 voxels). There was no increased activation for knee positioning and no decreased activation for knee force control in the high-risk group relative to the low-risk group. The decreased sensorimotor brain activity for knee positioning was associated with the increased cognitive-sensory-motor activity for knee force control ($r = -0.87$, $P =$ .01).

Conclusions: The failure of the high injury risk group to adequately engage neural attentional and sensory resources to control knee position may have resulted in increased demand on cognitive-sensory-motor resources to control knee loading. This increased neural activity in the high-risk group to control knee force may lead to a more rapid breakdown in neuromuscular coordination resulting in high knee abduction moments.

Abstract #5

Alterations in Knee Sensorimotor Brain Functional Connectivity Contributes to Anterior Cruciate Liga-

ment Injury in Male High-School Football Players: A Prospective Neuroimaging Analysis

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Context: Research indicates that differences in central nervous system function may contribute to musculoskeletal injury.

Objective: The purpose of this report was to prospectively examine differences in brain functional connectivity in male high school athletes who subsequently suffered an anterior cruciate ligament (ACL) injury relative to their non-injured peers.

Design: Prospective longitudinal case-control.

Setting: Functional magnetic resonance imaging (fMRI) facility and athletic field.

Patients or Other Participants: Sixty-two male high school football players were evaluated using fMRI prior to their competitive season. Three of these athletes later experienced an ACL injury (16.33 ± 0.58 years, 181 ± 10.97 cm, 107.93 ± 20.42 kg) during football activities. All three ACL injuries were confirmed via clinical MRI and occurred with no direct blows to the knee as verified by video evidence. Each ACL-injured participant was matched to four healthy teammates based on age, height, weight, and year in school (controls; total $n = 12$; 16.83 ± 0.39 years, 181.75 ± 4.54 cm, 102.97 ± 13.69 kg).

Intervention(s): MR scanning was conducted on a 3 Tesla scanner using a 32-channel, phased array head coil. Participants were asked to remain motionless and look at a crosshair for 10 minutes to evaluate functional brain connectivity at rest.

Main Outcome Measure(s): Twenty-five knee-motor regions of interest (ROIs) were created to prospectively identify differences in functional connectivity between the two groups. Functional connectivity was computed as the Fisher-transformed Pearson correlation coefficients between the average residual blood oxygen level-dependent signal time series of pairs of ROIs. Between-subject ANOVAs and independent *t* tests were used to determine significant connectivity differences between the two groups using a false discovery rate correction for multiple comparisons.

Results: The ANOVA revealed significant connectivity differences between the ACL-injured and control participants for the left secondary sensory cortex and all other target ROIs, $F(3, 11) = 10.46$, $P = .037$. Post-hoc independent *t* tests revealed significantly lower connectivity between the left secondary sensory cortex and the left supplementary motor area $t(13) = -4.19$, $P = .025$, right pre-motor cortex $t(13) = -3.76$, $P = .026$, right supplementary motor area $t(13) = -3.58$, $P = .026$, left primary sensory cortex $t(13) = -3.42$, $P = .026$, left primary sensorimotor cortex $t(13) = -3.32$, $P = .026$, and left primary motor cortex $t(13) = -2.91$, $P = .048$ in the ACL-injured when compared to the controls.

Conclusions: Our data indicate a potential sensorimotor disruption for male football players at baseline who subsequently experience an ACL injury; this abnormal connectivity could serve as a potential neural biomarker to guide ACL prevention methods. Specifically, practitioners could consider integrating motor learning principles, biofeedback technologies, vibration tools, and/or stroboscopic training to potentially enhance connectivity through the re-weighting of sensorimotor neural processes.

Abstract #6

A Preliminary Prospective Analysis of Electrocortical Signatures Underlying Anterior Cruciate Ligament Injury

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Context: Anterior cruciate ligament (ACL) injuries are commonly linked to motor coordination errors which occur, in part, due to the failure of the central nervous system (CNS) in maintaining joint stability when an athlete is navigating through a dynamic environment. Individuals who previously injured their ACL demonstrate altered electrocortical brain activity during a lower-limb force production task and a knee-joint-position task.

Objective: The purpose of this study was to prospectively examine differences in electrocortical activity between female high school athletes who subsequently suffered an ACL injury and their non-injured peers. We hypothesized that differences in CNS sensorimotor activity predispose an athlete to maladaptive sensorimotor strategies that increase risk for ACL injury.

Design: Prospective longitudinal case-control.

Setting: Laboratory and athletic field.

Patients or Other Participants: Seventy-two female high school soccer players were evaluated using resting-state electroencephalography (EEG) prior to their competitive season. Two of these athletes later experienced a non-contact ACL injury (16.0 ± 0 years, 169.0 ± 2.8 cm, 60.1 ± 8.3 kg); both injuries were confirmed with a clinical MRI. Each ACL-injured participant was matched to four teammates who did not go on to sustain an ACL injury based on school, age, height, weight, and year in school (controls; total $n = 8$, 15.9 ± 0.8 years, 164.0 ± 4.9 cm, 58.3 ± 7.6 kg).

Intervention(s): Participants wore a 64 electrode EEG cap and were asked to sit quietly with their eyes closed for two minutes while EEG data were acquired.

Main Outcome Measure(s): Power spectral density analysis was performed on each electrode across the Theta and Alpha-2 frequency bands. Considering the limited sample size, means, standard deviations, and effect sizes (Cohen's *d*) are reported to compare overall spectral power between the groups for each waveform.

Results: Results revealed that the ACL-injured group had lower power in the Theta frequency band ($M = 8.34$, $SD = 2.70$) compared to controls ($M = 12.51$, $SD = 2.74$), $d = 1.53$. Lower power was also observed in the Alpha-2 frequency band for the ACL-injured participants ($M = -5.07$, $SD = 0.98$) compared to the control group ($M = -0.29$, $SD = 0.84$), $d = 5.24$.

Conclusions: Theta frequency bands in EEG signals are believed to originate within attention-related brain regions, and alpha-2 frequency bands are strongly related to sensory function. These preliminary data provide novel evidence that deficient attentional and sensorimotor electrocortical functioning may contribute to the risk of future ACL injuries. While traditional methods of accessing ACL injury risk rely mainly on biomechanical profiles, identifying neural correlates of ACL injury risk may increase responsiveness to current prevention strategies and reduce risk factors associated with ACL injuries.

Abstract #7

Effects of Altered Attachment Sites of the Semitendinosus Following Anterior Cruciate Ligament Reconstruction

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Context: After harvest for anterior cruciate ligament (ACL) reconstruction, the semitendinosus (ST) tendon regenerates well, but often at different insertion sites on the semimembranosus and/or sartorius muscles. It is not known how changes in insertion sites could affect knee joint loads, and these altered knee loads could potentially increase risk of osteoarthritis.

Objective: To evaluate the change in ST moment arm and the resultant knee moment following altered ST insertion site.

Design: Simulation study using OpenSim. Two previously published models were used.

Setting: The first model included tibiofemoral contact locations, 18 body segments, and 92 muscle-tendon actuators that included force-length-velocity properties. This investigated how the insertion of the ST affected the muscle moment arm. The second model included 12 body segments and 92 muscle-tendon actuators. Running data at a speed of 5 m/s was included with this model and was used to investigate how the insertion of the ST affects the knee joint moments.

Patients or Other Participants: The experimental kinematics and kinetics included to drive the second model was from the same previously published work and is from male runners (29 ± 5 yr, 1.77 ± 0.04 m, and 70.9 ± 7.0 kg).

Intervention(s): Insertion sites of the ST were moved to the same attachment sites as the sartorius (SI) and semimembranosus (SMI) of the right knee of the model while the left remained unaltered.

Main Outcome Measure(s): The moment arms of the unaltered ST, semimembranosus, sartorius, and altered ST at various knee angles were calculated. Computed muscle control in the second model was rerun with altered moment arm data to examine the changes in torque contributions of the knee musculature.

Results: The moment arm of the ST decreased as a result of the change in insertion site (native = 4.74 cm, SMI = 4.00 cm, SI = 2.41 cm). While running at 5 m/s, there was no meaningful difference in total knee moment between the native and altered attachment sites. However, there were small decreases in peak flexor moment produced by the ST (native = 13.58 Nm, SMI = 9.13 Nm, SI = 5.09 Nm) while the peak flexor moment produced by the gastrocnemius increased substantially in both of the altered conditions (native = 4.80 Nm, SMI = 27.55 Nm, SI = 25.87 Nm).

Conclusions: The decrease in hamstring flexor moment and increase in gastrocnemius flexor moment could potentially increase risk of reinjury to the ACL because the hamstrings are protective of the ACL while the gastrocnemius stresses it. Even if compensation is in other muscles, these changes could increase risk of OA by altering the loading pattern in the knee. Further research is needed to confirm these findings in experimental subjects and to determine how altered moment arms are impacting contact stress in the joint.

Abstract #8

Comparison of Drop Jumping in Individuals Following Anterior Cruciate Ligament Reconstruction With Quadriceps Tendon Versus Patellar Tendon Autografts

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Context: Altered biomechanics (eg, ground reaction forces) during drop jumps have been demonstrated in individuals following anterior cruciate ligament (ACL) reconstruction (ACLR), however less is known regarding differences in graft types, particularly involving the quadriceps tendon (QT) autograft. The QT autograft is becoming increasingly popular, as it offers a unique soft-tissue option with larger and stronger anatomical area from which to harvest the graft.

Objective: The purpose of this study is to compare vertical ground reaction forces (vGRFs) during a drop jump in individuals with QT versus bone-patellar tendon-bone (BPTB) autografts. The hypothesis was that individuals with QT autografts would demonstrate more symmetrical vGRFs during landing and push-off phases.

Design: Cohort study.

Setting: Research laboratory.

Patients or Other Participants: Twenty-five active individuals with a history of primary, unilateral ACLR with QT (n = 14) or BPTB (n = 11) autografts (24 ± 8 years; 17 males; 10 ± 5 months post-ACLR; Tegner Activity Level = 7 ± 2; IKDC = 80 ± 11).

Intervention(s): The independent variable is autograft group. Following practice trials, participants of both groups completed three trials of drop jumping off a 20 cm box onto an instrumented treadmill with two separate embedded force plates. Participants were instructed to keep their hands on hips while they dropped off the box, landed with each foot on separate force plates, and then completed a maximal vertical jump. Kinetic data were collected at 1000 Hz. Peak vGRFs for each limb during landing phase of drop jump and push-off phase of rebound jump were normalized to body weight and averaged for analyses. Limb symmetry indices of vGRFs were expressed as a percentage of the surgical limb over the nonsurgical limb.

Main Outcome Measure(s): The dependent variables are limb symmetry indices during landing and push-off phases of drop jump. Given the small sample size, nonparametric Wilcoxon rank-sum tests were used to compare differences in limb symmetry indices between QT and BPTB autograft groups.

Results: The QT and BPTB autograft groups were similar on demographic variables (age = 25.9 ± 9.8 vs. 20.7 ± 5.3, *P* = .297; mass = 83.2 ± 16.2 vs. 75.2 ± 13.9, *P* = .208; BMI = 25.0 ± 4.5 vs. 23.8 ± 3.7, *P* = .381; months since surgery = 10.8 ± 5.8 vs. 9.0 ± 4.8, *P* = .389) Contrary to the hypothesis, there were no significant differences between QT and BPTB autografts for limb symmetry (%) of vGRF during landing phase (78.8 ± 20.0 vs. 78.5 ± 22.5, *P* = .870) or push-off phase (89.3 ± 10.9 vs. 83.7 ± 12.7, *P* = .352).

Conclusions: Individuals with QT autografts demonstrate similar limb symmetry in vGRFs during drop jumping compared to individuals with the more-standard BPTB autograft. Clinicians can feel more confident about outcomes following ACLR with QT autografts, but should note that deficits in vGRFs of the surgical limb were present in both autograft groups.

Abstract #9

Effects of Sex and Body Mass Index on Vertical Ground Reaction Force Throughout the Stance Phase of Walking in Individuals With Anterior Cruciate Ligament Reconstruction

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Context: Female sex and higher body mass index (BMI) are predominant risk factors for post-traumatic knee osteoarthritis (PTOA) development. Optimizing mechanical loading during walking in those with anterior cruciate ligament reconstruction (ACLR) may decrease the risk of PTOA; yet it remains unclear how BMI and sex influence mechanical loading during walking.

Objective: Determine the effect of sex and BMI on vertical ground reaction force (vGRF) during walking in individuals with ACLR.

Design: Retrospective cohort-comparison.

Setting: Laboratory.

Patients or Other Participants: We recruited 173 individuals with ACLR ≥ 6 months prior to testing and assigned participants into four groups based on sex and BMI (normal-weight = BMI ≤ 25 kg/m^2, overweight = BMI > 25 kg/m^2). Groups included overweight males (n = 32, 22.4 ± 4.2 years old, 28.0 ± 3.1 BMI), normal-weight males (n = 29, 22.6 ± 4.6 years old, 22.8 ± 1.6 BMI), overweight females (n = 32, 20.2 ± 2.2 years old, 28.4 ± 3.6 BMI), and normal-weight females (n = 80, 20.8 ± 3.1 years old, 22.2 ± 1.6 BMI)

Intervention(s): Participants walked barefoot at self-selected speed over two embedded force plates.

Main Outcome Measure(s): vGRF was time-normalized to 100% of stance phase and normalized to body weight (BW). A 2 × 2 functional analysis of variance was used to determine differences between sex and BMI. Mean between-group differences and corresponding 95% confidence intervals (CI) were plotted across stance; between-group differences existed whenever these CI excluded zero.

Results: An interaction existed between sex and BMI from 46–55% of stance and 66% to the end of stance. In overweight females compared to overweight males, vGRF was greater during the first 34% of stance (6% BW) and lesser from 85–91% (2% BW). In normal-weight females compared to normal-weight males, vGRF was greater in the first 36% of stance (7% BW) and from 66% to the end of stance (7% BW), but lesser during 41–61% of stance (–4% BW). In normal-weight compared to overweight males, vGRF was greater in the first 10% of stance (4%BW) but lesser from 29–39% (–2% BW) and from 60% to the end of stance (–3% BW). In normal-weight compared to overweight females, vGRF was greater during the first 24% of stance (5% BW) and from 67% to the end of stance (5% BW) and lesser during mid-stance from 36–54% (–2% BW).

Conclusions: While overweight females demonstrate lesser vGRF at both peaks and greater vGRF at mid-stance compared to normal-weight females, the relationship was opposite between overweight and normal-weight males. While overweight females demonstrate greater vGRF compared to overweight males only in the initial part of stance, normal-weight females demonstrate greater vGRF at both peaks and lesser vGRF at mid-stance compared to normal males. Both sex and BMI should be considered when developing interventions to optimize loading following ACLR.

Abstract #10

Influence of Body Mass Index and Anterior Cruciate Ligament Reconstruction on Gait Biomechanics

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Context: Obesity and anterior cruciate ligament reconstruction (ACLR) independently contribute to knee osteoarthritis (OA) via alterations in gait biomechanics. However, the interaction between these factors is unclear.

Objective: To examine the influence of body mass index (BMI) and ACLR on gait biomechanics.

Design: Cross-sectional study.

Setting: Research Laboratory.

Patients or Other Participants: 151 adults with and without primary unilateral ACLR were recruited for this study and further classified by BMI as normal weight (BMI: 18.5 to 24.9) or overweight/obese (BMI: 25.0 to 40.0). There were 19 normal weight adults with ACLR (Males = 4, Females = 16, Age = 21.5 ± 2.3 years, BMI = 22.3 ± 1.7 kg/m^2) and 15 overweight/obese with ACLR (Males = 6, Females = 8, Age = 23.2 ± 3.3 years, BMI = 30.0 ± 4.1 kg/m^2. There were 64 normal weight adults without ACLR (Males = 27, Females = 37, Age = 21.8 ± 2.4 years, BMI = 21.7 ± 1.7 kg/m^2) and 53 overweight/obese adults without ACLR (Males = 27, Females = 26, Age = 23.0 ± 3.4 years, BMI = 32.7 ± 3.9 kg/m^2).

Intervention(s): Participants completed 5 walking trials at a self-selected speed in standardized footwear along a 10 m runway and struck consecutive force plates while 3 dimensional kinematics (240 Hz) and kinetics (2400 Hz) were recorded.

Main Outcome Measure(s): Outcome variables were extracted from the first 50% of stance and included the peak knee flexion angle (KFA) and external moment (KFM), peak knee adduction angle (KAA) and external moment (KAM), and peak vertical ground reaction force (vGRF) and loading rate (vLR). GRF and joint moment data were normalized to body weight and a product of body weight and height, respectively. Data from the involved limb (ACLR participants) and from the dominant limb (non-ACLR participants) were used in analysis and compared using a 2 (BMI group: normal weight and overweight/obese) by 2 (ACLR history: ACLR and non ACLR) analysis of co-variance (co-variates: self-selected speed and sex) ($\alpha = .05$).

Results: There was a significant interaction between BMI group and ACLR history for peak KAM ($F_{1,125} = 3.83$, $P = .04$) and peak vGRF ($F_{1,125} = 4.08$, $P = .04$). There was a higher peak KAM in overweight/obese participants with ACLR compared to overweight/obese participants without ACLR [0.032 (95% CI: 0.026, 0.038) versus 0.021 (95% CI: 0.018, 0.024) BW × Height]. Peak vGRF was lower in normal weight participants with ACLR compared to normal weight participants without ACLR [1.10 (95% CI: 1.08, 1.12) vs. 1.15 (95% CI: 1.13, 1.17) BW]. Conversely, peak vGRF was higher in overweight/obese participants with ACLR compared to overweight/obese participants without ACLR [1.15 (95% CI: 1.11, 1.19) vs. 1.11 (95% CI: 1.09, 1.13) BW]. The interaction between BMI group and ACLR history was not significant for KFM ($P = .51$), KFA ($P = .50$), KAA ($P = .85$), or vLR ($P = .48$).

Conclusions: BMI and ACLR uniquely influence gait biomechanics. A higher KAM and vGRF contribute to elevated medial compartment joint loading, which may contribute to knee OA progression. These findings suggest that high BMI should be considered when designing gait retraining protocols for individuals with a history of ACLR.

Abstract #11

Gait Biomechanics Differ in Weak Individuals Compared to Strong Individuals Following Anterior Cruciate Ligament Reconstruction

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Context: While quadriceps strength is hypothesized to decrease the risk of posttraumatic osteoarthritis (PTOA) onset following anterior cruciate ligament reconstruction (ACLR), it remains unclear if gait biomechanics differ in stronger compared to weaker individuals.

Objective: Determine if vertical ground reaction force (vGRF), knee flexion angle (KFA) and internal knee extension moment (KEM) differ between strong and weak ACLR individuals throughout the stance phase of gait.

Design: Comparison-control.

Setting: Research laboratory.

Patients or Other Participants: Individuals who received unilateral ACLR ≥12 months prior to testing were dichotomized into strong (n = 31, 36% female, 22.4 ± 3.4 years old, 24.7 ± 3.8 body mass index [BMI]) and weak groups (n = 116, 75% female, 20.9 ± 3.2 years old, 24.4 ± 3.6 BMI).

Intervention(s): Isometric quadriceps strength was collected at 90° of knee flexion using an isokinetic dynamometer. Peak torque values were normalized to body mass. Based on previous work, individuals demonstrating ≥3.0 Nm/kg were considered strong.

Main Outcome Measure(s): Three-dimensional biomechanics were collected as participants walked barefoot at a self-selected speed over two force plates. Biomechanical data were time normalized to 100% of the stance phase of gait (ie, heel strike to toe-off). vGRF was normalized to body weight (BW). Inverse dynamics were used to calculate sagittal plane moments, which were normalized to the product of body weight (BW) and height (m). Pairwise comparison functions were calculated for each outcome to identify between-group differences for each percentile of stance. Mean between-group differences (ie, between strong and weak groups), and corresponding 95% confidence intervals (CI), were plotted for the entire waveform across the stance phase of gait; between-group differences existed whenever these CI did not cross zero.

Results: vGRF was greater in weak participants for the first 22% of stance (average difference of 6.2% BW) and lesser in weak participants between 36–43% of stance (1.4% BW). KFA was

greater (ie, more flexion) in strong participants between 6–62% of stance (average of 2.3°) and lesser between 68–79% of stance (average of 1.0°). KEM was greater in strong participants between 7–62% of stance (average of 0.007 BW*height).

Conclusions: Stronger individuals demonstrated greater KFM and knee flexion excursion during the majority of the first half of stance, which may be a beneficial movement strategy for attenuating energy around the knee following ACLR. Greater vGRF in the first 22% of stance may be associated with an impaired ability to control loading of the extremity shortly following heel strike in weaker individuals. Overall, these data suggest individuals with the capacity to generate knee extension torque ≥3.0 Nm/kg exhibit different biomechanical gait profiles, which may allow for better energy attenuation compared to weaker individuals following ACLR. Future research should determine if individuals who meet the ≥ 3.0 Nm/kg cutoff are less likely to develop PTOA following ACLR.

Abstract #12

Trunk and Pelvic Kinematic Differences Between Anterior Cruciate Ligament Reconstructed Athletes and Healthy Controls During a Single Leg Hop Landing: A Temporal Approach

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Context: The trunk and pelvis account for 60% of body mass and may be substantial contributors to movement deficits in anterior cruciate ligament reconstructed (ACL-R) individuals. Understanding how the trunk and pelvis move in ACL-R individuals is critical for the development of more effective rehabilitation strategies.

Objective: The aim of this study was to compare 3D trunk and pelvic kinematics throughout the landing phase of a single leg hop landing between athletes who have undergone ACL-R and healthy controls.

Design: Cross-sectional study.

Setting: Controlled, laboratory setting.

Patients or Other Participants: Twenty-four recreational college-aged athletes participated in this study (12 ACL-R 7F/5M; 20.8 ± 2.1 years; 1.68 ± 0.08 m; 70.1 ± 6.7 kg); 12 healthy gender/activity matched controls (23.9 ± 1.4 years; 1.72 ± 0.08 m; 69.6 ± 11.5 kg). ACL-R participants (10 patella tendon; 1 hamstring tendon; 1 allograft) were an average of 32 months from surgery (range 9–58 months). Both groups were recreationally active at a Tegner Activity Level of seven.

Intervention(s): An 8 camera motion analysis system sampling at 240 Hz collected kinematic data for the trunk and pelvis for five trials of a single leg hop for distance landing. Participants' hands were placed on their hips and jumped distance for the hop was 80% of participants' maximum single leg hop distance. The reconstructed limb was of interest in the ACL-R group and the limb was matched in the control group.

Main Outcome Measure(s): 3D trunk and pelvic kinematics were collected along with hip strength data. Single leg hop distance and absolute limb symmetry index (LSI) calculated for both groups. Statistical parametric mapping (SPM) t-tests were used to compare trunk and pelvis time series curves between groups.

Results: ACL-R participants displayed less lateral trunk lean throughout the entire landing phase (mean lateral lean: 6.8° vs 8.7°, $P < .001$) along with increased pelvis contralateral tilt from 0–93% of the landing phase (mean pelvic tilt: 3.3° vs 6.6°, $P = .009$). From 0–10%, ACL-R participants displayed similar ipsilateral pelvic rotation (mean pelvic rotation: 7.5° vs 7.7°), but displayed less ipsilateral pelvic rotation from 11–100% of the landing phase (5.1° vs 4.1°, $P = .005$). Movement patterns related to trunk flexion and rotation and pelvic tilt were similar between groups.

Conclusions: Individuals following ACL reconstruction appear to demonstrate less lateral trunk flexion and more contralateral pelvic drop during the landing phase of a single leg hop for distance. In addition, these individuals demonstrated decreased pelvic movement pattern variability within the transverse plane. Limited movement variability has been suggested as a cause of injury and as a possible link to subsequent ACL injury and post-traumatic osteoarthritis.

Abstract #13

Quadriceps Muscle Structure Following Anterior Cruciate Ligament Reconstruction: Influence on Muscle Weakness

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Context: Changes in muscle structure contribute to persistent muscle weakness, which is common following anterior cruciate ligament reconstruction (ACLR). Traditional magnetic resonance imaging (MRI) techniques have shown gross reductions in quadriceps volume in ACLR patients but are unable to detect underlying tissue changes. Diffusion tensor imaging (DTI) allows for noninvasive assessment of subclinical muscle structure without using invasive tissue biopsies. Understanding the relationship between DTI derived values and clinical evaluations of muscle strength allows for improved identification of muscle dysfunction and may allow for personalized rehabilitation programs.

Objective: Assess the association between muscle strength, muscle volume, DTI derived fractional anisotropy (FA) and fiber angle of the quadriceps in patients with a history of ACLR.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Eleven individuals with unilateral ACLR (age: 21.6 ± 1.8 y; height: 1.67 ± 0.07 m; mass: 66.2 ± 12.2 kg; months post-surgery: 69.4 ± 22.4).

Intervention(s): Quadriceps strength, MRI and DTI were performed bilaterally during a single session.

Main Outcome Measure(s): Quadriceps strength was assessed via maximal voluntary isometric contractions (MVIC) normalized to body mass at 90° of knee flexion. For MRI and DTI, patients were positioned supine/feet-first in a 3 Tesla Siemens Prisma MRI. Muscle volume was quantified by manual annotation of the vastus medialis (VM) using T1-weighted images. DTI data were registered to the segmented T1 images using DTITools for mathematica (github.com\mfroeling\DTITools), and average FA and muscle fiber angles were calculated. FA describes the anisotropy of the diffusion signal which is sensitive to fiber size changes. Fiber angles were defined as the angle of muscle fiber tracts with respect to the femur. Paired samples *t* tests were conducted to identify differences in MVIC, muscle volume, FA, and fiber angle between limbs. Spearman correlations and subsequent hierarchical linear regression were performed between structural variables and MVIC for the injured limb.

Results: The injured limb demonstrated reduced MVIC (2.95 ± 0.56 Nm/kg, $P = .03$) and VM volume (313.1 ± 151.8 cm^3, $P = .02$), and increased fiber angle (28.5 ± 5.3°, $P < .001$) compared to the uninjured limb (MVIC: 3.27 ± 0.70 Nm/kg; VM volume: 329.2 ± 151.4 cm^3; angle: 17.6 ± 5.4°). No differences were observed in FA (injured: 0.191 ± 0.009; uninjured: 0.192 ± 0.010, $P = .91$). Increases in VM volume ($\rho = 0.65$, $P = .02$) and fiber angle ($\rho = 0.794$, $P = .01$), and decreases in FA ($\rho = -0.66$, $P = .03$) of the injured limb were significantly correlated with greater MVIC. The regression predicted 47.6% of the variance in MVIC ($R^2 = 0.47$, $P = .05$; $\text{MVIC} = 0.05_{\text{angle}} + 5.80_{\text{FA}} + 0.001_{\text{Volume}} + 0.10$). Fiber angle alone accounted for 42% ($R^2 = 0.42$, $P = .05$) of variance in MVIC; FA and volume accounted for insignificant increases of 0.1% ($\Delta R^2 = 0.001$, $P = .91$) and 5.1% ($\Delta R^2 = 0.05$, $P = .24$) respectively.

Conclusions: The injured limb of ACLR patients demonstrated reduced muscle volume and increased fiber angles compared to their uninjured side. Increased fiber angle was the strongest predictor of muscle weakness, indicating that clinical function is altered due to underlying structural changes in the muscle, and can be quantified via DTI. This information can help guide future evidence-based clinical trials to target these modifiable factors of muscle function.

Abstract #14

Investigating the Neural-Morphologic Link on Quadriceps Strength After Anterior Cruciate Ligament Reconstruction

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Context: Neural inhibition and muscle atrophy are two of the most common sources of physical dysfunction that impede recovery after anterior cruciate ligament reconstruction (ACLR). Depressed neural activity is harmful to quadriceps strength, as altered neural activity is known to restrict full volitional muscle contractions. Morphological deficits also influence muscle force generation and recent evidence suggests that selective fiber-type atrophy is present after ACLR. The relationship between neural inhibition and phenotypic changes after injury are complex. Based on the need to untangle this relationship, we sought to use a mediation analysis to preliminarily explore different neural and morphological pathways that can help explain quadriceps strength recovery after ACLR.

Objective: Use an exploratory mediation analysis to assess the direct effect of neural inhibition and the indirect effect of vastus lateralis fiber-type characteristics on quadriceps strength after ACLR.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: Ten individuals with unilateral ACLR volunteered (age: 23 ± 1.9 years; height: 1.66 ± 0.75 m; mass: 65.4 ± 12.6 kg; years' post-surgery: 5.8 ± 1.9 years).

Intervention(s): Neural inhibition, vastus lateralis fiber-type characteristics, and quadriceps strength were collected during a single session.

Main Outcome Measure(s): Quadriceps strength was assessed via maximal voluntary isometric contractions (MVIC) normalized to body mass (Nm/kg) and performed at 90° of knee flexion. Hoffmann-reflexes normalized to maximal muscle responses (H : M) were used to measure spinal-reflexive excitability. Using transcranial magnetic stimulation, corticospinal excitability was evaluated by active motor thresholds (AMT) and motor evoked potentials elicited at 120% of AMT normalized to maximal muscle responses (MEP). Mean diffusivity (MD) of the vastus lateralis (VL), a variable that describes water diffusion in muscle and has been used to identify fiber-type changes, was quantified by registering DTI scans with segmented T1-weighted MRI scans of the VL (3-Tesla Siemens MRI). DTI data were processed using DTITools for mathematica (github.com\m-froeling\\DTITools). AMT, H : M and MEP outcomes were combined using a principal component analysis to represent a comprehensive neural function outcome. The direct effect of comprehensive neural function (0.49 ± 0.77) on MVIC (2.97 ± 0.58 Nm/kg) mediated by VL MD (1.64 ± 0.09 mm^2/sec) was tested using Hayes' PROCESS (version 3.1) model 4 for mediation in SPSS (a priori, $P < 0.05$).

Results: The total model, using comprehensive neural function as the direct effect and VL MD as the mediator, was significant ($F = 6.99$, $P = .02$, $R^2 = 0.46$). 88% of the total effect was due to the direct effect of comprehensive neural function on MVIC ($P = .04$, 95% CI: 0.19, 0.70). 12% of the model was due to mediation by VL MD (95% CI: −0.44–0.32), which indicates that MVIC is explained by characteristics of VL fiber-type that are influenced by the neural environment.

Conclusions: Quadriceps isometric strength after ACLR is largely explained by spinal-and-cortical sources of muscle inhibition. VL MD also impacts MVIC and helps to provide an additional explanation for the interrelationships between the neural-morphologic environments after ACLR.

Abstract #16

The Mediated Link: Evaluating Quadriceps Neuromechanics and Dynamic Muscle Function After Anterior Cruciate Ligament Reconstruction

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Context: Quadriceps architectural gear ratio (AGR), or the ability of muscle to dynamically change shape to meet physical demands, is highly related to patient reported outcomes after anterior cruciate ligament reconstruction (ACLR). While important, it remains unclear what neuromechanical mechanisms influence AGR. Quadriceps inhibition and static architectural changes are well established after ACLR and may influence AGR by restricting dynamic muscle shape change.

Objective: To explore the relationship between AGR and neuromechanical deficiencies that are common after ACLR.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: 14 individuals with a history of unilateral ACLR (5m/9f; age: 21 ± 3 years; height: 1.70 ± 0.12 m; mass: 67.20 ± 13.08; years since surgery: 4.52 ± 2.66).

Intervention(s): Quadriceps inhibition and muscle architecture were assessed during a single session.

Main Outcome Measure(s): Participants completed maximum voluntary isometric contractions (MVIC) on an isokinetic dynamometer with the knee flexed to 90° while a superimposed electrical stimulus was delivered to the quadriceps. Quadriceps inhibition was evaluated via the central activation ratio (CAR: [MVIC Torque] ÷ [MVIC + superimposed burst torque]), which quantifies the amount of muscle available for volitional contraction. Simultaneously, a 4 cm linear ultrasound transducer was affixed over the vastus lateralis to capture muscle architecture at 50% of quadriceps length and synchronized with the dynamometer data. Vastus lateralis architecture (fiber length and pennation angle) was evaluated from the initiation of contraction (>10 Nm) to immediately prior to the superimposed burst. AGR was subsequently calculated ([Δ length muscle] ÷ [Δ length fiber]) during that time. The direct effect of CAR and mediated indirect effects of fiber length and pennation angle on AGR were assessed using Hayes' PROCESS (version 3.1) model 6 for multiple-mediation in SPSS (a priori $P < .05$).

Results: The total model, using CAR (93.98 ± 4.60), fiber length (6.43 ± 1.68 cm), and pennation angle (19.93 ± 6.56°) predicted significant variance in AGR (1.07 ± 0.06; $F = 4.304$, $P = .034$, $R^2 = 0.564$). No direct effect was present between CAR and AGR, indicating that CAR does not independently influence AGR ($P = .549$). However, the effect of CAR on AGR was significant when mediated through fiber length and then pennation angle (95% CI: 0.001, 0.013). This multiple-mediation relationship explains the indirect effect of CAR on AGR via fiber characteristics.

Conclusions: Our work demonstrates that muscle inhibition after ACLR is capable of indirectly influencing AGR via individual architectural components of muscle fibers. It appears that neural input may enhance muscle shape change to optimize muscle function during activity. Because of the wide-reaching implications of neuromechanical function on patient recovery, further exploration of the dynamic neuromechanical interactions need to be considered.

Abstract #17

Quadriceps Muscle Quality Is Related to Single Limb Hopping Distance Following Anterior Cruciate Ligament Reconstruction

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Context: Diminished quadriceps function is common following anterior cruciate ligament reconstruction (ACLR), and can increase the risk of re-injury and performance deficits after return-to-sport. Quadriceps dysfunction is a byproduct of arthrogenic muscle inhibition leading to decrease activation and atrophy. Altered activation is a mechanism in fatty infiltration into a muscle and potentially affects those with ACLR, contributing to functional deficits. In elderly and other pathological populations, poor quadriceps muscle quality (QMQ) is linked poorer strength and function.

Objective: Determine the relationship between QMQ and single limb hop (SLH) distance in individuals with ACLR.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Thirty-six individuals (20 F, 16 M; 22 ± 4 y/o; 23.7 ± 2.8 BMI; 50 ± 35 months since ACLR) at least 6 months removed from unilateral ACLR volunteered. All participants were cleared for return to activity and were physically active.

Intervention(s): Images of the vastus lateralis (VL) and rectus femoris (RF) were obtained using B-mode ultrasound. Panoramic images were obtained at 50% of the femur length, defined as the midpoint between the greater trochanter and lateral epicondyle. Ultrasound images were then analyzed using ImageJ software by outlining the muscle and excluding the surrounding fascia. Three SLH trials were completed after a warmup consisting of 3 properly executed hops.

Main Outcome Measure(s): QMQ was defined as the echo-intensity (EI) of each muscle. EI is a measure of the brightness of the image and is represented by an arbitrary gray scale value (0–255) corrected for subcutaneous fat thickness. Higher EI is due to greater amounts of fat and fibrous tissue, and is therefore representative of poorer QMQ. The cross-sectional area (CSA) of each muscle was also calculated. SLH distance (cm) was averaged across the 3 trials. The relationships between EI and SLH distance, and the CSA of VL and RF were determined by Pearson product-moment correlations.

Results: Greater EI of the VL (86.4 ± 25) ($r = -0.727$; $P < .001$) and RF (89.84 ± 19) ($r = -0.739$; $P < .001$) was strongly correlated with shorter SLH hop distance (127.9 ± 34 cm). CSA of the VL (23.3 ± 6 cm^2) was weakly associated with SLH ($r = 0.354$; $P = .034$) while CSA of the RF (9.2 ± 2 cm^2) was not significantly associated with SLH ($r = 0.111$; $P = .519$).

Conclusions: Poorer QMQ, not CSA, was associated with poorer SLH performance, a commonly used metric for return to sport following ACLR, indicating that the composition and not the size of the musculature is a stronger predictor of function. Following injury, adipose and fibrous tissue potentially have a deleterious effect on quadriceps function, and may be an indicator of re-injury risk. Ultrasound is a reliable, efficient tool that may aid clinicians in tracking changes in QMQ following injury. Future research is needed to evaluate how QMQ changes following injury and throughout the rehabilitation process and the implications for function and injury risk.

Abstract #18

Influence of Focused Plyometric Intervention on Strength and Function Limb Symmetry Indices in Patients After Anterior Cruciate Ligament Reconstruction

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Context: It has been estimated that 25% of individuals who undergo anterior cruciate ligament reconstruction (ACLR) will go on to sustain a second anterior cruciate ligament (ACL) injury to either the ipsilateral or contralateral limb. This suggests that risk factors for second ACL injury (i.e., quadriceps weakness and poor lower limb function) are not adequately reduced in all patients during post-operative rehabilitation. Plyometric exercise improves strength in healthy adults; therefore, focused plyometric exercise training may improve bilateral strength and function (i.e., increase limb symmetry) of the lower extremity in patients after ACLR. Improving limb symmetry may mitigate bilateral risk of second ACL injury.

Objective: Determine if focused plyometric training improves limb symmetry indices (LSI) of quadriceps strength and lower limb function (single leg [SL] hop) in patients after ACLR compared to those who receive no training.

Design: Randomized controlled clinical trial.

Setting: Research laboratory.

Patients or Other Participants: Thirty individuals post-ACLR were enrolled (plyometric: n = 15, age = 20.6 ± 2.8 years, body mass index [BMI] = 25.8 ± 4.3 kg/m^2, time post-ACLR = 40.5 ± 24.8 months; control: n = 15, age = 21.3 ± 3.5 years, BMI = 27.7 ± 4.8 kg/m^2, time post-ACLR = 45.3 ± 25.4 months).

Intervention(s): Participants completed a 4 week (3×/week) plyometric exercise intervention or no intervention (control group). Both unilateral and bilateral exercises were performed. Difficulty was progressed once a participant reported a Borg rating of perceived exertion (RPE) value ≤12 for two consecutive sessions.

Main Outcome Measure(s): Participants were assessed at baseline and 1-week post-intervention. Isokinetic quadriceps strength were tested at 60°/s. The peak torque value was obtained over 5 trials and normalized to body mass (Nm/kg). SL hop distance was averaged from 3 attempts as participants jumped forward as far as possible from a SL and landed on the same leg while maintaining balance. LSI were calculated as ([injured/uninjured]) × 100). An intention-to-treat analysis was utilized. One-way ANOVAs and paired t-tests compared quadriceps and SL hop LSI between and within groups, respectively ($\alpha < .05$).

Results: Neither quadriceps strength (pre: plyometric = 87.05 ± 16.47, control = 92.31 ± 30.11, $P = .557$; post: plyometric = 102.45 ± 24.34, control = 104.90 ± 59.00, $P = .883$) nor SL forward hop LSI (pre: plyometric = 97.37 ± 14.65, control = 95.18 ± 9.66, $P = .633$; post: plyometric = 96.76 ± 7.87, control = 95.85 ± 9.27, $P = .774$) differed between groups. The intervention group improved quadriceps strength LSI as a result of the intervention ($P = .048$); however, there SL hop LSI did not differ pre- to post-intervention ($P = .818$).Control participants demonstrated no differences in quadriceps strength LSI ($P = .520$) or SL hop LSI ($P = .793$).

Conclusions: Plyometric exercise improved quadriceps strength LSI in individuals following 4-weeks of training. However, there were no concurrent improvements in function as measured by SL hop LSI. Patients may benefit from a focused plyometric intervention during rehabilitation because quadriceps limb symmetry positively associates with biomechanical and patient-oriented outcomes.

Abstract #19

Development of Delivery Methods for Augmented Biofeedback Neuromuscular Training for Biomechanical Injury Risk Reduction

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Context: Non-contact anterior cruciate ligament (ACL) injury risk is associated with reduced lower extremity motor coordination. Neuromuscular training (NMT) has been successful in promoting safer movement patterns in high-risk athletes. However, the injury-resistant movement patterns resulting from current approaches may not transfer to sport as there has not been a decrease in national ACL injury rates in young female athletes despite efficacy of standard neuromuscular training to modify biomechanics in the lab.

The key knowledge gap to ensure transfer to sport and, hence, effective injury prevention is to understand the mechanisms the nervous system engages to acquire injury-resistant movement patterns from the targeted interventions.

Objective: The purpose of this study was to determine the relation between brain activation and biomechanical changes following NMT augmented with real-time biofeedback (aNMT).

Design: Longitudinal case-control.

Setting: Functional magnetic resonance imaging (fMRI) and 3D motion analysis laboratory.

Patients or Other Participants: Twenty high-school female soccer athletes (15.7 ± 0.95 years; 1.68 ± 0.05 m; 59.91 ± 5.62 kg) participated.

Intervention(s): Ten participants completed 6 weeks of aNMT designed to reduce knee injury-risk movements and 10 did not complete and NMT to serve as controls. Brain activation changes were measured with fMRI during a unilateral knee extension and flexion positioning task and a unilateral knee extension and flexion force control task. Knee injury-risk biomechanical changes were captured using a drop vertical jump task with a motion capture system (Motion Analysis Corp.).

Main Outcome Measure(s): Neuroimaging and motor assessment were completed before and after 6 weeks of NMT.

Results: Sensory (precuneus, voxels: 964; $P < .001$; z-max: 3.38), visual-spatial (lingual gyrus, voxels: 461; $P = .023$; z-max: 3.33) and motor planning (pre-motor cortex, voxels: 416; $P = .040$; z-max: 3.40) brain activity increased for leg positioning after NMT. This network of increased brain activity was correlated with a post-training decrease in knee abduction moment (28% ± 6.47%, $P < .050$) during landing ($r = .67$, $P = .036$). Motor cortex (voxels: 380, $P < .001$, z-max: 6.88) activity decreased for leg force control after NMT. This decreased brain activity was not correlated with the post-training decrease in knee abduction moment ($r = -0.32$, $P = .38$). No significant changes or relationships between brain activity and motor control were seen in controls.

Conclusions: Increased sensory, visual-spatial, and motor planning network activity for knee positioning control after NMT may improve neural processing to control knee positioning during landing, thereby reducing injury risk. The lack of a relationship between motor cortex activity changes and reduced injury risk (ie, knee abduction moment) from training may indicate that the key to improved landing mechanics is primarily related to sensory integration. Future work on enhanced visual stimuli that target sensory, visual-spatial, and motor anticipatory processes via technologies that enable personalized exercises, may further improve aNMT efficacy, portability, and clinical utility.

Abstract #20

Sport Specialization Elicits Alterations in Coordination and Maturational Biomechanics in Female Adolescent Basketball, Soccer, and Volleyball Athletes

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Context: Sport specialization (SS), or participation in one sport year-round at the exclusion of all others, is a growing concern in youth athletics. SS may be an independent risk factor for anterior cruciate ligament (ACL) injury by contributing to motor coordination differences and maturational changes in neuromuscular control that increase ACL injury risk in athletes.

Objective: The purposes of this study were to examine lower extremity biomechanics and coordination among pre-adolescent and adolescent sport-specialized and multi-sport female adolescent athletes, and to investigate the association between SS and aberrant biomechanics during maturational development.

Design: Prospective, longitudinal cohort study.

Setting: Research laboratory.

Patients or Other Participants: 732 adolescent female basketball, soccer, and volleyball players participated in the study with a mean age of 13.8 ± 2.0 years, height 160.7 ± 6.7 cm and weight 55.1 ± 10.3 kg. Via questionnaire data analyses, 366 female athletes were designated as *sport-specialized*, defined as ≥2 years of participation in 1 sport and fewer than 2 years of participation in any other sports. For comparison, *multi-sport* athletes were defined as ≥2 years of participation in ≥2 sports. All sport-specialized study participants were matched to multi-sport athletes based on age, anthropometrics, and pubertal status. Additionally, 158 athletes (79 sport-specialized and multi-sport athletes, respectively) who were classified as pre-maturational at the initial visit were followed longitudinally and assessed at a second visit in which they were classified as post-maturational. Maturational status was determined with a modified Pubertal Maturation Observation Scale questionnaire.

Intervention(s): 3D kinematic and kinetic data were collected on each participant performing a minimum of 3 trials of a drop vertical jump task from a 31 cm box.

Main Outcome Measure(s): Relative joint angular motion variability and seven kinematic pairings: hip flexion/knee flexion, knee flexion/ankle flexion, hip flexion/knee abduction, knee flexion/knee abduction, knee flexion/knee internal rotation, and knee abduction/knee internal rotation and group × limb (dominant/non-dominant) differences in peak hip and knee joint kinematics and kinetics over time.

Results: Sport-specialized athletes exhibited increased variability in hip flexion/knee flexion (12.8 ± 5.9° vs. 11.8 ± 5.4°, $P = .015$), knee flexion/knee abduction (14.7 ± 6.4° vs. 13.6 ± 6.1, $P = .017$), and knee flexion/knee internal rotation (14.9 ± 6.2° vs. 14.1 ± 5.9, $P = .046$). In the longitudinal cohort, sport-specialized athletes exhibited a smaller increase in peak knee extensor moment (19.3 ± 23.7 Nm vs. 25.3 ± 21.7 Nm, $P = .018$) and a larger increase in peak knee abduction moment (7.0 ± 10.1 Nm vs. 4.2 ± 11.8 Nm, $P = .017$) across visits compared to the multi-sport group. No significant differences were exhibited between groups in either cohort on any other measures.

Conclusions: SS was associated with both increased variability of critical hip and knee joint couplings that may underlie unstable or inefficient landing strategies, as well worsened biomechanics through maturation. The findings of this biomechanical study support SS as a risk factor for ACL injury in female athletes.

Abstract #21

A Simulated Indirect Anterior Cruciate Ligament Injury Mechanism Increased Knee Joint Loading Associated With a Quadriceps Dominance Landing Pattern

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Context: Limited research exists examining the indirect contact ACL injury mechanism, defined as a physical perturbation not directed at the knee during or immediately before the injury event. Quadriceps dominance (QD), the preferential use of the quadriceps muscles to stabilize the knee during landing, may increase anterior tibial translation and ACL injury risk. Understanding the indirect contact mechanism's influence on ACL injury is relevant for injury prevention.

Objective: To compare the differences in QD lower extremity landing patterns during a drop-vertical jump (DVJ) between a control and simulated indirect contact ACL injury mechanism.

Design: Descriptive laboratory study.

Setting: Motion analysis laboratory.

Patients or Other Participants: Nineteen healthy, physically active adult females volunteered (age = 21.4 ± 3.7 years, height = 1.67 ± 0.05 m, mass = 62.2 ± 8.9 kg). Participants had three or more years of experience in jump-landing activities, no history of lower extremity or spine injury resulting in instability or surgery, and no history of lower extremity or spine injury in the past six months that affected activity levels.

Intervention(s): The independent variable was condition [control, right perturbation (RPert), left perturbation (LPert)]. A three-dimension motion analysis system captured trunk, hip, and knee kinematic and kinetic data for participants as they performed a DVJ. During the first landing of the DVJ, participants randomly received an unanticipated in-flight lateral trunk perturbation at a force equivalent to 15% of body mass. A custom software program triggered the release of the contralateral spring resulting in a laterally delivered force to the ipsilateral trunk. The perturbation was delivered through a spring system attached to the participant's chest harness.

Main Outcome Measure(s): 1x3 repeated measures ANOVA with post-hoc tests analyzed the within-subjects perturbation effect. Kinematic variables were bilateral mean initial contact (IC) and peak deceleration (IC to peak knee flexion angle) angles for knee flexion. Kinetic variables were mean peak deceleration moments normalized to height and body mass for knee flexion and the knee flexion: hip flexion moment ratio (knee : hip ratio) where >1 represents greater knee flexion moments. Cohen's *d* effect sizes using pooled standard deviations were calculated for significant results.

Results: RPert significantly increased right-leg knee flexion deceleration moment compared to control [d = 0.76(0.10,1.42)] and LPert [d = –1.12(–1.81,–0.44)] trials (control = 2.10 ± 0.51 Nm/kgm, RPert = 2.53 ± 0.62 Nm/kgm, LPert = 1.85 ± 0.59 Nm/kgm; $P < .001$). LPert significantly increased left-leg knee flexion deceleration moment compared to control [d = 1.11(0.42,1.81)] and RPert [d = 1.32(0.61,2.03)] trials (control = 1.89 ± 0.63 Nm/kgm, RPert = 1.70 ± 0.72 Nm/kgm, LPert = 2.54 ± 0.53 Nm/kgm; $P < .001$). RPert significantly increased left-leg knee : hip ratio compared to control [d = –0.71(–1.37,–0.05)] and LPert [d = 1.11(0.42,1.80)] trials (control = –1.50 ± 0.67, RPert = –2.23 ± 1.29, LPert = –1.16 ± 0.39; $P < .001$). There were no statistically significant differences for kinematics.

Conclusions: A simulated indirect contact ACL injury mechanism increased knee joint loading associated with a QD landing pattern. ACL injury prevention programs should emphasize hip extensor and knee flexor musculature rather than the quadriceps to absorb landing forces.

Abstract #22

A Simulated Indirect Anterior Cruciate Ligament Injury Mechanism Increased Biomechanical Risk Factors Associated With a Ligament Dominance Landing Pattern

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Context: Limited research exists examining the indirect contact ACL injury mechanism, defined as a physical perturbation not directed at the knee joint during or immediately before the injury event. Ligament dominance, evidenced by increased dynamic valgus during landing may contribute to ACL injury risk. Understanding how an indirect contact mechanism influences ACL injury risk factors is relevant to developing prevention programs.

Objective: To compare the differences in ligament dominant lower extremity landing patterns during a drop-vertical jump (DVJ) between a control and simulated indirect contact ACL injury mechanism.

Design: Descriptive laboratory study.

Setting: Motion analysis laboratory.

Patients or Other Participants: Nineteen healthy, physically active females volunteered (age = 21.4 ± 3.7 years, height = 1.67 ± 0.05 m, mass = 62.2 ± 8.9 kg). Participants had three or more years of experience in jump-landing activities, no history of lower extremity or spine injury resulting in instability or surgery, and no history of lower extremity or spine injury in the past six months that affected activity levels.

Intervention(s): The independent variable was condition [control, right perturbation (RPert), left perturbation (LPert)]. A three-dimension motion analysis system captured trunk, hip, and knee kinematic and kinetic data for participants as they performed a DVJ. During the first landing of the DVJ, participants randomly received an unanticipated in-flight lateral trunk perturbation at a force equivalent to 15% body mass. A custom software program triggered the release of the contralateral spring resulting in a laterally delivered force to the ipsilateral trunk. The perturbation was delivered through a spring system attached to the participant's chest harness.

Main Outcome Measure(s): 1x3 repeated measures ANOVA with post-hoc tests analyzed the within-subjects perturbation effect. Kinematic variables were bilateral mean initial contact (IC) and peak deceleration (IC to peak knee flexion angle) angles for hip adduction, hip internal rotation (IR) and knee abduction. Kinetic variables included mean peak deceleration moments normalized to height and body mass for hip adduction, hip IR, and knee abduction.

Results: RPert significantly increased right-leg hip IR deceleration angle (control = 6.4 ± 7.0°, RPert = 7.7 ± 6.5°, LPert = 4.4 ± 6.1°; P = .018), right-leg hip adduction moment (control = –1.9 ± 0.7 Nm/kgm, RPert = –2.7 ± 0.9 Nm/kgm, LPert = –1.6 ± 0.5 Nm/kgm; $P < .001$), and knee abduction moment (control = –0.4 ± 0.3 Nm/kgm, RPert = –0.6 ± 0.5 Nm/kgm, LPert = –0.4 ± 0.2 Nm/kgm; P = .022). LPert increased left-leg hip IR deceleration angle (control = 2.9 ± 7.6°, RPert = 1.7 ± 8.9°, LPert = 6.1 ± 7.5°; P = .003), hip adduction moment (control = 0.6 ± 0.4 Nm/kgm, RPert = 0.5 ± 0.4 Nm/kgm, LPert = 1.1 ± 0.4 Nm/kgm; P = .016), and knee abduction moment (control = 0.24 ± 0.16 Nm/kgm, RPert = 0.18 ± 0.14 Nm/kgm, LPert = 0.47 ± 0.34 Nm/kgm; $P < .001$).

Conclusions: An unanticipated in-flight lateral trunk perturbation increased ligament dominance landing patterns as seen by increased peak hip kinematic and kinetics and peak knee abduction moments. These data suggest an increased reliance on static stabilizers during the landing phase of a simulated indirect contact mechanism compared to a control landing, therefore producing greater risk for ACL injury. ACL injury prevention programs should emphasize neuromuscular control of the dynamic stabilizers.

Abstract #23

Anterior Cruciate Ligament Injury Mechanisms in American Football

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Context: As NCAA football is among the sports with the highest incidence rates of anterior cruciate ligament (ACL) injuries, understanding the mechanisms of injuries is critical towards improving prevention efforts. The NCAA injury surveillance system provided critical information related to the nature and scope of the ACL injury problem. However, the mechanism of injury (MOI) categories used by this system (player contact, playing surface contact, noncontact, etc.) make it difficult to determine how many of these injuries are potentially preventable.

Objective: To describe the mechanisms of ACL injuries in American Football based on current ACL injury classifications: direct contact, indirect contact, or noncontact.

Design: Retrospective chart review (2011–2017), descriptive study.

Setting: A single NCAA Division 1 university.

Patients or Other Participants: Football athletes who sustained a first or second ACL injury during the study period which included all sanctioned team activities.

Main Outcome Measure(s): As a continuation of our initial investigation, UMCIRB approved, where football players are at ~13× greater risk of sustaining a second ACL injury (indirect contact or noncontact combined) compared to a first ACL injury, we describe here the MOIs associated with these injuries overall and then partitioned by first-time and second ACL injuries. Classification of injuries were as follows: noncontact (no player-to-player contact), indirect contact (player contact to a body part other than the injured limb, ie, trunk), and direct contact (player contact directly to the injured limb).

Results: Over the study period, 16 ACL injuries (10 first-time injuries, 6 second ACL injuries) occurred and were classified as noncontact (n = 9), indirect contact (n = 6), and direct contact (n = 1) overall. Among the 9 noncontact injuries, the MOI were: plant and cut/twist (n = 8) and landing from a jump (n = 1). For the indirect contact injuries (n = 6), the MOI were all plant and cut/twist in conjunction with either: engagement in a block (n = 3) or being knocked off balance (n = 3). 1 direct contact injury occurred where a player fell on the lateral aspect of the injured knee. Of the first-time ACL injuries, there were 5 noncontact and 5 indirect contact mechanisms. Second ACL injuries included 1 direct contact, 4 noncontact, and 1 indirect contact mechanism.

Conclusions: The current data suggests that many ACL injuries in football are potentially preventable as the majority of injuries sustained were noncontact or indirect contact, the latter of which included some form of perturbation to the upper body (trunk or arms). This research is limited to data from a single institution, and future research should seek to confirm these findings on a broader scale. Overall, American football is considered a high risk sport for sustaining ACL injuries and prevention efforts should focus on mitigating noncontact injuries as well as indirect contact injuries where upper body stabilization appears critical.

Abstract #24

What Are Our Patients Really Telling Us? Psychological Constructs Associated With Patient-Reported Outcomes After Anterior Cruciate Ligament Reconstruction

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Context: Recent data indicate that depressed patient-reported outcomes (PROs) are directly related to suboptimal rehabilitation outcomes in patients with anterior cruciate ligament reconstruction (ACLR). PROs provide a gross estimation of perceived function, but do not elucidate the underlying causes of self-perceived disability. In order to provide comprehensive personalized medicine, a better understanding of the unresolved factors influencing PRO responses is needed.

Objective: To identify the underlying factors that drive an individuals' responses on PRO scales via qualitative interviews after ACLR.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: Twenty-one individuals with unilateral ACLR volunteered (age: 21 ± 3 y; height: 1.72 ± 0.11 m; mass: 71.10 ± 13.36 kg; years' post-surgery: 4 ± 3 y).

Intervention(s): PROs and qualitative perceived function were assessed during a single session.

Main Outcome Measure(s): PROs assessing perceptions related to physical function included the International Knee Documentation Committee (IKDC) and Knee Injury and Osteoarthritis Outcomes Score (KOOS) pain, symptoms, activities of daily living (ADL) and sport subscales. PROs assessing perceptions of psychological wellness included the KOOS-quality of life (QOL), ACL-Return-to-Sport after Injury (ACL-RSI) and Tampa Scale of Kinesiophobia (TSK). Existing PRO thresholds were used to stratify patients into pass/fail categories. A hierarchical cluster analysis was used to identify sub-groups based on PRO scores. Qualitative interviews were also conducted to provide deeper supplemental understanding of patients' responses and were analyzed using a general inductive approach. Independent *t* tests examined differences between clusters on qualitative themes. Spearman's rho correlations were performed to determine associations between PROs and themes identified via qualitative interviews.

Results: Two groupings (high [n = 11] and low function [n = 10]) emerged from the cluster analysis. Individuals in the high function cluster scored better on all PROs ($P < .05$, mean-difference [MD] ± standard error difference [SED]: IKDC, –16.65 ± 3.78; KOOS-pain, –8.23 ± 2.76; KOOS-symptoms, –10.87 ± 4.56; KOOS-sport, –21.5 ± 4.25; KOOS-QOL, –28.49 ± 3.96; TSK, 7.54 ± 1.66; ACL-RSI, –30.63 ± 6.14), except for KOOS-ADL ($P = .06$, MD ± SED: –1.23 ± 1.39). Two themes (psychological and physical factors) and 4 subthemes (psychological facilitators, psychological barriers, physical facilitators, physical barriers) emerged from the interviews. There was a significant difference between cluster groups and presence of reported statements related to psychological themes ($P = .001$, MD ± SED: facilitators, –25.82 ± 6.87; barriers, 25.83 ± 6.87) and physical themes ($P = .05$, MD ± SED: facilitators, –18.42 ± 9.00; barriers, 18.42 ± 9.01). There were moderate correlations between TSK, scores and perceived facilitators (psychological: $\rho = -0.689$, $P = .001$; physical: $\rho = -0.513$, $P = .017$), and barriers (psychological: $\rho = .689$, $P = .001$; physical: $\rho = 0.513$, $P = .017$). ACL-RSI scores were also moderately associated with facilitators (psychological: $\rho = 0.651$, $P = .001$; physical: $\rho = 0.548$, $P = .01$) and barriers (psychological: $\rho = -0.651$, $P = .001$; physical: $\rho = -0.548$, $P = .01$).

Conclusions: Psychological PROs were associated with statements related to all qualitative subthemes. TSK scores indicated those with less fear of reinjury reported more psychological and physical facilitators, and individuals who demonstrated greater fear reported more statements related to barriers. Higher ACL-RSI scores, indicating improved readiness to return-to-sport, were associated with greater psychological and physical facilitators compared with those less ready to return. These findings support the need to consider psychological wellness during recovery after ACLR. Clinical PROs may be helpful identifying individuals who would benefit from additional support and/or psychological counseling.

Abstract #25

Integrating External Load Measurements Into Anterior Cruciate Ligament Rehabilitation: A Case Study

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Background: Current evidence supports the use of limb symmetry indices (LSI) during performance testing to gauge an athlete's ability to safely return to sport after anterior cruciate ligament (ACL) reconstruction. However, second ACL injury rates are high, with a majority of injuries occurring relatively soon after return to play. This suggests that athletes may not be ready for the external load demands of the sport at the time of return to play. Thus, external load metrics, measured through wearable technology, during the rehabilitation period may provide complementary information to standard LSI data in the decision-making process. The purpose of this case study was to provide preliminary data showing the progression of LSI and external load throughout rehabilitation of a typical patient after ACL reconstruction.

Patient: The patient was a 12 year-old female soccer player (height = 1.62 m, mass = 56.7 kg) that suffered a non-contact ACL injury during a cutting maneuver and subsequently underwent surgical reconstruction with a semitendinosus autograft.

Intervention or Treatment: The patient received rehabilitative care 2×/week that focused on the early restoration of range of motion, neuromuscular training of the quadriceps, hamstrings, and hip musculature, and progressive plyometric, core, and agility training per the standard physician-directed post-surgical protocol. External loads were tracked using wearable technology (activity monitor, accelerometer), and analyzed at 26 weeks post-surgery as a common timepoint for return to sport.

Outcomes or Other Comparisons: The patient successfully achieved >90% LSI for the lower extremity Y-balance test (post-surgical week 12), isometric quadriceps strength (week 14), single leg hop battery (week 23), and isokinetic hamstrings strength (week 26), and >80% LSI isokinetic quadriceps strength (week 25) by 26 weeks post-surgery. External load metrics indicated that the patient's most intense rehabilitation session (rating of perceived exertion = 8/10) consisted of 13.5% less frequent movements and 62% less distance traveled over a 22% shorter training duration than published normative values of youth soccer during a competitive soccer match.

Conclusions: Though LSI can help in the return to play decision making process as a key indicator of an athlete's performance and movement patterns, standard rehabilitation may not provide enough load to prepare an athlete for a safe return to their sport. Measuring external load during the rehabilitation period can help clinicians adequately progress workload to the necessary demands of the patient's sport.

Clinical Bottom Line: With the current emphasis on restoring limb symmetry, clinicians may be underloading patients during rehabilitation after ACL reconstruction.

Abstract #26

Hidden Asymmetries in Anterior Cruciate Ligament Reconstruction Patients Who Pass Triple Hop Test Following Anterior Cruciate Ligament Reconstruction

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Context: The triple hop (TrH) test is a dynamic movement often used to evaluate readiness to return to play following anterior cruciate ligament reconstruction (ACLR). We have previously reported that ACLR individuals that achieve 90% limb symmetry for TrH distance use asymmetrical knee flexion angles and moments. Defining the underlying biomechanical strategies that contribute to asymmetrical mechanics is crucial for understanding the limitations of hop tests that can permit a patient to return to sport prematurely, increasing risk of reinjury. Less frequently reviewed, joint power and joint work are two metrics that may help account for these alternative inter-limb strategies.

Objective: To assess hip, knee, and ankle joint power and work in ACLR individuals that pass the TrH limb symmetry for distance task.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: Sixteen subjects with history of unilateral ACLR (age: 21 ± 3 yr; height: 1.72 ± 0.11 m; mass: 68.94 ± 13.07 kg; years from surgery: 4 ± 3) participated.

Intervention(s): Bilateral hip, knee, and ankle kinetic and kinematic measures were recorded using 3D motion capture during the TrH test.

Main Outcome Measure(s): Sagittal plane peak joint powers ($W{\cdot}kg^{-1}$) and work ($J{\cdot}kg^{-1}$) were calculated from heel-strike to peak-knee-flexion-angle (defined as the landing phase), and from peak-knee-flexion-angle to toe-off (defined as the propulsion phase). In order of peak knee power (energy absorption), the landing strategy was categorized into a knee-hip- ankle, knee-ankle-hip, or ankle-knee-hip strategy. Dependent *t* tests were performed to assess inter-limb differences in power and work during both phases. Cohen's kappa scores were used to determine agreement between the inter-limb landing control strategies.

Results: Peak knee power in the ACLR limb (–15.5 ± 5.3 $W{\cdot}kg^{-1}$) was found to be significantly lower ($P = .044$) than the contralateral limb (–18.0 ± 5.3 $W{\cdot}kg^{-1}$) during the landing phase. This corresponds to significantly lower values ($P = .019$) in knee work of the ACLR limb (–0.71 ± 0.2 $J{\cdot}kg^{-1}$) and contralateral limb (–0.84 ± 0.2 $J{\cdot}kg^{-1}$). No statistical significance in power or work was found at the ankle (*P* values ranged: 0.210–0.349) or hip (*P* values ranged: 0.512–0.884) in either phase or for the knee during propulsion (*P* values ranged: 0.383–0.506). Disagreement or asymmetry ($k = -0.036$; $P = .868$) in the control strategy was also found.

Conclusions: Despite achieving 90% limb symmetry for TrH distance, joint power and joint work asymmetries persist in the ACLR knee during the landing phase; revealing a shift away from the ACLR knee and a redistribution of joint power. The ACLR limb landing phase strategy also resulted in a knee-hip-ankle control strategy compared to the contralateral limb knee-ankle-hip strategy. The utilization of different control strategies and the redistribution of joint power suggests there are neuromuscular compensations that the TrH test fails to capture.

Abstract #27

Patients With Prior Anterior Cruciate Ligament Injury That Do Not Suffer Secondary Anterior Cruciate Ligament Injury Demonstrate Greater Hip and Knee Muscle Strength in the Uninjured Limb Compared to Healthy Subjects

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Context: Comparison between the injured and uninjured limb is commonly performed to determine if muscle strength is restored following anterior ligament reconstruction (ACLR). It is assumed the uninjured limb is an ideal comparison for determining sufficient strength. However, it is unknown whether uninjured limb strength values of those with ACLR are similar to healthy subjects with no history of ACL injury or if there are differences between patients who suffer a second ACL injury and those who do not.

Objective: The objective of this study was to compare lower extremity muscle strength in patients with prior ACL injury who have returned to physical activity and did not suffer re-injury to patient with prior ACL injury who did suffer secondary ACL injury and healthy subjects.

Design: Retrospective cohort study.

Setting: Field research.

Patients or Other Participants: Participants were enrolled in the Joint Undertaking to Monitor and Prevent ACL Injuries (JUMP-ACL) Study.

Intervention(s): From this cohort (n = 5906), we identified participants who reported a prior unilateral ACLR and did not suffer a subsequent injury during study enrollment (ACLR Group, n = 123), participants who reported ACLR and did suffer a subsequent ACL injury during study enrollment (ACLR-injured Group, n = 17), and participants with no prior ACL injury, who did not suffer an ACL injury during study enrollment (Control Group, n = 5408).

Main Outcome Measure(s): We compared isometric torque normalized to body mass (Nm/kg), using a hand-held dynamometer, for knee extension, knee flexion, hip extension, hip internal rotation, hip external rotation, and hip abduction. Measures were collected on the dominant leg of the Control Group and the uninjured leg of the ACLR groups. Groups were compared using multiple one-way ANOVAs ($\alpha = .05$). Tukey's HSD was performed for any significant main effect.

Results: We observed significant main effects for knee extension torque ($F_{2,5547} = 3.59$, $P = .03$), and hip abduction torque ($F_{2,5547} = 4.58$, $P = .01$). The ACLR group demonstrated greater normalized isometric knee extension torque as compared to the Control Group

(ACLR Group: 1.96 ± 0.49, Control Group: 1.85 ± 0.49) and greater normalized hip abduction torque (ACLR Group: 1.50 ± 0.39, Control Group: 1.39 ± 0.40). ACLR-injured Group was not significantly different than either group for knee extension torque (1.80 ± 0.46) or hip abduction torque (1.47 ± 0.47). We observed no other significant main effects ($P > .05$).

Conclusions: Our observations indicate that patients who return to physical activity and do not suffer re-injury demonstrate greater hip and knee strength as compared to healthy subjects. This indicates that increasing lower extremity strength is helpful for patients to return to physical activity and avoid re-injury, and ACLR patients may need to achieve strength levels beyond those of healthy controls to offset the effects of injury.

Abstract #28

Neural Correlates of Lower Extremity Force Control Using a Novel MR Compatible Device

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Context: While the knowledge regarding how the brain controls upper extremity motion is becoming more quantified, similar breakthroughs in the lower extremity have been slow in coming due to limited technical innovation. The knowledge of brain activation during lower limb movement can contribute to the intervention for pathologies affecting gait and postural control.

Objective: To determine neural correlates of a single leg press at different force levels.

Design: Cohort study.

Setting: Neuroimaging center.

Patients or Other Participants: Five healthy (2 males/3 females; aged 24.2 ± 3.27 years, range 21–29 years, mass 58.63 ± 3.86 kg), right-handed, and physically-active college students without a history of significant injury participated in this study.

Intervention(s): Participants performed intermittent 5% or 10% bodyweight isometric single leg press exercise of the left limb while placed in a 3T MR scanner using a custom-made MR-safe device that provided real-time force target output to the participant. Participants were initially familiarized with the task outside of the MR environment. A block design involved four 30s contraction blocks interleaved with five 30s rest blocks. Two separate runs included contraction blocks with intermittent isometric single leg presses at 5%BW and 10%BW with a metronome at 1.2Hz.

Main Outcome Measure(s): First level analyses contrasted brain regions of the contract blocks with the rest blocks. Second level fixed-effects contrasted brain activation between 5%BW and 10%BW (significant clusters were identified a priori as $z > 2.3$).

Results: Absolute head motion during contractions was 0.2 ± 0.1mm for both the 5%BW & 10%BW conditions. The 5%BW > Relax contrast demonstrated increased activation clusters including the R inferior/superior lateral occipital cortex (Zmax = 3.35), R Broca's area (Zmax = 2.95), and R premotor and primary motor cortices (Zmax = 3.7). The 10%BW > Relax contrast demonstrated increased activation clusters including R primary motor, primary somatosensory, and premotor cortices (Zmax = 3.68); R inferior lateral occipital cortex (Zmax = 3.36), and R secondary somatosensory cortex (Zmax = 3.68).

Conclusions: While no differences were noted between force levels, this study demonstrated that closed-chain single-leg press exercise in a novel leg press device that provided real-time force feedback resulted in increases in brain activation associated with visual recognition, information processing to plan/select movements, movement execution, and action sequencing. Understanding brain activation patterns during the leg press task in a healthy population may serve as the foundation for future studies that aim to understand limitations in neural function in injured and/or diseased populations.

Abstract #29

Somatosensory Deficits Influence Gait Biomechanics Linked to Post-Traumatic Osteoarthritis in Individuals With Anterior Cruciate Ligament Reconstruction

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Context: Anterior cruciate ligament reconstruction (ACLR) is associated with a heightened risk of post-traumatic knee osteoarthritis (PTOA), and aberrant gait biomechanics are a primary contributor. Proprioceptive deficits exist following ACLR that impair sensorimotor function and potentially alter gait biomechanics. However, the association between proprioceptive function and gait biomechanics linked to PTOA development has not been evaluated following ACLR.

Objective: To evaluate associations between proprioception and gait biomechanics linked to PTOA development in individuals with ACLR. We hypothesized that individuals with poorer proprioception would display gait biomechanics consistent with greater PTOA risk.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: Seventy-three volunteers with unilateral primary ACLR (20 males, 53 females; age = 21 ± 3 years; time since ACLR = 27 ± 16 months, range 6–59 months) participated.

Intervention(s): Gait biomechanics were assessed via an optical motion capture system integrated with embedded force plates as subjects walked barefoot at their preferred speed. Proprioception was assessed as the ability to reproduce a target knee angle during partial weight bearing via an electromagnetic motion capture system.

Main Outcome Measure(s): Gait biomechanics outcomes included the peak vertical ground reaction force (vGRF) and its instantaneous loading rate (first time derivative), peak internal knee extension and valgus moments, and peak knee flexion and varus angles during the first 50% of stance. Quadriceps and hamstrings EMG data were also sampled and used to calculate a co-activation index. Proprioception was assessed by calculating the absolute difference between the target and reproduced angles (ie, active joint position sense error – JPSE). Partial Pearson correlations were used to evaluate associations between JPSE and each gait biomechanics outcome controlling for gait speed (mean = 1.33 ± 0.16 m/s). Forces and loading rates were normalized to body weight (xBW) while moments were normalized to the product of body weight and height (xBW × Ht).

Results: Poorer proprioception (ie, greater JPSE; mean = 2.9 ± 1.4°) was associated with lower vGRF loading rates ($r = -0.250$, $P = 0.034$; mean = 60.93 ± 20.85 xBW) and peak internal knee extension moments ($r = -0.387$, $P = 0.001$; mean = 0.031 ± 0.014 xBW × Ht), and greater co-activation ($r = 0.293$, $P = 0.035$; mean = 58 ± 16%). JPSE was not correlated with any of the gait kinematics outcomes ($P > 0.05$).

Conclusions: Poorer proprioception was associated with gait biomechanics that have been linked to poor joint health following ACLR. Individuals who develop PTOA 5 years post-ACLR display smaller sagittal plane moments compared to those without PTOA. Additionally, lower vGRF loading rates are associated with poorer knee cartilage composition (proteoglycan density) 6 months post-ACLR. Lastly, greater co-activation has been linked to greater compressive joint loading. These results suggest that interventions targeting proprioception may merit greater emphasis in ACLR rehabilitation to reduce PTOA risk.

Abstract #30

Associations Between Jump-Landing Biomechanics and T1rho Magnetic Resonance Imaging Inter-Limb Relaxation Time Ratios of the Lateral Tibiofemoral

Compartment 12 Months Following Anterior Cruciate Ligament Reconstruction

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Context: Following anterior cruciate ligament reconstruction (ACLR), individuals are at a heightened risk for developing posttraumatic knee osteoarthritis (PTOA). T1rho magnetic resonance imaging (MRI) relaxation times associate with proteoglycan density within cartilage and are elevated 12-months post-ACLR. The lateral femoral (LFC) and tibial (LTC) condyles commonly sustain a traumatic bone contusion during ACL injury, which can predispose the lateral compartment cartilage to changes in composition. Altered loading during walking associates with greater T1rho relaxations times at 6 and 12 months post-ACLR. However, the relationship between T1rho relaxation times and biomechanics during tasks of greater magnitude loading, such as a jump-landing task, early post-ACLR is not well understood.

Objective: To determine associations between jump-landing biomechanics of the ACLR limb and T1rho relaxation time inter-limb ratios (ILR) 12 months post-ACLR. We hypothesized that greater vGRF and KEM, as well as lesser KFA would associate with greater ILR 12 months post-ACLR.

Design: Cross-sectional.

Setting: Research laboratory.

Patients of Other Participants: Twenty-seven individuals with a unilateral ACLR (48% female, 22.11 $\pm$ 3.88 years old, 23.88 $\pm$ 2.51 kg/m^2) participated.

Intervention(s): Peak jump landing biomechanics (peak vertical ground reaction force [vGRF], peak internal extension moment [KEM], peak flexion angle [KFA]) and T1rho MRI were collected at 12 months post-ACLR. Five trials of jump-landing biomechanics were performed and averaged for analysis.

Main Outcome Measure(s): Mean T1rho ILR for the entire (Global) weight bearing LFC and LTC were calculated (ILR = ACLR limb/Uninjured limb). The Global-LFC and LTC were divided into three regions of interest (ROI) corresponding to cartilage overlaying the anterior meniscus, between the meniscal horns (central), and the posterior meniscus. Separate, stepwise linear regressions were used to determine associations between peak vGRF, KEM, and KFA and T1rho ILR after accounting for meniscal/chondral injury in the lateral compartment at the time of ACLR ($P \leq .05$).

Results: Greater ACLR limb vGRF (2.24 $\pm$ 0.59 bodyweight [BW]) associated with greater T1rho ILR for Central-LFC (1.12 $\pm$ 0.12 ms; $\Delta R^2 = 0.14$, $\beta = .39$, $P = .05$). Similarly, lesser ACLR limb KEM (–0.13 $\pm$ 0.03 BW $\times$ Height) significantly associated with greater T1rho ILR for Global-LTC (1.04 $\pm$ 0.08 ms; $\Delta R^2 = 0.17$, $\beta = .44$, $P = .04$) and Anterior-LTC (0.99 $\pm$ 0.08 ms; $\Delta R^2 = 0.18$, $\beta = .44$, $P = .04$) Peak KFA (73.84 $\pm$ 12.73°) did not significantly associate with T1rho ILR for any ROI.

Conclusions: Greater peak vGRF and lesser KEM of the ACLR limb during jump-landing significantly associates with greater T1rho ILR in the lateral tibiofemoral compartment 12-months post-ACLR. These data suggest that individuals who demonstrate greater peak vGRF and lesser sagittal plane moments during dynamic tasks, in the injured limb, may exhibit worse cartilage composition 12-months post-ACLR. It may be necessary to develop strategies aimed at correcting alterations in jump-landing biomechanics post-ACLR in order to maintain long-term cartilage health. Future work should determine how targeting alterations in peak vGRF and KEM during jump-landing influences measures of cartilage health post-ACLR.

Abstract #31

Changes in Infrapatellar Fat Pad Volume Between 6 and 12 Months Following Anterior Cruciate Ligament Reconstruction and Associations With Patient Reported Outcomes

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Context: The infrapatellar fat pad (IFP) contributes to the metabolic processes associated with development of idiopathic knee osteoarthritis, yet little is known regarding the IFP's role in the development of posttraumatic osteoarthritis (PTOA) following anterior cruciate ligament reconstruction (ACLR). Previous work in idiopathic knee osteoarthritis has suggested hypertrophy of the IFP is linked to deleterious synovial changes, as well as joint pain related to mechanical tissue impingement.

Objective: Examine changes in IFP volume from 6 to 12 months post-ACLR, and determine associations between patient-reported outcomes and IFP volume at each time point, as well as volume change over time. We hypothesized IFP volume would decrease from 6 to 12 months as inflammation subsided, and greater IFP volume would associate with worse patient-reported outcomes.

Design: Longitudinal cohort.

Setting: Research Laboratory.

Patients or Other Participants: Twenty-four individuals (11 Female, 22.0 $\pm$ 3.7 years old, 178.5 $\pm$ 11.8 cm, 76.9 $\pm$ 12.7 kg) with a unilateral bone-patellar-bone autograft ACLR were evaluated.

Intervention(s): Proton density-weighted, fat-suppressed magnetic resonance images (MRI), as well as patient self-reported outcomes, were collected during 6- and 12-month follow-up exams.

Main Outcome Measure(s): MRIs were semi-automatically segmented and manually edited to determine IFP volume. International Knee Documentation Committee (IKDC) subjective knee evaluation scores were collected at 6- and 12-month follow-ups to determine self-reported knee function. A dependent *t* test was utilized to compare IFP volume between 6- and 12-month follow-ups ($P \leq .05$). Step-wise linear regressions, separately accounting for body mass index (BMI) and sex, were conducted to determine associations between IFP volume and IFP volume change (predictor variables) and IKDC scores at 6 and 12 months (criterion variables), respectively ($P \leq .05$).

Results: IFP volume significantly increased from 6 (20.0 $\pm$ 6.4 cm^3) to 12 months (21.5 $\pm$ 7.1 cm^3)($t_{23} = -3.6$, $P = .002$) post-ACLR. Additionally, a greater percent increase in IFP volume between 6 and 12 months (8.0 $\pm$ 9.7%) associated with better 6-month IKDC scores (73.3 $\pm$ 11.6%) after separately accounting for BMI ($\Delta R^2 = 0.17$, $\beta = .42$, $P = .04$) and sex ($\Delta R^2 = 0.19$, $\beta = .44$, $P = .04$). We did not find any significant associations between IFP volume at 6 or 12 months and patient-reported outcomes.

Conclusions: Contrary to our hypothesis IFP volume increased between 6 and 12 months and individuals with better IKDC scores at 6 months demonstrated larger increases in IFP volume. It is unclear if the increase in IFP volume between 6 and 12 months post-ACLR is due to hypertrophy of the IFP or a return to pre-surgical volume following a partial resection that may occur during ACLR. It is possible the IFP plays a protective metabolic or mechanical role early post-ACLR, as individuals with better early function demonstrated a greater increase in IFP volume over time. Future longitudinal studies, including a presurgical assessment of the IFP, should aim to determine the role of the IFP in joint health following ACLR.

Abstract #32

Acute Changes in Serum Biomarkers of Cartilage Collagen Turnover and Joint Metabolism Following Anterior Cruciate Ligament Injury

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Context: Knee joint injury is a risk factor for posttraumatic osteoarthritis; however, little is known about how anterior cruciate ligament (ACL) injuries impact cartilage collagen matrix turnover and joint metabolism acutely post-injury.

Objective: The purpose of this study was to examine early changes in serum biomarkers of cartilage collagen turnover and joint metabolism between the time of ACL injury, the time of ACL reconstruction, and 6 months post-surgery in cases and uninjured controls matched for sex, age, height, and weight.

Design: Prospective cohort.

Setting: US Service Academy.

Patients or Other Participants: 54 subjects sustaining an incident ACL injury and 54 uninjured matched controls.

Intervention(s): Serum samples for ACL injured cases were obtained within 15 days of injury and again just prior to ACL reconstruction and 6 months following surgery. Samples for matched control subjects were obtained at time points corresponding with the time of injury and follow-up time points for the ACL injured subject with whom they were matched.

Main Outcome Measure(s): Two serum biomarkers for type II collagen and aggrecan synthesis (CPII and CS846, respectively) and two biomarkers of types I and II collagen degradation and type II collagen degradation only (C1,2C and C2C, respectively) were studied using commercially available ELISA assays. Serum concentrations were analyzed, as well as the ratios of collagen degradation to syntheses (C1,2C/CPII and C2C/CPII), at each time point. Two types of regression models were used to address the study aims: 1) matched-pairs analyses; and 2) within-group longitudinal analyses.

Results: The majority of ACL injured cases were males (n = 31, 57%). The average age (20 ± 1.4 vs. 20 ± 1.5 years), height (69 ± 3.7 vs. 69 ± 3.8 inches), and weight (175 ± 36.2 vs. 171 ± 33.9 pounds), was comparable between cases and controls, respectively. All initial samples were collected within 15 days from the time of injury in ACL injured cases. The average time from initial sample to time of surgery (24 ± 14.3 vs. 26 ± 19.1 days), time of surgery to 6-month follow-up (192 ± 23.0 vs. 186 ± 50.1 days), and total time from injury to 6-month follow-up (216 ± 26.7 vs. 211 ± 54.6 days) were also comparable between groups. The most significant results observed pertain to two ratio measures, the ratio of C1,2C to CPII and the ratio of C2C to CPII. For both of these ratios, there were statistically significant differences between the ACL-injured cases and the matched uninjured controls at the time of injury (0.050 ± 0.019, $P = .014$ and 0.026 ± 0.010, $P < .001$, respectively). Furthermore, these ratios significantly changed from the time of injury to 6-month follow-up in the ACL cases (0.534 ± 0.065 vs. 0.411 ± 0.022, $P = .022$ and 0.231 ± 0.094 vs. 0.201 ± 0.088, $P = .001$) but not in the controls.

Conclusions: These findings suggest that acute changes in serum biomarkers of cartilage collagen turnover are different between ACL injured cases and uninjured controls within the first 6 months following injury and surgery.