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Primary Anterior Cruciate Ligament Risk and Risk Reduction: Abstracts #1–10

Abstract #1

Sex-Specific Changes in Physical Risk Factors for Anterior Cruciate Ligament Injury by Chronological Age and Stages of Growth and Maturation From 8 to 18 Years of Age

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[1]Shultz, Casey, Dompier, Ford, Pietrosimone, Schmitz, and Taylor are co-first authors.

Objective: To critically assess the literature focused on sex-specific trajectories in physical characteristics associated with anterior cruciate ligament (ACL) injury risk by age and maturational stage.

Data Sources: PubMed, CINHAL, Scopus, and SPORTDiscus databases were searched through December 2021.

Study Selection: Longitudinal and cross-sectional studies of healthy 8- to 18-year-olds, stratified by sex and age or maturation on 1 measure of body composition, lower extremity strength, ACL size, joint laxity, knee-joint geometry, lower extremity alignment, balance, or lower extremity biomechanics were included.

Data Extraction: Extracted data included study design, participant characteristics, maturational metrics, and outcome measures. We used random-effects meta-analyses to examine sex differences in trajectory over time. For each variable, standardized differences in means between sexes were calculated.

Data Synthesis: The search yielded 216 primary and 22 secondary articles. Less fat-free mass, leg strength, and power and greater general joint laxity were evident in girls by 8 to 10 years of age and Tanner stage I. Sex differences in body composition, strength, power, general joint laxity, and balance were more evident by 11 to 13 years of age and when transitioning from the prepubertal to pubertal stages. Sex differences in ACL size (smaller in girls), anterior knee laxity and tibiofemoral angle (greater in girls), and higher-risk biomechanics (in girls) were observed at later ages and when transitioning from the pubertal to postpubertal stages. Inconsistent study designs and data reporting limited the number of included studies.

Conclusions: Critical gaps remain in our knowledge and highlight the need to improve our understanding of the relative timing and tempo of ACL risk factor development.

Abstract #2

The Effect of Maturation on Single Limb Landing Biomechanics in Young Female Soccer Players

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Context: The risk of anterior cruciate ligament (ACL) injury in female athletes increases throughout the stages of maturation. Previous evidence has indicated a lack of dynamic knee control during double-limb jump landings throughout maturation, yet the extent of biomechanical changes that occur throughout maturation during single-limb landings are not well understood. A maturational analysis of high-risk biomechanics during single-limb landings may elucidate and inform injury risk reduction efforts.

Objective: To determine differences in single-limb landing biomechanics between pre-pubertal, pubertal, and post-pubertal female soccer players.

Design: Cross-sectional (pre-testing component of a randomized controlled trial)

Setting: Research biomechanics laboratory

Patients or Other Participants: 151 competitive female soccer players

Intervention(s): Participants were categorized based on percent of adult stature into pre-pubertal (PRE: $<$84% of adult stature, n=23), pubertal (PUB: 87%-94% of adult stature, n=36), and post-pubertal (POST: $>$94% of adult stature, n=92) maturational groups.

Main Outcome Measure(s): All participants were instrumented for standard three-dimensional motion analysis and completed three trials of an ipsilateral single-limb hop and land over a 4-inch hurdle. Variables of interest included peak landing kinematics (hip flexion, hip adduction, hip internal rotation, knee flexion, knee abduction, ankle dorsiflexion) and peak landing external moments and ground reaction forces normalized to body mass (hip flexion, knee flexion, knee abduction, vertical ground reaction force). Multivariate analysis of variance (MANOVA) was used to compare the biomechanical variables of the dominant limb (preferred kicking limb) between maturational groups (α=0.05). Pearson's correlational analyses identified the relationship between the estimated percent of adult stature and lower extremity biomechanical variables.

Results: There were significant differences in lower extremity kinematics (λ=0.79, $p<0.001$) and kinetics (λ=0.78, $p<0.001$) between maturational groups. POST landed in less hip internal rotation (POST: -0.3$\pm$5.4°) than PRE (3.8$\pm$7.0°, d= 0.67, p=0.008) and PUB (3.4$\pm$6.0°, d= 0.65, p=0.004), and greater knee abduction (POST: 5.1$\pm$4.8°) than PUB (2.4$\pm$3.4°, d= 0.66, p=0.009). POST also landed with vertical ground reaction forces 14% lower (POST: 3.20$\pm$0.76 xBW) than PRE (3.69$\pm$0.78 xBW, d= 0.62, p=0.01) and 13% lower than PUB (3.65$\pm$0.47 xBW, d= 0.73, p=0.005). Weak relationships were identified between the estimated percent of adult stature and peak hip internal rotation angle (r=-0.26) and vertical ground reaction force (r=-0.31).

Conclusions: Post-pubertal female soccer players performed single-limb landings with lesser hip internal rotation, greater knee abduction, and lower vertical ground reaction forces. These findings are inconsistent with previous evidence that indicates higher risk movement strategies in post-pubertal athletes. The single-limb landing over a standardized hurdle height may not provide a

comprehensive biomechanical picture for which to assign injury risk profiles.

Abstract #3

Comparing Laboratory and Field Agility Knee Kinematics in Paediatric Female Soccer Players: Implications for Anterior Cruciate Ligament Injury Prevention

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Context: Researchers have identified modifiable biomechanical anterior cruciate ligament (ACL) injury risk factors in laboratory settings with change of direction tasks. To preserve athlete-environment relationship, it has been advocated to assess movement strategies on the field rather than only in the laboratory. However, the kinematic differences between laboratory and on-field settings have never been investigated.

Objective: To investigate the knee kinematics of female soccer players during agility movements performed both in laboratory and in soccer field environments.

Design: Observational.

Setting: Research laboratory and field.

Patients or Other Participants: Twenty healthy female soccer players (14.9 ± 0.9 years, height 167.9 ± 4.8 cm, mass 56.4 ± 7.3 kg) participated.

Intervention(s): Unanticipated sidestep cutting tasks with the dominant leg (towards the non-dominant leg) were collected both in the laboratory and on the field. In the laboratory, the players used a 5m approach run followed by a 1-foot landing and a 40°-50° change of direction followed by running through a gate 5m away. On-field tasks were recorded during a game performed as part of their regular training session. Kinematics were collected through wearable inertial sensors (Xsens Technologies, Enschede, The Netherlands). One-way ANOVA was used to compare knee joint kinematics between the conditions, with level of significance set at $p<.05$. Waveform consistency was investigated through Pearson's correlation coefficient and standardized z-score vector.

Main Outcome Measure(s): For both conditions, 3D joint angles were defined using the Euler sequence ZXY and exported from the Xsens software (Xsens MVN Analyze 2020.0.1) to a customized Matlab (The MathWorks 2019a, Natick, Massachusetts, US) script. The ultimate foot contact before the change of direction was used and data were processed in a time-normalized interval from 50ms prior to the initial contact (0%) to 25ms after (100%). For the field, 40°-50° changes of direction were extracted for comparison with the laboratory condition.

Results: On-field agility yielded vastly different knee kinematics compared to lab agility. At initial contact, the average knee flexion angle on-field was 31.96° - 36.92° versus 19.47° - 21.15° in the laboratory ($p=.004$). For the frontal plane at initial contact, we found -1.08° - -2.31° knee abduction in the field and 0.29° - 0.67° knee adduction in the laboratory ($p=.007$). The peak knee angles in frontal and sagittal planes were comparable among the two conditions. Waveform correlation was poor-to-excellent between laboratory and field (r: 0.20-1.00).

Conclusions: Movement strategies used for changes of direction tasks in the laboratory were different from the on-field movement strategies in young female soccer players. This could be attributed to the differences in the environment and support the need for on-field injury risk screening.

Abstract #4

Diminished Strength of the Hip Extensors Relative to the Knee Extensors Predicts ACL Reinjury in Female Athletes: A Retrospective Case-Control Study

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Context: Increased knee extensor moments relative to hip extensor moments during landing have been proposed as a risk factor for ACL injury in females. Diminished strength of the hip extensors relative to the knee extensors has been shown to predict an increased knee-hip extensor moment ratio during the deceleration phase of landing.

Objective: To determine if decreased strength of the hip extensors relative to the knee extensors predicts re-injury in females who have returned to sport following ACL reconstruction (ACLR).

Design: Retrospective, case-control

Setting: Patient clinic

Intervention(s): Maximum isometric strength of the hip and knee extensors was measured using a motor-driven dynamometer (BTE Primus; BTE) as part of return to sport testing following ACLR. Patients were contacted to participate in an online survey concerning their return to sport and ACL injury status at least 12 months following testing.

Patients or Other Participants: 345 females post ACLR who had previously undergone baseline strength testing were surveyed. The survey response rate was 54%. Respondents who sustained an ipsilateral ACL re-injury (non-contact) within 36 months of returning to sport were considered as cases.

Main Outcome Measure(s): Twelve cases (14-22 years) were identified and matched with 2-4 non-injured controls ($n=41$) based on sport level, athletic exposures, age, and graft type. Peak isometric strength for the hip and knee extensors was identified for each case and control from patient records. The hip-knee extensor strength ratio was calculated by dividing the peak strength of the hip extensors by the knee extensors (expressed as percentage). Logistic regression was performed to determine if the hip-knee extensor strength ratio predicted ACL re-injury, adjusted for known confounders (athletic exposures, age, graft type, months ACLR to return to sport). Receiver operator characteristic (ROC) curve analysis was conducted to determine the cutoff for the hip-knee extensor strength ratio that distinguished between high-risk and low-risk outcomes.

Results: Cases had a lower hip-knee extensor strength ratio compared to controls (0.83 ± 0.16 vs. 0.98 ± 0.17, $p=0.007$). The hip-knee extensor strength ratio significantly predicted ACL re-injury ($p=0.036$, adjusted OR = 0.944, 95% CI: 0.894, 0.996). For every 1% increase in the hip-knee extensor strength ratio, there was 5.6% lower odds of re-injury. ROC curve analysis revealed an area under the curve of 74.8% [95% CI: 58.7%, 90.9%] ($p=0.010$), indicating fair prediction accuracy. The cutoff for the hip-knee extensor strength ratio to define high risk was <= 97.1% (sensitivity: 91.7%, specificity: 51.2%).

Conclusions: Female athletes with a lower hip-knee extensor strength ratio following ACLR are at greater risk of ACL re-injury (ipsilateral limb). These results suggest that return to sport testing to assess risk for ACL re-injury should consider the inclusion of hip and knee extensor strength.

Abstract #5

Pediatric ACL Reinjury Risk Model: Clinician Informed Machine Learning Can Identify High-Risk Athletes and Modifiable Individual Risk Factors to Reduce Risk

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Context: Upwards of 30% of youth athletes sustain a repeat anterior cruciate ligament (ACL) injury after ACL reconstruction. While specific risk factors for re-injury and predictive models exist, these models are: 1) Limited in scope, failing to consider the large number of variables related to re-injury, 2) Overly simplistic, overlooking the interaction amongst variables, 3) Too broad, identifying risk factors within a group context and 4) non-actionable, utilizing risk factors that cannot be altered in recovery.

Objective: The goal of this study was to develop an ACL re-injury prediction model capable of evaluating each patient's individual risk, identifying modifiable risk factors and ranking these factors on the order of importance and ability to be modified.

Design: Retrospective database study of 432 patients (mean age 15.0, Female 50.7%) who underwent ACL reconstruction. This dataset represented a targeted extraction from a larger dataset and had a reinjury rate of 30%.

Setting: The dataset included variables across the following categories: Demographics, injury information, family history of ACL injury, surgical variables, rehabilitation & performance testing and re-injury information.

Intervention(s): Machine learning (ML) techniques leveraging clinician domain knowledge were utilized to develop a model capable of determining a patient's risk for repeat ACL injury. Two highly experienced surgeons and a physical therapist independently assessed risk factors and ranked their contribution to injury and ability to be modified during recovery. These classifications were integrated into the modeling, allowing clinician expertise to improve upon standard ML methodologies. After patient risk classification, the model ranks the most significant risk factors according to impact and ease of modification.

Main Outcome Measure(s): Multiple weighting methods and hyperparameter schemes were evaluated to obtain the highest accuracy classifying patients into high, medium or low risk categories, and weighting of modifiable risk factors. Model accuracy was determined using a 5-fold cross validation process over a 20% holdout dataset. An *a-priori* goal of classifying double the rate of re-injury across the entire dataset into high-risk patients (54%) and half this rate (13.5%) into low-risk.

Results: The final model included 23 modifiable variables represented mostly by performance factors (e.g. normalized quad peak torque, quad/hamstring strength ratio, hop testing performance or time to return to sports). The model adjusts risk factor weight on a case-by-case basis. Performance goals were achieved with ACL re-tear rates of 58% in high-risk and 7% in low-risk categories, with sensitivity of 89% and specificity of 66% and verified within the cross-validation process.

Conclusions: This ACL-Reinjury Risk Prediction Model can improve clinical care through accurate risk stratification and identification of patient specific modifiable risk factors, that can inform ongoing reinjury reduction or rehabilitation programs. Continued improvements in model accuracy will incorporate additional features, developing more intelligent labeling functions and adding confidence metrics.

Abstract #6

Outcomes of a Randomized Controlled Trial of Neuromuscular Training With Real-Time Biofeedback in Young Female Athletes

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Context: The high incidence of anterior cruciate ligament (ACL) injuries in young female soccer players compared to their male counterparts has led to a large body of work aimed at reducing injury.

Objective: To determine the effects of neuromuscular training using biomechanical biofeedback in order to reduce the risk of ACL injuries in adolescent female athletes.

Design: Randomized controlled clinical trial; Level of evidence, 1.

Setting: Research laboratory

Patients or Other Participants: 150 (age:13.3±2.2yrs; height: 156.1±10.6cm; mass:50.2±11.3kg) female soccer players.

Intervention(s): A prospective, randomized, active comparator, open blinded, end-point trial was conducted. Participants were randomized into one of three study arms where each received neuromuscular training plus 1) sham biofeedback as an active control (NMT), 2) knee-focused biofeedback (NMT+K), and 3) hip-focused biofeedback (NMT+H).

Main Outcome Measure(s): Each participant completed a pre-intervention baseline session and a post-intervention session to determine knee abduction moment (KAM) during a double leg drop vertical jump (DVJ) and an unplanned single leg cutting task at discrete time points and at specific time points during the stance phase. Athletic exposures and ACL injuries were tracked weekly for six months following the post-test session.

Results: 140 participants (93.3%) completed the 6-week intervention and post-test. No ACL injuries were reported among any of the intervention groups six months following post-testing. Peak KAM was significantly improved in all three intervention groups from baseline to the post-test during the drop vertical jump (NMT: baseline -21.4Nm [95% CI: -25.4, -17.4], post -16.6Nm [95% CI: -19.7, -13.5], p=0.001, d=-0.48; NMT+K baseline -19.5Nm [95% CI: -23.2, -15.8], post -14.6Nm [95% CI: -17.6, -11.7], p=0.003, d=-0.42; NMT+H baseline -22.2Nm [95% CI: -26.9, -17.8]; post -17.6Nm [95% CI: -21.1, -14.1], p=0.002, d=-0.45). The primary outcome in this RCT, peak KAM, had mean improvement of 22.7% from baseline to post-testing which did not differ between groups during the DVJ ($p>0.05$). However, statistically significant differences in peak KAM during the unanticipated cutting task were only found in the NMT+H intervention group (NMT: baseline -25.0Nm [95% CI: -30.4, -19.6], post -25.0Nm [95% CI: -29.6, -20.5], p=0.49, d=004; NMT+K baseline -23.6m [95% CI: -28.9, -18.3], post -22.8Nm [95% CI: -28.0, -17.6], p=0.377, d=-0.05; NMT+H baseline -29.5Nm [95% CI: -35.3, -23.8]; post -22.9Nm [95% CI: -27.8, -18.0], p=0.003, d=-0.44).

Conclusions: While female soccer players involved in neuromuscular training programs regardless of intervention group exhibit significant improvements in KAM during a double leg landing, those that engage in hip-focused biofeedback compared to knee-focused or sham biofeedback exhibit decreased KAM during an unanticipated cutting maneuver. Neuromuscular training programs that aim to modify the high-risk biomechanics associated with ACL injury may benefit from targeting the underlying components of injury, such as underutilization of hip musculature during dynamic sport related movements.

Abstract #7

Increases and Retention of Isokinetic Hip Extension Strength Following a Six Week Intervention

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Context: Neuromuscular training (NMT) programs have been shown to modify high-risk biomechanics and ACL injury risk. However, it is unknown which neuromuscular factors are modified following the completion of NMT programs. Hip strength has been suggested to be an important factor in ACL injury risk and is commonly emphasized in NMT programs. Understanding the immediate effects and retention of hip strength following a NMT

program will provide insight into the effectiveness of NMT programs in reducing ACL injury risk.

Objective: To examine the increase and retention of isokinetic hip strength in female adolescent soccer players following a neuromuscular training (NMT) program.

Design: Prospective cohort study.

Setting: Research laboratory.

Patients or Other Participants: 126 adolescent female soccer players (age=13.2±2.1yrs, height=156.4±10.2cm, mass=49.9±11.0kg) were included in this subgroup analysis that completed all isokinetic hip strength assessments.

Intervention(s): Participants volunteered to complete 6 consecutive weeks of a neuromuscular training (NMT) program with a frequency of 3 times a week. The NMT program included progressive exercises that included components of lower extremity strengthening, plyometrics, and core strengthening. Using an isokinetic dynamometer, 5 repetitions of isokinetic concentric (CON) and eccentric (ECC) hip extension (HEXT) torque were measured at 60 deg•s^{-1} bilaterally prior to (PRE) and following (POST) the NMT program. Retention (RET) of hip strength was assessed 6-months following the completion of the NMT program.

Main Outcome Measure(s): The average peak torque (Nm) of the middle 3 repetitions for CON and ECC HEXT strength measures of the right and left limb during each testing session were used for analyses. Separate repeated measures ANOVAs were used to compare differences in HEXT strength between PRE, POST, and RET. Post-hoc pairwise comparisons with Bonferroni correction were performed when appropriate.

Results: HEXT strength (CON, ECC) were significantly different between testing sessions. Specifically, POST right (146.9±48.3 Nm, 150.0±57.9 Nm) and left (147.4±47.7 Nm, 144.2±52.7 Nm) were greater than PRE right (138.8±44.0 Nm, P=0.007; 139.6±56.5 Nm, P= 0.026) and left (138.4±45.0 Nm, P=0.009; 139.4±56.2 Nm, P=0.035). RET right (130.2±48.8 Nm, 133.5±50.2 Nm) and left (131.9±46.2 Nm. 133.2±50.2 Nm) were less than POST (P_{range}= <0.001-0.007). However, neither right or left HEXT strength were different between PRE and RET (P_{range}=0.094-0.203).

Conclusions: In female adolescent soccer players, increases in isokinetic HEXT strength were observed immediately following a 6-week NMT program. However, the increases in hip strength were not retained 6-months following the completion of the NMT program. While the immediate increases in hip strength may contribute to the effectiveness of NMT programs in reducing ACL injury risk, these positive changes appear to decrease over time. This suggests that adolescent athletes may need to continuously engage in NMT programs to maintain the immediate observed increases in hip strength.

Abstract #8

Autonomy Support or Enhanced Expectancies Delivered Via Virtual-Reality Improves Frontal-Plane Single-Leg Squatting Kinematics

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Context: Despite decades of research and innovation, primary and secondary ACL injury rates remain high. Traditional injury prevention programs focus on biomechanical-related outcomes, neglecting to maximize more cognitively-driven processes that capitalize on motor learning principles. The advent of virtual reality technology allows for seamless integration of targeted motor learning strategies into injury prevention regimens, which may lead to improved acquisition and retention of safe movement patterns.

Objective: Determine the efficacy of a brief virtual-reality intervention to deliver specific motor learning principles of autonomy support (AS) or enhanced expectancies (EE) for superior retention of safe frontal plane single-leg squatting kinematics. We hypothesized that AS and EE would result in greater improvements compared to a control group.

Design: Quasi-experimental repeated measures

Setting: Three-dimensional motion analysis laboratory

Patients or Other Participants: Our sample included forty-five participants (21 male: 22.2±2.3 yrs, 181.2±9.4 cm, 79.6±16.9 kg; 24 female: 21.8±2.2 yrs, 163.0±7.3 cm, 63.1±12.3 kg) who demonstrated risky frontal plane single-leg squatting patterns. Study inclusion required no history of concussion, vertigo, lower extremity surgery, or lower extremity injury for six months prior. Due to data loss, the final sample was 39.

Intervention(s): Participants were quasi-randomized to one of three groups (control, AS, or EE) such that the male:female ratio was constant across groups. All participants wore virtual reality goggles that displayed an avatar (posterior/frontal plane view) performing exemplary single-leg squats. Participants were instructed to mimic the avatar while performing 5 sets of 8 single-leg squats on the left leg. The AS group chose their avatar color prior to each set. The EE group received real-time positive biofeedback in the form of joint-specific green highlights when kinematics remained within predefined injury-resistant constraints.

Main Outcome Measure(s): Participants were digitized for three-dimensional motion capture and completed five repetitions of left leg single-leg squats. Peak frontal plane knee, hip, and trunk angles were measured before and immediately following the intervention. Pre-post changes were assessed with 3x2 (group x time) RMANOVAs.

Results: A main effect for time indicated that all groups demonstrated increased pre-post hip adduction (p=.01; η^2_p=.18; control Δ=1.5°, AS Δ=3.2°, EE Δ=0.7°). Group by time interactions revealed that the control group demonstrated greater pre-post increases in knee abduction (Δ=2.3° increase) compared to AS (Δ=0.1° increase) and EE (Δ=0.4° decrease) (p=.003; η^2_p=.28) and that EE demonstrated greater decreases in ipsilateral trunk lean (Δ=11.7° decrease) compared to AS (Δ=6.3° decrease) and control (Δ=3.3° decrease) (p=.002; η^2_p=.30).

Conclusions: Hip adduction worsened in all groups, suggesting hip-abductor fatigue. Despite this, AS and EE groups maintained baseline knee kinematics, while the control group worsened. Knee maintenance was likely accomplished through decreases in ipsilateral trunk lean. Incorporation of motor learning principles appears to mitigate the detrimental effects of fatigue via increased learner motivation and engagement.

Abstract #9

Effects of Self-Controlled Feedback on Sidestep Cutting Techniques in Order to Decrease ACL Injury Risk

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Context: Providing choices to athletes during practice increases intrinsic motivation and therefore, positively influences the motor learning process. Autonomy on the timing of feedback (self-controlled feedback) seems promising to optimize movement techniques. The effects of self-controlled feedback on optimizing the technique of sidestep cutting (SSC), a task that is highly related with ACL injury risk, are unknown.

Objective: To investigate the effect of self-controlled feedback on SSC technique. It was expected that the self-controlled group progresses more after receiving the training than the yoked group.

Design: Randomized controlled trial.

Setting: Research laboratory.

Patients or Other Participants: Thirty healthy ball team sport athletes (22.6±1.7 years, 185.3±6.6 cm, 78.2±8.3 kg) were

recruited from local sports clubs. Based on arrival, participants were assigned to the Self Control (SC) or Yoked (YK) group.

Intervention(s): On day 1 and day 2 (one week later), participants performed five anticipated 45° SSC trials as pre-test, immediate-post test and retention test. Training consisted of three randomized conditions: an anticipated 45° SSC task and two conditions in which participants had to catch and throw or receive and pass a ball to the test leader. All participants received expert video instructions and were asked to 'copy the movement of the expert to the best of their ability'. The SC group was allowed to ask for feedback after every trial during training. Feedback consisted of 1) the Cutting Movement Assessment Score (CMAS), 2) posterior and sagittal videos of the last trial and 3) an external focus verbal cue on how to improve their technique. The participants' goal was to lower the score. The yoked counterparts received feedback after the same trial on which their partner in the SC group had requested feedback.

Main Outcome Measure(s): CMAS scores (range 0-11) between groups and sessions were analysed with repeated measures ANOVA, with level of significance set at $p<.05$.

Results: Pre-test scores between groups were equal ($p>.05$). Regardless of group, CMAS scores at pre-test (2.8 ± 1.0) were higher compared to training (1.8 ± 1.1), immediate-post (2.0 ± 1.0) and retention test (2.1 ± 1.1) ($p<.001$). Compared to pre-test (2.8 ± 1.9), the SC group improved technique during training (2.0 ± 1.1), which was maintained in the immediate-post (2.0 ± 1.0) and retention test (1.8 ± 1.0), $p>.05$. The YK group showed higher scores in immediate-post (2.0 ± 1.0) and retention test (2.4 ± 1.1), compared to training (1.6 ± 1.0) ($p<.001$).

Conclusions: The SC group maintained their improved technique during the retention test, whereas the YK group got back to their baseline level. Self-controlled feedback may benefit optimizing SSC technique and could be considered as a valuable tool to implement in ACL injury prevention programs.

Abstract #10

Knowledge, Attitudes, and Beliefs of Lower Extremity Injury Prevention Exercise Programs Among Sport Stakeholders: A Systematic Literature Review

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Context: Over the last twenty years, researchers have developed evidence-based injury prevention exercise programs (IPEPs) capable of reducing the rate of ACL injury. However, youth sport stakeholders have been slow to implement these programs and injury rates continue to rise. Previous studies have largely focused on the efficacy of IPEPs during controlled conditions. Recent research demonstrates that implementation factors impact the effectiveness of IPEPs in real-world settings. Understanding and intervening on implementation barriers and facilitators may be important for improving the adoption and effectiveness of IPEPs in youth sports.

Objective: To systematically review and synthesize the knowledge, attitudes, and beliefs of youth sport stakeholders towards IPEPs.

Data Sources: An electronic database search was conducted in November 2021 using PubMed and Google Scholar. A combination of search terms including, "knowledge," "attitude," "belief," "injury prevention program," "youth," "sport," "ACL," and "lower extremity" were entered. Results were limited to articles printed in English. Addition studies were added following a citation search for those meeting criteria.

Study Selection: Studies with partially overlapping data were merged and duplicate studies were removed. Studies that did not evaluate injury prevention in sport were excluded as were abstracts, white papers, dissertation and thesis manuscripts, supplements, book chapters, and conference papers. One author reviewed the remaining studies and removed those which did not include knowledge, attitudes, and/or beliefs, did not partially focus on the knee, and only included populations outside of youth sport (U9-U19).

Data Extraction: Nineteen studies comprising responses from 2774 sport stakeholders, 2473 coaches (Age: 18-66 years; Sex: 629 male, 196 female 1648 not reported; Coaching Experience: 1-40 years), were collected. Data pertaining to knowledge (95%), attitude (32%), and beliefs (74%) toward IPEPs were reported in the included studies. Quality of studies was not evaluated.

Data Synthesis: Themes influencing barriers to IPEP implementation include lack of knowledge (53%) and lack of access to materials to increase knowledge (21%). Themes influencing facilitators to IPEP implementation include positive attitudes toward IPEPs (42%), belief that youth athletes are at high risk of injury (21%), and belief that IPEPs help reduce injury (58%).

Conclusions: The recurring themes identified though this literature review support the need for programs, protocols, and policies to enhance knowledge and support of youth sport stakeholders responsible for implementing IPEPs. Limitations of the evidence contained in the review include: 13 of the 18 studies came from outside the U.S, the majority focused on soccer and/or basketball (84%), and when sex of respondent was identified, the majority (76%) were men. The use of implementation science frameworks such as the Consolidated Framework for Implementation Research and the Theoretical Domains Framework, will be beneficial in identifying constructs that affect implementation and developing programming to meet the needs of individual program deliverers.

Neurocognitive Factors: Abstracts #11–19

Abstract #11

Altered Neural Activity in Athletes With a History of Sports-Related Concussion: Isolating a Neural Mechanistic Pathway Towards Future ACL Injury Risk

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Context: Sports-related concussion (SRC) increases risk of lower extremity musculoskeletal injury, including ruptures to the anterior cruciate ligament (ACL). Residual deficits in neuromuscular control following SRC implicate a central nervous system (CNS) disruption that may propagate injury-risk knee movements. Isolating the SRC-disrupted neural activity for bilateral knee motor control could inform more comprehensive concussion rehabilitation programs that reduce subsequent risk for ACL injury.

Objective: The purpose of this study was to isolate neural activity differences for bilateral knee motor control in adolescent female athletes with a history of SRC versus age- and sport-matched controls without concussion history.

Design: Case-Control.

Setting: Emory SPARC.

Patients or Other Participants: Thirty-four female high school athletes were evaluated using fMRI during a lower extremity motor task. Seventeen female athletes with a history of SRC ($15.2 + 1.2$ years, $166.2 + 8.2$ cm, $62.4 + 5.6$ kg, and $24.2 + 21.8$ months post-concussion) were matched with seventeen age- and sport-matched healthy controls ($15.2 + 1.2$ years, $162.5 + 6.5$ cm, $60.3 + 7.9$ kg).

Intervention(s): Participants completed bilateral ankle, knee, and hip flexion/extension movements (supine leg press) against resistance, paced to a metronome at 1.2 Hz during brain fMRI.

MR scanning was conducted on a 3 Tesla scanner using a 48-channel, phased array head coil.

Main Outcome Measure(s): Paired t-tests were conducted with a mixed effects model to contrast neural activity between athletes with a history of SRC and healthy controls. Multiple comparison corrections were conducted with a Gaussian random field cluster approach and *a priori* significance level was set at $z > 3.1$, $p < .05$.

Results: Athletes with a history of SRC exhibited lesser neural activity in the left supramarginal gyrus (voxels: 2517; $z_{max} = 5.92$; MNI: x = -53, y = -46, z = 51) during bilateral knee motor control compared to matched controls.

Conclusions: Athletes with a history of SRC exhibit a reduction of neural resources allocated to a brain region important for proprioception. Lesser neural activity in those with a history of SRC may lead to proprioceptive deficits, placing athletes at an increased risk for subsequent lower extremity injury. Additionally, concussion rehabilitation programs should consider focusing on interventions that improve reliance on proprioception in athletes to reduce the potential risk for future ACL injury.

Abstract #12

The Impact of Differential Knee Laxity on Brain Function and Structure

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Context: Higher anterior knee laxity (AKL) is a risk factor for ACL injury. Individuals with higher AKL exhibit impaired proprioception and decreased functional knee joint stability. While the brain plays an essential role in processing and integrating sensory signals to maintain joint stability, the impact of AKL on brain function and structure is not yet well known.

Objective: To identify key differences in brain function and structure between individuals with higher AKL and low AKL.

Design: Cohort study.

Setting: Research laboratory.

Patients or Other Participants: Twenty-seven healthy and physically active female participants volunteered for this study (20.4±1.8 years; 166.05±6.8 cm, 64. 5±8.2 kg).

Intervention(s): Anterior knee laxity was measured using a knee arthrometer to assign participants either to the higher AKL (HL) group (AKL> 9.5 mm; N=15) or low AKL (LL) group (AKL<8.5 mm; N=12). A 3.0 T MRI scanner was used to measure the brain images with a 12-channel head coil. Functional brain images were obtained during anterior knee joint loading using a novel MR safe joint loading device, which is designed to translate the tibia anteriorly to the femur. Participants went through 30 sec of rest followed by 30 sec of passive anterior knee joint loading on the left leg for a total of 4 cycles.

Main Outcome Measure(s): Gray matter volumes of somatosensory areas were measured using T1-weighted magnetic resonance imaging. Independent t-tests were conducted to analyze the structural differences between two groups (P<.05). BOLD signals were measured to determine brain functional activity. The first-level analysis and the higher level GLM analysis were performed with z threshold at 3.1 and p threshold at 0.05 random field cluster corrected for multiple comparison.

Results: The HL group demonstrated significant diminished cortical activation in the left superior parietal (p=0.0012, z-max=4.59) and right premotor cortex (p=0.0025, z-max=4.23) when compared to the LL group. The HL group also demonstrated significantly higher activation in the right cerebellum (p=0.0109, z-max=4.96). There were no significant structural differences in the somatosensory areas (p>.05). However, there was a neared statistical significance in the right premotor cortex (p=0.053). The HL group showed a larger gray matter volume in the right premotor cortex compared to the LL group (Cohen's d= 0.8, HL: 18269.3±2049.9 mm3; LL:16845.9±1436.4 mm3).

Conclusions: The superior parietal lobe and premotor cortex play a vital role in maintaining awareness of body position and planning movements. The current findings suggest that individuals with higher AKL may have different perception of their body's position as well as altered strategies in planning potential movements. The results contribute to the identification of possible functional and structural neuroplasticity influenced by knee laxity. This may help clinicians develop specific preventive therapeutic intervention programs for individuals who are at high risk of ACL injury.

Abstract #13

The Role of Chronological Age in Brain Activity for Knee Motor Control: Consideration of Additional Neurophysiologic ACL injury Risk Factors in Young Female Athletes

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Context: Anterior cruciate ligament (ACL) injuries are a life changing event for young female athletes. With peak incidence rates averaging ~227 per 100,000 cases between the ages of 14 and 18, increased injury risk trajectories in maturing females are often attributed to rapid height and mass changes, leading to altered motor control and high-risk biomechanics. However, the role of the central nervous system and neurodevelopmental brain plasticity related to age and altered knee motor control are unknown.

Objective: To determine the relationship between chronological age and brain activity for bilateral knee motor control in young female athletes.

Design: Observational.

Setting: Emory SPARC.

Patients or Other Participants: Forty-four female middle school and high school athletes (15.1+1.4years [range 12-17], 162.8+6.7cm, 61.3+8.2kg) who participated in school and club sports (Basketball: 10, Soccer: 12, Volleyball: 22) were recruited.

Intervention(s): Athletes completed a bilateral knee motor control task against resistance. Knee, hip, and ankle flexion/extension movements (supine leg press) were completed during brain fMRI paced to a metronome at 1.2Hz. MR scanning was performed on a 3 Tesla scanner using a 48-channel phased array head coil.

Main Outcome Measure(s): Brain activity was evaluated using a mixed effects regression-based analysis (chronological age used as a predictor variable) with a significance level of $p < 0.05$, Gaussian random field cluster correction for multiple comparisons, and a threshold of $z > 3.1$.

Results: Greater age was associated with lesser brain activity in the right angular gyrus while performing the bilateral knee motor control task (180 voxels; z_{max}=4.65 [MNI x=44, y=-70, z=50], p = .008).

Conclusions: Given the role of the right angular gyrus for spatial cognition, self-location, and attention, a reduction of brain activity in older female athletes may indicate greater neural efficiency during knee motor control. However, this increased efficiency and automation may lead to elevated injury risk as older athletes may allocate fewer neural resources to brain regions involved in proprioception and self-location. Further research is warranted to investigate the relationship between neurodevelopment and proprioceptive mechanisms that may lead to increased ACL injury risk.

Abstract #14

Knee-Related Brain Activity Contributes to Future ACL Injury in Female High-School Athletes: A Prospective Neuroimaging Analysis

Diekfuss JA*, Zuleger TM*†, Slutsky-Ganesh AB*, Grooms DR‡, Kim HW‡, Warren S*, Anand M*, Simon JE‡, Barber Foss KD*, Wong PK*, Lamplot JD*, Hammond, KE*, Xerogeanes JW*, Myer GD*: *Emory Sports Performance and Research Center (SPARC), Flowery Branch, GA; †University of Cincinnati College of Medicine Neuroscience Graduate Program, OH; ‡Ohio University, Athens

Context: Anterior cruciate ligament (ACL) injuries often result from motor coordination errors during landing and cutting maneuvers in athletes. Prospective data indicate that altered *resting-state* brain connectivity may identify an athlete at risk for future ACL injury.

Objective: The purpose of this study was to examine prospective measures of brain activity during an *active* bilateral lower extremity motor control task in female adolescent athletes who subsequently suffered an ACL injury relative to non-injured matched controls.

Setting: Emory SPARC.

Patients or Other Participants: Ninety-three female middle and high school athletes who participate in soccer, basketball, and/or volleyball were evaluated using brain fMRI prior to their competitive sports season. Two athletes sustained an ACL injury (14.5 + 0.7 years; 160.02 + 1.79 cm; 55.5 + 8.06 kg) during soccer activities. Both ACL injuries were confirmed via knee MRI and were sustained to the dominant limb (right side). Each athlete with an ACL injury was matched to two healthy age-, sport-, weight-, height-, and limb dominant teammates ($n = 4$; 14.25 + 0.96 years; 157.2 + 4.9 cm; 54.9 + 2.2 kg).

Intervention(s): Athletes completed bilateral cyclical resisted ankle, knee, and hip flexion/extension movements paced to an auditory metronome (1.2 Hz) during brain fMRI (supine leg press concurrent with neuroimaging). MR scanning was completed on a 3 Tesla scanner using a 48-channel, phased array head coil.

Main Outcome Measure(s): Task-related activity was contrasted between athletes who experienced a subsequent ACL injury and matched controls using a mixed effects analysis with Gaussian random field correction for multiple comparisons. *A priori* significance level was set at $z > 3.1$ and $p < 0.05$.

Results: Brain activity was greater in the left supramarginal gyrus (3897 voxels, z_{max}=7.71, MNI: x=-40, y=-34, z=40) and right supramarginal gyrus (1326 voxels, z_{max}= 8.27, MNI: x=69, y=19, z=31) in athletes with subsequent ACL injury relative to healthy controls. Meanwhile, healthy controls exhibited greater activity in the right postcentral gyrus (1180 voxels, z_{max}=10.1; MNI: x=2, y=-46, z=74) and left middle temporal gyrus (894 voxels; z_{max}= 5.0; MNI: x=-63, y=-36, z=-18) relative to those who experienced a subsequent ACL injury.

Conclusions: Greater bilateral supramarginal gyrus activity in athletes who went on to sustain an ACL injury may indicate increased proprioceptive demand to coordinate bilateral knee motor control. These data expand upon prior work using resting state fMRI by isolating additional brain regions that may contribute to ACL injury risk during active states. If confirmed with larger samples, these data may provide a neural signature associated with ACL injury to inform the development of novel injury prevention strategies that promote adaptive neuroplasticity. Such interventions may optimize brain activity during functional movement training and reduce future ACL injury risk.

Abstract #15

Relationship Between Brain Activity and Knee Biomechanics During a Bilateral Leg Press in Adolescent Female Athletes

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Context: Increased anterior cruciate ligament (ACL) injury risk in female athletes is in part due to reduced motor coordination during landing contributing to increased prevalence of knee valgus. There is currently limited evidence regarding central nervous system contributions to knee motor coordination and subsequent injury.

Objective: To determine brain activity related to sagittal and frontal plane knee joint coordination during a bilateral leg press task in adolescent female athletes.

Design: Observational

Setting: Neuroimaging suite at Emory SPARC

Patients or Other Participants: Forty-four healthy adolescent female athletes (15.1±1.4years [range 12-17], 162.8±6.7cm, 61.3±8.2kg) who participated in school sports (Basketball: 10, Soccer: 12, Volleyball: 22) were enrolled.

Intervention(s): A neuroimaging-compatible leg press was used to engage resisted bilateral hip, knee, and ankle flexion\extension in a blocked design with five 30-second rest blocks and four 30-second movement blocks located between rest blocks. Blood-oxygen-level-dependent (BOLD) signal (indirect measure of neural activity) was captured via a 3-Tesla MR scanner with a 48-channel phased-array head coil. Bilateral lower extremity biomechanical data (hip, knee, and ankle kinematics; mean range of motion [ROM] for each joint) were simultaneously collected with eight MRI-compatible 3D motion analysis cameras and thirty-eight retroreflective markers.

Main Outcome Measure(s): The ratio of sagittal to frontal plane knee ROM was the biomechanical variable of interest; lower ratios are considered superior coordination (high flexion with low frontal excursion), and higher ratios are considered poorer coordination (lower flexion and\or higher frontal excursion). Neuroimaging data were analyzed with an a priori threshold at $z>3.1$ and $p<0.05$ with cluster correction for multiple comparisons. The number of movement cycles to control for any missed cycles during the task and age were entered as covariates for all analyses. Group-level mixed-effect correlation analysis was conducted with an explanatory variable (knee ROM ratio) and three contrasts (group mean and brain activity positively & negatively correlated with knee ROM ratio).

Results: There was no difference in sagittal and frontal knee biomechanics between left (sagittal: 25.85±10.88°, frontal: 2.3±1.63°) and right limbs (sagittal: 24.72±10.24°, frontal: 2.75±1.92°); the limb with higher knee ROM ratio (0.13±0.06°) was used in neuroimaging analysis. Greater knee ROM ratio was associated with less brain activity in the left dorsolateral prefrontal cortex (153 voxels [peak MNI voxel x=-24, y=28, z=40], z=4.45, p=.019).

Conclusions: Less brain activity in the left dorsolateral prefrontal cortex (DLPFC) in participants with reduced knee motor coordination may suggest that people with higher ACL injury risk knee biomechanics fail to initiate motor planning processes for bilateral motor control. The DLPFC is involved in visuospatial integration and working memory, which are vital for motor control. Therefore, these data may indicate that reduced knee coordination is secondary to not only explicit sensorimotor processes but cognitive appraisal, working memory, and visuospatial integration.

Abstract #16

Motor Cortex Neuroplasticity Associated With ACL Injury Prevention Neuromuscular Training in Adolescent Female Athletes

Chaput M*, Grooms DR*, Zuleger TM†, Slutsky-Ganesh AB†, Kim HW*, Warren SM†, Diekfuss JA†, Anand M†, Schlink BR†, Barber Foss KD†, Riehm CD†, Thomas S†, Schille A†, Slaton JA†, Simon JE*, Farraye B*, Bennison JC*, Roe JW*, Schnittjer AJ*, Pierce S*, Hogg JA‡, Myer

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Context: Neuromuscular training (NMT) programs improve lower extremity biomechanics and reduce anterior cruciate ligament (ACL) injury risk. Although neuromuscular adaptations and biomechanical changes enhance motor coordination, there is a paucity of mechanistic research quantifying the central nervous system (CNS) response associated with NMT. Characterizing CNS adaptations in response to NMT may allow for enhanced injury risk reduction strategies focused on adaptive neuroplasticity for optimal motor coordination and injury-resistant movement.

Objective: To evaluate neural activity changes of the primary (M1) and premotor (M2) cortices following six weeks of NMT.

Design: Prospective cohort

Setting: Sports Performance And Research Center

Patients or Other Participants: Fifty-one adolescent female soccer, basketball, and volleyball athletes participated from local area schools (15.2±1.5 years [range 12-17 years], 162.9±6.8 cm, 61.5±9.0 kg).

Intervention(s): Participants completed a NMT program consisting of whole-body strength and lower extremity plyometric exercises three times per week for 90-minute sessions. NMT was prescribed in the group setting (<10 athletes per group) and athletes were trained by the same two interventionalists for the duration of the study. Functional magnetic resonance imaging (fMRI) was used to quantify Blood-oxygen-level-dependent (BOLD) signal (indirect measure of neural activity) with a 3 Tesla MR scanner using a 48-channel, phased array head coil. A bilateral leg-press motor task during brain fMRI was performed prior to (pre-training) and following NMT (post-training). The bilateral task consisted of alternating rest (n=5) and movement (n=4) blocks, each 30 seconds in duration. The bilateral task consisted of cyclical ankle, knee, and hip, flexion/extension movements against resistance paced to an auditory metronome (1.2Hz).

Main Outcome Measure(s): Task-related neural activity was contrasted between timepoints (pre/post NMT) with a single-group paired t-test analysis and restricted to a bilateral M1 and M2 mask. An a priori significance level of $p<0.05$, z-threshold >3.1, and correction for multiple comparisons using Gaussian random field cluster approach was applied.

Results: Following NMT, neural activity decreased bilaterally in M1 (z-max=8.06, $p<0.001$, 1174 voxels) and increased bilaterally in M2 (Left: z-max=5.57, $p<0.001$, 447 voxels; Right: z-max=4.73, $p<0.001$, 185 voxels).

Conclusions: Decreased neural activity bilaterally in M1 may indicate a neural efficiency adaptation for motor coordination following NMT. Increased M2 activity may be secondary to the extensive cuing and directed attention towards knee control employed during NMT. Neural efficiency of the motor cortex is associated with enhanced motor learning and classically present in those with high levels of expertise in various motor skills. Reductions in M1 activity may be the underlying neural mechanism driving desirable neuromuscular adaptations that support injury-resistant movement following NMT. Future research on ACL risk reduction programs should consider NMT strategies that target neural efficiency (e.g., integrating goal-directed sport specific exercise into NMT) to further optimize acquisition of injury resistant movement patterns.

Abstract #17

ACL Injury Risk Reduction Programs Using Real-Time Visual Biofeedback Promotes Both Implicit and Explicit Motor Learning

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Context: The use of visual feedback and biofeedback to foster injury-resistant movement acquisition in adolescent athletes is a rapidly growing research area. While the effectiveness of different biofeedback interventions has been demonstrated, the underlying motor learning strategies adopted by athletes is mostly unknown. Visual biofeedback is typically thought to promote an external focus of attention and thereby foster *implicit learning*, where learners subconsciously arrive at desirable movement solutions. However, biofeedback may also induce *explicit learning*, specifically if the athlete consciously uses visual information to develop a specific movement-related plan to achieve desired outcomes.

Objective: To determine the degree a visual biofeedback intervention, designed for implicit learning, induces implicit or explicit learning.

Design: Prospective cohort.

Setting: 3D motion analysis laboratory.

Patients or Other Participants: Twenty-five adolescent female soccer athletes were enrolled (15.9±0.9 yrs, 164.9±5.67 cm, 58.9±10.3 kg).

Intervention(s): Participants completed a standard six-week neuromuscular training intervention (three 90-minute sessions/week), with added visual biofeedback sessions (two sessions/week). For the biofeedback training, participants interacted with a visual rectangular stimulus that was mapped to key parameters associated with injury risk that transformed in real-time with participant's squatting and jumping movements. Following each session, participants answered four Likert-type questionnaires about the difficulty of interacting with the stimulus and two open-ended questions probing them to describe their learning strategies while interacting with the stimulus.

Main Outcome Measure(s): Three raters independently categorized the open-ended questions as ''externally focused'' (i.e., implicit learning), ''internally focused'' (i.e., explicit learning), ''mixed focus'', or ''other.'' The Likert-type questions were scored from 0-7, with higher scores indicating greater ease of use.

Results: In total, 171 open-ended responses were collected. Of these, 38.6% were categorized as external, internal, or mixed focus and 61.4% concerned ''other'' statements (e.g., ''it went well''). Of the 38.6%, the majority were externally focused (42.4%; e.g., ''I found it hard to keep inside the rectangle''), followed by mixed (36.4%; e.g., ''I moved slowly and tried to keep the box straight''), and internal focus (21.2%; e.g., ''my hips weren't in line with the rest of my body''). Participants rated the biofeedback as being responsive to their movement (median=6, range=5-7) yet moderately difficult to use (median=4, range=3-7).

Conclusions: Although more participants reported an external focus, a substantial number of statements contained an internal or mixed focus sentiment. These data indicate that conscious explicit movement strategies, as well as implicit and 'mixed' learning strategies, are present during visual biofeedback training for a cohort shown to positively transfer acquired injury-resistant movement mechanics to landing (published previously). Future ACL injury risk reduction research should consider the optimal implicit/explicit learning strategy on a continuum, with a focus towards developing *personalized* biofeedback stimuli to maximize the retention and transfer of injury-resistant biomechanics.

Abstract #18

Asymmetric Sensorimotor Brain Activity in Individuals With Anterior Cruciate Ligament Reconstruction for Knee Motor Control

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Context: Anterior cruciate ligament injury and reconstruction (ACLR) result in strength and functional performance asymmetries that persist beyond return to activity and may contribute to secondary injury. Although previous work has established brain activation differences between ACLR and healthy controls, brain activity asymmetries between the injured and uninjured limb in an ACLR cohort remain largely unexplored.

Objective: The purpose of this investigation was to examine sensorimotor brain activity and organization differences between injured and uninjured limbs for knee motor control in an ACLR cohort. We hypothesized movement of the injured limb would generate greater cortical activity and larger areas of activation relative to the uninjured limb in ACLR individuals.

Design: Cross-sectional.

Setting: Research laboratory.

Patients or Other Participants: Eighteen participants with left knee ACLR (10 females, 8 males, 21.67±2.63 years, 171.72±10.28 cm, 70.48±15.70 kg, Tegner activity level 7.44±1.15, 45.94±32.04 mo. post-surgery) were enrolled in the study from two neuroimaging centers.

Intervention(s): Participants performed a unilateral knee flexion/extension task during functional magnetic resonance imaging (fMRI). Four blocks of 30-second knee flexion/extension movements with 5 blocks of a 30-second rest were completed for both the injured and uninjured limb.

Main Outcome Measure(s): We used the Oxford Centre for Functional MRI of the Brain Software Library (FSL) for all neuroimaging analyses. A general linear model with a second-level mixed-effect paired group analysis was performed to compare neural activity between limbs with an *a priori* threshold at $z>3.1$, $p\leq0.05$ and cluster correction for multiple comparisons. The number of voxels activated in each participant within the sensorimotor cortex and cerebellum were calculated by Featquery (masks were generated from a group brain activation map) and used to determine relative cortical region organization. A paired sample t-test was conducted for each brain region (cerebellum and sensorimotor cortex) to determine if there was a significant difference in number of voxels between injured and uninjured limbs.

Results: The injured limb displayed a larger area of brain activation in the ipsilateral cerebellum (108±23.09 voxels) as opposed to the uninjured limb (90.39±17.52 voxels), with a statistically significant mean difference of 17.61 (95% CI, 12.07 to 23.15 voxels), $p<0.001$, $d=1.58$. The injured limb also had a larger area of activation in the contralateral sensorimotor cortex (536±137.38 voxels) as opposed to the uninjured side (217.06±57.96 voxels), with a statistically significant mean difference of 318.94 (95% CI, 256.37 to 381.52 voxels), $p<0.001$, $d=2.5$.

Conclusions: Patients with ACLR displayed asymmetric cerebellar and sensorimotor brain area activity during a knee motor control task. These results suggest a compensatory shift in cortical organization to maintain knee motor control after ACLR.

Abstract #19

Sex Differences in Lower Extremity Visuomotor Reaction Time in Individuals With History of ACL Reconstruction

Genoese FM, Walaszek MC, Collins KA, Reiche ET, Triplett AN, Harkey MS, Kuenze CH, Baez SE: Michigan State University, East Lansing

Context: Individuals who sustain a non-contact ACL injury exhibit deficits in neurocognitive functioning, specifically slower reaction time, prior to their injury. Visuomotor reaction time (VMRT) is the time it takes to respond to sequentially appearing visual stimuli and slow VMRT has been associated with musculoskeletal injury risk in athletes. Females have an increased risk of secondary ACL injury after primary ACL reconstruction (ACLR) when compared to males. However, there is limited evidence that has explored sex differences in potential neurocognitive risk factors for secondary ACL injuries, such as VMRT, in individuals with history of ACLR.

Objective: To compare lower extremity VMRT between biologic males and females at least 4-months post-ACLR.

Design: Cross-sectional study

Setting: Research laboratory

Patients or Other Participants: Thirty-five individuals (25 females, 10 males; age= 20.6±7.3years) with history of primary, unilateral ACLR at least four-months post-surgery (14±15months) were included. Individuals were excluded if they had previous knee surgery or concurrent multi-ligament reconstruction.

Intervention(s): Participants completed a demographics questionnaire that collected data on biological sex.

Main Outcome Measure(s): Lower extremity VMRT was measured using a novel and reliable task utilizing a series of wireless light discs. Participants were placed at the center of a 180° semicircle with five light discs (FitLight Trainer™, FitLight Sports Corp.) secured to the ground in increments of 45°. Participants were instructed to respond to randomly generated visual stimuli and deactivate the series of targets by tapping the illuminated disc with their foot as quickly as possible. Participants completed three 30-second familiarization trials followed by one 60-second test trial on both the injured and uninjured limb. The average time between target hits was calculated in seconds and used to measure lower extremity VMRT. Descriptive statistics were calculated for injured and uninjured limb VMRT (median [IQR]) and Mann-Whitney U Tests were used to compare individuals based on biologic sex in injured and uninjured limb VMRT. A-priori α was set at $p < 0.05$.

Results: Biologic females exhibited slower median injured limb VMRT (sec) (females=0.522 [0.124]), males=0.460 [0.072]; p=0.04) and uninjured limb VMRT (sec) (females=0.559 [0.097], (males=0.477 [0.088]; p=0.03) when compared to males.

Conclusions: Males and females differ in lower extremity VMRT post-ACLR with females exhibiting slower VMRT compared to males. VMRT is a modifiable factor that, if addressed appropriately, could mitigate the risk of secondary ACL injury. Future research should investigate intervention strategies to improve lower extremity VMRT in females after ACLR.

Considerations After Anterior Cruciate Ligament Reconstruction: Abstracts #20–30

Abstract #20

Mechanism of Injury Impact on Outcome Following ACL Reconstruction In Adolescents

Hopper HM, Bruce AS, Thompson XD, Hart JM: University of Virginia, Charlottesville

Context: Persistent muscle weakness and sub-optimal outcomes following ACL reconstruction (ACLR) are common. One possible factor that may impact strength recovery and perceived function is the mechanism of initial ACL injury. Individuals who sustained a non-contact mechanism of injury may have pre-existing muscle impairments and subsequent perceived dysfunction or fear that could impact their progress after ACLR.

Objective: To compare strength and patient reported outcomes between patients with ACLR who sustained a non-contact vs contact injury.

Design: Observational Study.

Setting: University Laboratory.

Patients or Other Participants: 43 adolescent participants (23 females, 20 males, 16.1±1.5 years, 172.2±25.7 cm, 73.7±20.9 kg) completed a single testing session at 6.87±1.59 months after a primary, unilateral, and uncomplicated ACLR.

Intervention(s): Isokinetic strength testing of the quadriceps and hamstrings were measured bilaterally with a multi-mode dynamometer at 90deg/s for 8 repetitions. Each participant also answered a series of questionnaires which included self-reported mechanism of injury, the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC) and the Tampa Scale of Kinesiophobia (TSK).

Main Outcome Measure(s): Peak knee extension and flexion torque were recorded for the ACLR limb and normalized to body mass. Limb symmetry was also calculated using the contralateral limb as the reference limb and expressed as a unitless ratio where 1.0 = perfect symmetry. Each participant's mechanism of injury was recorded as a contact or non-contact injury based on subjective history and compared with independent sample t-tests.

Results: There was no significant differences for average normalized peak extension torque between the non-contact group (1.68±0.61 Nm/kg) versus the contact group (1.85±0.60 Nm/kg, p=0.403). There was no significant difference for average normalized peak flexion torque between the non-contact group (1.02±0.29 Nm/kg) versus the contact group (1.10±0.40 Nm/kg, p=0.466). There was no significant difference between the non-contact group peak extension LSI (0.70±0.20), and peak flexion torque LSI (0.92±0.22) versus the contact group peak knee extension LSI (0.71±0.15, p=0.822) and peak flexion torque LSI (1.00±0.16, p=0.181). Finally, there were no significant differences for IKDC between the non-contact (84.5±10.8) and contact group (87.6±7.0, p=0.313) nor any differences in TSK between the non-contact (32.6±5.5) and contact group (31.7±5.4, p=0.594).

Conclusions: Mechanism of initial ACL injury does not appear to impact 6-month strength recovery, perceived joint function or fear of movement following ACLR in adolescent patients.

Abstract #21

Physical Activity Level and Sex Differences Impacting Pediatric Patient Outcomes After Anterior Cruciate Ligament Reconstruction (ACLR)

Bruce AS, Thompson XT, Kaur M, Hart JM: University of Virginia, Charlottesville

Context: Prior research has reported strength deficits in the hip abductors and adductors in patients recovering from ACLR. Hip strength deficits have been associated with increased amount of valgus collapse, particularly in females, during physical activity and therefore increases risk of reinjury. It is unclear as to how physical activity and sex might influence patient outcomes in pediatric individuals recovering from ACLR.

Objective: The objective was to highlight hip strength discrepancies between high and low physically active pediatric individuals, as well as between sexes post-ACLR.

Design: This was an observational laboratory study.

Setting: This study was conducted in a controlled laboratory setting as part of a large point-of-care, collaborative research program at a large academic health system.

Patients or Other Participants: Fifty-three patients with primary, unilateral, and uncomplicated ACLR (26 Males/27 Females, 16.14±1.51yrs, 169.10±10.72cm, 73.87±19.61kg, 6.64±2.22mo post-ACLR) were consented and enrolled in this study.

Intervention(s): The independent variables included limb (ACLR vs Contralateral), sex, and Tegner Activity Scale (High vs Low). Tegner activity scale (TAS) was recorded indicating preinjury physical activity level defined as high (≥9) or low activity (≤8).

Main Outcome Measure(s): The dependent variables of hip abduction (AB) and adduction (AD) were performed by patients bilaterally during maximal isometric contractions to assess strength via peak torque (PT) normalized to body mass (Nm/kg) in a supine hook lying position with hips and knees flexed to 45° and 90° respectively. Two 2X2 repeated measures ANOVA (Limb-by-activity and limb-by-sex) were used to compare AB and AD PT between limbs and across competitive and recreationally active individuals and across sexes. *Post hoc* t-test were used where appropriate. The Alpha level was set at $\alpha \leq 0.05$.

Results: No significant differences between TAS level and hip strength PT were observed. Males had significantly greater PT than females for hip AB bilaterally (ACLR: Males: 1.95±0.52 Nm/kg, Females: 1.67±0.42 Nm/kg; Contralateral: Males: 1.98±0.49 Nm/kg, Females: 1.71±0.39 Nm/kg) and hip AD of the contralateral limb only (Males: 1.81±0.49 Nm/kg, Females: 1.60±0.37 Nm/kg). No limb-by-activity (AB: $F_{(1,51)}$=1.92, p=0.28; AD: $F_{(1,51)}$=0.90, p=0.35) nor limb-by-sex (AB: $F_{(1,51)}$=0.29, p=0.59; AD: $F_{(1,51)}$=0.50, p=0.49) interactions were observed.

Conclusions: Neither physical activity level nor sex seemed to impact strength recovery in pediatric patients approximately 6-months post-ACLR although, on average, males were stronger than females. Clinicians should consider evaluation of hip AB and AD strength in a return-to-sport testing battery and throughout rehabilitation to identify treatable strength deficits.

Abstract #22

Symmetric Strength Appears Sufficient: Uninjured Limb Strength in Individuals With a History of an ACL Injury is Equivalent to Dominant Limb Strength in Those Without

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Context: Muscle strength is important for successful return to activity and long-term outcomes after ACL injury. Equivalent strength between the uninjured and injured limbs is the standard for quantifying sufficient strength. However, negative strength adaptations occur in both limbs after ACL injury, which may mask strength deficits in the injured limb. As such, questions regarding the appropriateness of uninjured limb strength being the standard for comparison have been raised.

Objective: To compare strength of the quadriceps, hamstrings, and gluteus medius muscles in males and females between the uninjured limb (UNINJ) of those with prior ACL injury (ACL-I) and the dominant limb (DOM) of those with no prior ACL injury (Control).

Design: Cross-sectional.

Setting: Field Research Laboratory Testing.

Patients or Other Participants: A total of 5,650 cadets were tested. The ACL-I group (n=206, age=18.92+0.94 years, height=173.56+9.45 cm, weight=74.67+14.83 kg) consisted of 125 males and 81 females. The Control group (n=5,444, age=18.74+0.91 years, height=173.23+9.21 cm, weight=71.75+12.92 kg) consisted of 3,326 males and 2,118 females.

Intervention(s): Isometric strength was assessed using a handheld dynamometer. The UNINJ limb (ACL-I group) and the DOM limb (Control group) were tested. Average force (N) during a 5-second maximum voluntary isometric contraction was recorded across two trials and averaged together. Normalized torque values (Nm/kg) were calculated by multiplying the average force (N) by the lever arm length (m) and then dividing by the subject's body mass (kg). Intra-rater reliability for each muscle tested ranged from ICC = 0.73 to 0.98.

Main Outcome Measure(s): Separate two-way ANOVAs were performed for each muscle group with limb (UNINJ, DOM) and sex (male, female) as the between subject factors and normalized torque as the dependent variable (α<.05). Cohen's d effect sizes (ES) were calculated between the UNINJ and DOM limbs.

Results: No limb-by-sex interactions were observed for the quadriceps (p=0.998), hamstrings (p=0.506), or gluteus medius (p=0.320). There were significant main effects for limb as we observed greater strength in the UNINJ limb for the quadriceps (UNINJ=1.92+0.49 N*m/kg; DOM=1.85+0.458 N*m/kg; p=0.007; ES=0.16), hamstrings (UNINJ=0.95+0.21 N*m/kg; DOM=0.92 + 0.22

N*m/kg; p=0.036; ES=0.13), and gluteus medius (UNINJ=1.49+0.40 N*m/kg; DOM=1.39+0.40 N*m/kg; p=0.001; ES=0.24).

Conclusions: We found no evidence of reduced muscular strength in UNINJ limb of the ACL-I group compared to DOM limb of the Control group. While UNINJ limb strength was significantly greater, these may not represent meaningful differences given the small associated effect sizes (ES<0.25). Therefore, determining sufficient strength by using the UNINJ limb as the standard in those with ACL-I seems appropriate as strength values are equivalent to the DOM limb of Control subjects. A limitation should be noted in that time from injury was not controlled and should be explored in future research.

Abstract #23

ACL Re-Injuries: A Case Series

Hart JM*, Cousins M†, Riem L†, Sumpter A†, Meyer C*, Blemker S*, Knaus K*, Feng X*: *University of Virginia, Charlottesville; †Springbok Analytics, Charlottesville, VA

Context: Persistent muscle weakness is common following ACL reconstruction (ACLR). Over the course of recovery, impairments and/or imbalances can impact all muscles in the lower limb and potentially impact patient outcomes. Serial evaluation of muscle function using low-risk, highly precise measurement techniques can help identify treatable impairments in patients with ACL injury and reconstruction.

Objective: Evaluate muscle symmetry in all lower body muscles in 4 patients with ACL injury or reconstruction surgery

Design: Case series

Setting: Imaging Facility

Patients or Other Participants: Patient 1: 19y/o male with primary left side ACL injury evaluated within a week from his injury; Patient 2: 37y/o male with left-side primary ACLR evaluated at the time of release from rehabilitation; Patient 3: 20 y/o female elite level soccer player with left-side ACL tear within a year following contralateral primary ACLR; Patient 4: 23 y/o female elite soccer player with a history of 3 ACLR on the right and 1 ACLR on the left, evaluated approximately 6 months following her most recent right side ACLR.

Intervention(s): MRI scans were performed on a Siemens 3T scanner to obtain fat-suppressed proton-density-weighted images bilaterally of the entire lower limb from T12 vertebral level to distal to the fibular malleoli.

Main Outcome Measure(s): Automated MR image segmentation was used to precisely identify the boundaries for all 35 muscles on each leg to calculate individual muscle volumes. Symmetry is reported as a percentage, where larger numbers indicate greater asymmetry.

Results: Patient 1 had smaller volumes of the injured side vasti (7.5-8.1%) that did not affect the rectus femoris and 24% larger volume of the injured side biceps femoris (long head). Patient 2 had ACLR-side smaller vasti (range 6.2-10.5, greatest in the rectus femoris), sartorius (4%) and tibialis anterior (9.3%). Semitendinosus (24%) and gracillis (22.5%) asymmetry reflect graft harvest. Patient 3 had smaller vasti (5.8-8.6%), medial gastrocnemius (14.3%) and flexor digitorum longus (18.4%) but larger gluteus maximus (10.9%) and medius (5.7%) for the side with prior ACLR compared to the contralateral side with the recent ACL tear. Patient 4 had lower volumes on the right side vasti (8.9-18.0%) but not the rectus femoris, and a smaller tibialis posterior (12.8%), obturator internus (11.7%) and piriformis (7.7%). Also observed was larger hip musculature including gluteus maximus (7.7%) and deep hip rotators (13.3%). The right side gastrocnemius lateral head was larger (10.2%) whereas the left side medial head (7.9%) was larger.

Conclusions: The variability and non-uniformity in muscle volume response to primary and recurrent ACL injury and appears to become more complex with repeated injuries. These findings reinforce the need for early, precise, and serial measurements of muscle function to identify treatable impairments and prevent potentially harmful muscular compensations.

Abstract #24

Long-lasting Impairments in Quadriceps Mitochondrial Health, Muscle Size, and Phenotypic Composition are Present After Non-Invasive Anterior Cruciate Ligament Injury

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Context: Despite rigorous rehabilitation aimed at restoring muscle health, anterior cruciate ligament (ACL) injury is often hallmarked by significant long-term quadriceps muscle weakness. Derangements in mitochondrial function are a common feature of various atrophying conditions, yet it is unclear to what extent mitochondria are involved in the detrimental sequela of quadriceps dysfunction after ACL injury.

Objective: Using a preclinical, non-invasive ACL injury rodent model, our objective was to explore the direct effect of an isolated ACL injury on mitochondrial function, muscle atrophy, and muscle phenotypic transitions.

Design: Prospective randomized controlled laboratory study.

Setting: Research laboratory.

Patients or Other Participants: A total of 40 male and female, Long Evans rats (16-weeks-old, equivalent to 16 years of age in humans) were exposed to non-invasive ACL injury, while 8 additional rats served as controls.

Intervention(s): Rats were euthanized at 3, 7, 14, 28, and 56 days after ACL injury, and vastus lateralis muscles were extracted to measure the mitochondrial respiratory control ratio (RCR; state 3 respiration / state 4 respiration), mitochondrial reaction oxygen species (ROS) production, fiber cross sectional area (CSA), and fiber phenotyping.

Main Outcome Measure(s): Alterations in mitochondrial function and ROS production were detected using two-way (sex, group) analyses of variance. Average fiber type CSA and fiber type percent distributions were compared between ACL-injured and controls rats by sex with independent t-tests. Individual linear mixed effect models with a random effect of rat were used to investigate the influence of mitochondrial function on fiber CSA in males and females. Significance was set at $p<0.05$ and all analyses were performed using RStudio.

Results: Mitochondria-derived ROS increased 30-100% from days 7-56 after ACL injury (control:9.72 ± 0.74pmol·s^{-1}·mg^{-1} vs. ACL-injured groups range:12.81-27.08 ±0.74pmol·s^{-1}·mg^{-1}, $P<0.05$), concomitant with a 2-fold reduction in RCR (control:4.04 ± 0.42pmol·s^{-1}·mg^{-1} vs. ACL-injured groups range:1.40-1.81 ± 0.53pmol·s^{-1}·mg^{-1}, $P<0.05$). Post-injury, male rats displayed decreases in fiber CSA (days 7, 14, 56; $P<0.05$), loss of Iia fibers (day 7, $P < 0.05$), and an increase in Iib fibers (day 7, $P<0.05$), while females displayed no changes in CSA or phenotyping ($P>0.05$). Males displayed a positive relationship between state 3 respiration and CSA at days 14 and 56 ($P<0.05$), while females only displayed a similar trend at day 14 ($P=0.05$).

Conclusions: Long-lasting impairments in quadriceps mitochondrial health are present after ACL injury and play a key role in the dysregulation of quadriceps muscle size and composition. Our preclinical data indicate that mitoprotective therapies may be a potential therapeutic strategy to mitigate alterations in muscle size and characteristic after ACL injury. Recognizing the multitude of factors that contribute to dysfunctional muscles after ACL injury is especially important for the adolescent athlete given their elevated injury risk and susceptibility for more years lived with disability.

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Abstract #25

The Relationship Between Self-Reported Function and 2D Knee Kinematics Among Young Athletes After ACLR

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Context: Low patient-reported function has been associated with movement deficits among young athletes following anterior cruciate ligament reconstruction (ACLR). While 3-dimensional motion analysis is often inaccessible in a clinical setting, two-dimensional (2D) motion analysis is a reliable and more feasible method of assessing an athlete's kinematics.

Objective: To test the hypothesis that the ability to meet patient-reported outcome (PRO) target scores contributes to variance in 2D landing kinematics at time of return-to-sport (RTS) among young athletes after ACLR.

Design: Cross-sectional cohort study

Setting: Research laboratory

Patients or Other Participants: Twenty-nine athletes following primary ACLR (22 female, 7 male; mean age: 17.8±3.2 years)

Intervention(s): Within 8 weeks of clearance to RTS, all participants completed 3 PROs: International Knee Documentation Committee (IKDC) questionnaire, Knee injury and Osteoarthritis Outcome Score (KOOS), and ACL Return to Sport after Injury (ACL-RSI) questionnaire. Participants' responses were compared to age- and activity-relevant target scores for each PRO. Of the 5 KOOS subscales, only Sport and Quality of Life (QoL) were analyzed for this study.

Main Outcomes Measure(s): 2D kinematic data at initial contact of a drop vertical jump task were collected using a 2D motion analysis system. Knee flexion angle (KFA) and knee valgus angle (KVA) of the involved (IN) and uninvolved (UN) limbs were the variables of interest analyzed in Image J. Multiple linear regression analyses were used to determine how much variation in 2D kinematics is explained by achievement of PRO target scores, while adjusting for age and sex.

Results: Sixteen of the 29 (55.2%) participants met IKDC cut score of 90/100, 13/29 (44.8%) met KOOS Sport cut score of 92/100, 8/29 (27.6%) met KOOS QoL cut score of 92/100, and 17/29 (58.6%) met ACL-RSI cut score of 77/100. For the regression analyses of 2D movement variables, the KOOS Sport score model was significantly associated with KFA-IN, ($F(3,25) = 3.88$, $p=0.02$, adj. $R^2=0.24$), with age as the only significant predictor, explaining 24.1% ($p=0.006$) of the total variance. All regression models for KFA-UN were significant ($p<0.001$; adj. $R^2=0.448$-0.459), with age explaining between 26.0-38.7% ($p<0.01$) of the total variance for all models, and sex explaining 8.7% ($p=0.044$) of the total variance within the IKDC score model. All regression models for KVA-UN were significant ($p=0.001$-0.003; adj. $R^2=0.347$-0.399), with sex explaining between 16.1-29.8% ($p=0.001$-0.004) of the total variance for all models, and age explaining 12.0% ($p=0.026$) of the total variance within the KOOS Sport score model. Younger age and male sex were associated with increased KFA and decreased KVA within the respective analyses, while PRO cut scores were not.

Conclusions: Contrary to our hypothesis, the ability to meet PRO target scores did not contribute to the variance in 2D knee landing kinematics among young athletes after ACLR. However, younger age and male sex were associated with less risky landing patterns.

Abstract #26

Landing Kinetics Do Not Differ Based on Meniscal Surgical Interventions at the Time of ACL Reconstruction

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Context: Approximately 87% of individuals who undergo anterior cruciate ligament reconstruction (ACLR) also require surgery for meniscal injuries. Patients with meniscal surgery at the time of ACLR experience weaker quadriceps and worse patient-reported outcomes compared to those without meniscal injuries.

Objective: To compare limb symmetry indices (LSI) for first peak vertical ground reaction forces (vGRF) and external knee abduction moments (KAM) during a drop vertical jump (DVJ) between individuals with and without meniscal surgery at the time of ACLR.

Design: Cross-sectional

Setting: Research Laboratory

Patients or Other Participants: Twenty-five individuals who were 14-30 years old and 5-10 months post-primary, unilateral ACLR participated. Participants were assigned to groups (2) based on meniscal surgery status. The ACLR only group (n=13; 19.3±3.9 years; 7.0±1.3 months post-ACLR) included individuals who did not undergo a meniscal surgery at the time of ACLR while the meniscal group (n=12; 18.9±3.4 years; 6.8±1.1 months post-ACLR) included individuals who underwent a meniscal repair or meniscectomy at the time of ACLR.

Intervention(s): Participants were prepared with retroreflective marker clusters on the trunk and bilateral lower extremities to capture kinematics during a DVJ task. They jumped from a 30-cm box positioned a distance participant height from the center of two force plates and landed to capture kinetics. Immediately upon landing, participants completed a vertical jump for maximal height. Participants completed 3 successful trials with each limb contacting the center of the force plate without loss of balance. Kinematic and kinetic data were sampled at 120 Hz and at 1200 Hz, respectively.

Main Outcome Measure(s): Bilateral first peak vGRFs and external KAMs were extracted and used to calculate LSIs. Dependent variables (vGRF LSI% and KAM LSI%) were calculated using the LSI equation: |(Uninvolved limb – ACLR limb)/(0.5*(Uninvolved limb + ACLR limb))|*100 – where 0% indicates complete symmetry. Dependent variables were compared between groups using independent samples t-tests, 95% confidence intervals (CI), and Hedges g effect sizes (ES).

Results: The ACLR only group demonstrated greater first peak vGRF asymmetry (49.5±50.4%; CI: -27.4, 45.0; ES: 0.232) compared to the meniscal group (39.4±30.5%; CI: -33.0, 54.8; ES: 0.198) without statistical significance ($p=0.40$). Mean peak external KAM between limb asymmetry was greater in the ACLR group (72.4±44.6%) compared to the meniscal group (61.5±60.9%) but did not reach statistical significance ($p=0.31$).

Conclusions: Individuals with and without meniscal interventions at the time of ACLR demonstrate asymmetrical first peak loading and abduction forces exerted on the knee during a DVJ task. Both limbs are loaded asymmetrically during plyometric tasks which may be leading to the high rates of ACL re-injury following RTS. Focusing on symmetrical landing mechanics and neutral knee positioning will provide shared loading between limbs during common plyometric activities required for sport and reduce ACL re-injury rates.

Abstract #27

Stance Phase Gait Biomechanics Differ Between Adolescents and Adults After ACLR

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Context: Aberrant gait biomechanics following anterior cruciate ligament reconstruction (ACLR) are associated with knee osteoarthritis development. Many studies assess combined samples of adults and adolescents despite reported differences in development and rehabilitation after ACLR. It is unclear if gait biomechanics differ between adults and adolescents following ACLR.

Objective: To compare gait biomechanics associated with knee osteoarthritis between adolescents and adults post-ACLR.

Design: Case-control

Setting: Laboratory

Patients or Other Participants: Thirteen adolescents (77% Female, 16.7±0.6 years, 22.2±3.7 kg/m^{2,} height=1.7±0.1 m) and 13 adults (77% Female, 22.3±4.0 years, 22.9±3.3 kg/m^2, height=1.7±0.1 m) participated. All participants underwent gait biomechanics assessment during a single session within 6-12 months of primary, unilateral ACLR. Adolescents (<18 years) were matched to adults based on sex and time since ACLR (±2 months).

Intervention(s): Participants completed 5 overground walking trials within 5% of self-selected gait speed while marker trajectories and forces were collected using 3D motion capture and 2 staggered embedded forces plates.

Main Outcome Measure(s): ACLR limb vertical ground reaction force (vGRF), internal knee abduction moment (KAM), internal knee extension moment (KEM), and knee flexion angle (°) were extracted during the stance phase and time-normalized across 101 points (0-100%). vGRF was normalized to body weight (BW) and knee moments were normalized to the product of BW and height. Gait speed was compared between groups using independent t-tests. Functional waveform analyses were used to compare gait biomechanics between groups throughout stance with and without controlling for gait speed.

Results: Gait speed was slower in adolescents (1.150±0.110 m/s) compared to adults (1.277±0.130 m/s, $p<0.001$). Adolescents walked with lesser vGRF (9-15% of stance, peak mean difference=-0.043, 95%CI=[-0.073,-0.013]) and KAM (12-25% of stance, peak mean difference=-0.004, 95%CI=[-0.001,-0.006]) during early stance and lesser KEM during late stance (80-99% stance, peak mean difference=-0.004, 95%CI=[-0.002,-0.007]). Adolescents also walked with greater knee flexion angle throughout most of stance (0-21% and 29-100% of stance, peak mean difference=4.163, 95%CI=[2.604,5.724]). When controlling for gait speed, adolescents walked with greater vGRF (4-9% and 16-18% of stance, peak mean difference=0.048, 95%CI=[0.020,0.075]) and KEM (17-32% of stance, peak mean difference=0.004, 95%CI=[0.007,0.001]) during early stance compared to adults, and there were no differences in KAM. Adolescents continued to walk with greater knee flexion angle throughout stance when controlling for gait speed (0-100% of stance, peak mean difference=4.003, 95%CI=[2.239,5.764]).

Conclusions: Adolescents walked at slower gait speeds compared to adults, which is associated with worse posterior femoral cartilage composition in adults. While adolescents walked with greater knee flexion angle overall, they also walked with more crouched gait kinematics characterized by smaller knee flexion excursion (i.e. smaller knee flexion range of motion from early to mid-stance). Future studies should determine if limited knee flexion excursion during gait localizes knee joint loading to the posterior tibiofemoral compartment.

Abstract #28

Patterns of Gait Variability are Similar Between Adolescent and Adult Patients With ACLR

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Context: Individuals with anterior cruciate ligament reconstruction (ACLR) demonstrate a more regular and less adaptable gait pattern compared to uninjured controls. An adaptable gait pattern is the hallmark of a healthy locomotor system and can be examined via sample entropy, a measure of variability. It is hypothesized that a more regular gait pattern would result in a more consistent loading pattern from step-to-step, which may localize loading to a limited portion of the articulating tibiofemoral surface, thus negatively influencing knee joint health. A more regular knee flexion pattern during gait in adults with ACLR is associated with deleterious changes in cartilage composition linked to early osteoarthritis development. Gait regularity has been evaluated extensively in adults, but not in adolescents, and it remains unknown if gait regularity differs between adolescents and adults.

Objective: To determine if gait regularity differs between adults and adolescent patients with ACLR during overground walking.

Design: Cross-Sectional, Case Controlled Study.

Setting: Laboratory.

Patients or Other Participants: All participants were between 6-12 months post-ACLR at the time of participation. Thirteen adolescents (10 females; 9±3 months post-ACLR, age: 17±0.5 years old, height:168±8 cm, mass: 68±10 kg) were sex-, height-, and mass-matched with 13 adult participants (10 females; 8±2 months post-ACLR, age: 24±4 years old, height: 170±6 cm, mass: 67±10 kg).

Intervention(s): Five trials of overground gait biomechanics were completed at each participant's preferred gait speed. Bilateral knee kinematics were collected with a 10-camera 3D motion capture system (200Hz).

Main Outcome Measure(s): Frontal plane (flexion/extension angles) and sagittal plane (abduction/adduction angles) knee kinematics of the ACLR limb were extracted to calculate sample entropy, a measure of gait regularity. Sample entropy produces values ranging from 0 bits to 2 bits with lower values reflecting greater regularity. Independent samples t-tests were used to compare frontal and sagittal plane gait regularity between the groups.

Results: Adolescents and adults demonstrated similar patterns of gait regularity in both the frontal (t_{24}=0.14, p=0.65, d=0.17; adolescents: 0.11±0.16 bits, adults: 0.06±0.12 bits) and sagittal (t_{24}=0.92, p=0.08, d=0.26; adolescents: 0.12±0.16 bits, adults: 0.08±0.12 bits) planes.

Conclusions: There were no differences in gait regularity between adolescents and adults with ACLR. These findings are of concern given that a more rigid gait pattern may contribute to a less adaptable gait strategy and an increased rate of early cartilage degeneration. Considerable skeletal maturation occurs throughout adolescents that may influence gait regularity; therefore, a limitation was the age range of the adolescent group (16-17 years old). It is of interest to determine if these patterns are consistent in younger individuals to better understand how ACLR influences gait regularity prior to skeletal maturity. Future studies should evaluate effects of knee stability on cartilage composition over time in adolescents post-ACLR.

Abstract #29

Psychological Readiness and Injury-Related Fear are Associated With Early Knee Osteoarthritis Symptoms After ACL Reconstruction

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Context: Poor psychological responses after ACL reconstruction (ACLR) have been associated with increased secondary ACL injury risk. In patients with radiographic knee osteoarthritis (OA), poor psychological responses have been associated with worse knee symptoms. However, we do not know whether poor psychological responses after ACLR are associated with self-reported symptoms of early knee OA.

Objective: To examine the association between psychological responses (i.e., psychological readiness and injury-related fear) and

the presence of self-reported early knee OA symptoms in participants 6-12 months after ACLR.

Design: Cross-sectional study

Setting: Research laboratory

Patients or Other Participants: One-hundred and two participants (58 females, age=18.5 ± 2.7 years, time since surgery = 8.0 ± 1.6 months) were recruited. Participants were included if they were ages 13-25 years old, and 6 to 12 months post primary, unilateral ACLR. Participants were excluded if they had previous knee surgery, multi-ligament reconstruction, or had an articular cartilage lesion surgical procedure at the time of their ACLR.

Intervention(s): Participants completed the ACL Return to Sport after Injury Scale (ACL-RSI) to measure psychological readiness and the Tampa Scale of Kinesiophobia-11 (TSK-11) to measure injury-related fear.

Main Outcome Measure(s): The Knee Injury and Osteoarthritis Outcome Score (KOOS) was used to identify early knee OA symptoms. The KOOS consists of 5 subscales: pain, symptoms, quality of life, sport and recreation, and activities of daily living. KOOS subscale scores were used to dichotomize participants into those with and without early knee OA symptoms based on the classification criteria described by Luyten et al. The presence of early knee OA symptoms was defined as scoring $\leq$ 85.0 on 2 or more of the KOOS pain, symptoms, quality of life, or activities of daily living subscales. Descriptive statistics were calculated for the ACL-RSI and TSK-11. Separate logistic regression models with 95% confidence intervals (CI_{95}) were developed to determine if psychological readiness or injury-related fear were associated with the presence of self-reported early knee OA symptoms.

Results: Seventy participants (69%) met the criteria for early knee OA symptoms. Participants with self-reported early knee OA symptoms exhibited increased injury-related fear (TSK-11=20.6±4.1) and decreased psychological readiness (ACL-RSI=63.2±21.1) when compared to those without self-reported early knee OA symptoms (TSK-11=15.6 ±4.5, ACL-RSI=89.0±14.1). For every standard deviation (SD; 22.6) decrease in ACL-RSI, a participant had 8.6 times greater odds of reporting early knee OA symptoms (CI_{95}: 3.3, 22.4). For every SD (4.8) increase in TSK-11, a participant had 3.9 times greater odds of reporting early knee OA symptoms (CI_{95}: 2.1, 7.4).

Conclusions: Participants with poor psychological readiness and elevated injury-related fear after ACLR have greater odds of experiencing early knee OA symptoms. The incorporation of psychological therapies may be effective in reducing symptoms and maintaining long-term knee joint health for individuals after ACLR.

Abstract #30

Elevated Injury-Related Fear is Associated With Greater Knee Abduction Angle During Jump-Landing in Individuals With ACL Reconstruction

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Context: Injury-related fear (IRF) after ACL reconstruction (ACLR) is associated with secondary ACL injury. Increased knee abduction angle (KAA) during jump-landing tasks have also been associated with secondary ACL injury risk. However, it is unknown whether IRF is associated with KAA during jump-landing tasks in individuals post-ACLR.

Objective: To determine whether IRF was associated with involved limb KAA during the first 100ms of landing in individuals 5-12 months post-ACLR. We hypothesized that elevated IRF would be associated with greater involved peak KAA during landing.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: Thirty-six participants between 14 and 35 years old at 5-12 months post primary unilateral ACLR (females=19, age=19.9 ± 5.1 years, height=172.5 ± 9.4 cm, weight=76.7 ± 20.0 kg, time since surgery (TSS)=7.2 ± 1.7 months) were recruited from a sports medicine clinic. Participants were excluded if they had previous knee surgery or multi-ligament reconstruction.

Intervention(s): Participants completed the Tampa Scale of Kinesiophobia-11 (TSK-11) to measure IRF.

Main Outcome Measure(s): Participants completed 3 successful trials of a standard drop vertical jump task. A trial was considered successful if the participant landed at the center of the force plate without loss of balance. Participants were prepared with reflective markers affixed bilaterally to the lateral aspects of the thighs and shanks, the dorsal surface of the feet, and the thoracic and lumbar spine. A ten-camera three-dimensional motion capture system sampled at 120 Hz (Vicon Motion Systems Ltd., Oxford, UK) and two embedded force plate platforms (Advanced Medical Technology Inc., Watertown, MA, USA) sampled at 1200 Hz were used to capture peak involved KAA during the first 100ms of landing. 100ms was selected as ACL injuries often occur during this timepoint. Descriptive statistics were calculated for TSK-11 and KAA. Multiple linear regression was used to examine the association between IRF and peak involved limb KAA within the first 100ms of landing after controlling for TSS and sex. Alpha was set a priori $P < 0.05$.

Results: Participants averaged 5.2±4.8 degrees for involved limb KAA during landing and scored 20.1±4.3 on the TSK-11, suggesting elevated levels of IRF in this sample. Injury-related fear, sex, and TSS explained 20% of the variance observed in involved limb KAA ($p = 0.02$). When controlling for sex and TSS, for every 1-point increase on the TSK-11, involved limb KAA increased by 0.37° ($p = 0.04$).

Conclusions: Elevated IRF was associated with increased involved limb KAA in the first 100ms of landing in individuals 5-12 months post-ACLR. Modifying IRF and high-risk jump-landing biomechanics is needed to decrease secondary ACL injury risk. Future research should investigate feasible psychological interventions to reduce IRF and improve KAA in patients post-ACLR.

Return to Sport After Anterior Cruciate Ligament Reconstruction: Abstracts #31–35

Abstract #31

Development of an Interactive Dashboard for Comparison of Performance-Based and Patient-Reported Outcome Measures Among Adolescents 5 to 7 Months After ACL Reconstruction

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Context: Biologic sex and age play a vital role in determining the trajectory of recovery for adolescents following ACL reconstruction (ACLR). Providing clinicians and researchers with user-friendly tools to compare adolescents' performance on clinical outcome measures to biologic sex and age-group specific reference values enables patient-centered understanding of rehabilitation progress after ACLR.

Objective: To develop an interactive dashboard of age-group and sex-specific reference values for performance-based and patient-

reported outcome measures for adolescents 5-7 months after ACLR.

Design: Cross-sectional study

Setting: Seven hundred eighty-seven participants (438 females) were recruited from 3 university-affiliated sports medicine clinics and 2 children's hospitals.

Patients or Other Participants: Participants were 12-20 years old and had undergone primary, unilateral ACLR 5-7 months prior to assessment. Participants were excluded if they experienced a serious surgical or post-operative complication that resulted in a second surgery.

Intervention(s): Participants reported their biologic sex and were sub-divided into age categories based on recommendations from the Centers for Disease Control: 1) early-adolescence (N=183, 51.9% female): 12-14 years old; 2) mid-adolescence (N=459, 57.3% female): 15-17 years old; 3) late-adolescence (N=145, 55.2% female): 18-20 years old.

Main Outcome Measure(s): Participants completed the following patient-reported outcome measures: 1) International Knee Documentation Committee Subjective Evaluation Form (IKDC, N=345), 2) Pediatric IKDC (N=419), 3) Knee Injury and Osteoarthritis Outcomes Score (KOOS, N=344), 4) ACL Return to Sport after Injury Scale (ACL-RSI, N=427). The following performance outcomes were captured bilaterally: 1) single hop (% leg length; N=449), 2) triple hop (% leg length; N=413), 3) crossover hop (% leg length; N=343), 4) 60°/s isokinetic quadriceps and hamstrings strength (Nm/kg; N=300). Measures of central tendency and variability were calculated for the sample and all combinations of biologic sex and age. Distributions were developed for each outcome measure for the total sample and all combinations of biologic sex and age group after which, deciles were calculated within each distribution.

Results: Descriptive statistics were used to create an interactive dashboard that displays the decile of the distribution in which a study participant falls when compared to the total sample and individuals of the same age group and biologic sex. For example, among biologic females a KOOS Quality of Life (KOOS-QOL) score of 63 would fall 4th decile during early-adolescence (KOOS-QOL= 70.6±20.6), the 5th decile during mid-adolescence (KOOS-QOL= 67.4±18.5), and the 6th decile during late-adolescence (KOOS-QOL= 65.6±17.6).

Conclusions: The findings of this study indicate that age and biologic sex should be considered when evaluating patient-reported function and performance at an important clinical time point (~6 months) after ACLR. Our findings, and the interactive dashboard, will allow clinicians to compare their patient's data to biologic sex and age-appropriate peers to better understand the patient's functional status during the late stage of rehabilitation.

Abstract #32

Evaluation of Hop Performance in Anterior Cruciate Ligament Reconstructed Children Using Reference Data of Healthy Peers

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Context: Evaluation of functional performance in children after anterior cruciate ligament (ACL) reconstruction may benefit from comparison to reference values of healthy peers.

Objective: To evaluate the hop performance in children one year after ACL reconstruction with a comparison to reference values of healthy peers.

Design: Cross-sectional study.

Setting: Clinical (physiotherapy).

Patients or Other Participants: In this study, data of four hop performance tests from 141 ACL reconstructed children (52% girls) one year post-surgery were included and compared with existing reference data from 531 healthy Danish schoolchildren (52% girls). All pediatric ACL patients were treated and rehabilitated at the same university hospital in Copenhagen, Denmark.

Intervention(s): All participants performed four one-legged hop tests: 1) single hop (SH), 2) 6 m timed hop (6 m-timed), 3) triple hop (TH), and 4) cross-over hop (COH) on both legs.

Main Outcome Measure(s): The best hop result (longest/fastest hop) from each leg was registered. The limb asymmetry was assessed by setting values of the best performing leg to 100%; relating values of the other leg to this and subsequently subtract this from 100. Between-group differences in hop performance and limb asymmetry were estimated, with adjustment for relevant covariates (age/gender/height/body-mass). The operated/non-operated legs were compared with the corresponding right/left legs of the healthy children.

Results: No statistically significant between-group differences were observed in any of the hop tests regarding the operated leg of the ACL reconstructed children. Differences between the operated right/left leg and the right/left healthy control leg were (mean±SE): SH: 2.9±3.5 cm/3.6±3.4 cm, P=0.404/P=0.292; 6 m-timed: 0.02±0.07 $m{\cdot}s^{-1}$/0.04±0.06 $m{\cdot}s^{-1}$, P=0.771/P=0.489; TH: 4.1±10.1 cm/5.4±9.4 cm, P=0.681/P=0.569; COH: 13.2±10.5 cm/15.6±10.0 cm, P=0.208/P=0.119. In contrast, the differences between the non-operated left leg and the healthy children's left leg showed statistically significant differences for all hop tests (mean SE): SH: 11.3±3.6 cm; 6 m-timed: 0.24±0.07 $m{\cdot}s^{-1}$; TH: 29.8±9.9 cm; COH: 28.7±10.6 cm, $P < .001$. While, the ACL reconstructed children had less limb asymmetry than the healthy children except for COH where they had 14% more, these differences were not statistically significant. Generally, the asymmetry outcome confidence intervals were wide indicating that some ACL reconstructed children may have ~23% more/less limb asymmetry than their healthy peers.

Conclusions: The hop performance of the ACL reconstructed children one year post-surgery matched the level of the healthy children and they performed better on their non-operated left leg than the healthy children in all hop tests. Difference in limb asymmetry was modest. However, it cannot be excluded that functional deficits exist among some of the ACL reconstructed children. Thus, a future goal is to use the reference material to identify those pediatric ACL patients who are below the functional performance level of their healthy peers.

Abstract #33

Limb Symmetry of the Single-Leg Hop for Distance Pre and Post Anterior Cruciate Ligament Reconstruction

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Context: Current return to play (RTP) decisions rely on various components of function, typically using the contralateral limb as reference. However, functional deficits have been shown to occur bilaterally following lower extremity injuries.

Objective: Determine the change in single-leg hop performance (SLHOP) and symmetry from pre-injury to RTP following anterior cruciate ligament reconstruction (ACLR).

Design: Longitudinal study

Setting: High school gymnasium

Patients or Other Participants: Two-hundred eighty-five high school athletes were enrolled (76 females, 175.08±9.71cm, and 78.96±6.99kg). Fourteen participants sustained an ACLR during

their athletic season and completed follow-up testing (6 females, 176.17±9.21cm, 78.29±9.70kg, and 209.79±30.79 days time lost).

Intervention(s): All participants completed the SLHOP before their athletic season (pre-injury). Individuals were excluded if they had a history of a lower extremity surgery, lower extremity injury in the last 3 months, or were not cleared for their sport. Individuals completed two practice trials of the SLHOP on each leg and then completed three documented trials on each leg. Individuals had to maintain balance for 2 seconds without additional hopping or the contralateral limb touching the ground. After baseline testing, individuals completed their respective sport and if they sustained an ACLR, were enrolled in follow-up testing. Individuals with ACLR completed the Knee Osteoarthritis Outcome Score (KOOS) at time of surgery, 3 months post-surgery, and 6-months post-surgery. Additionally, at RTP participants completed the SLHOP.

Main Outcome Measure(s): To evaluate changes in SLHOP from baseline to RTP, three paired t-tests were conducted. The independent variable was time (baseline, RTP) with the following dependent variables: injured limb (cm), uninjured limb (cm), and limb symmetry (%) hop distance. To evaluate changes in KOOS, five repeated-measures ANOVAs were conducted. The independent variable was time (time of surgery, 3-months post-surgery, and 6-months post-surgery) and the dependent variables consisted of the 5 KOOS subscales. Alpha level was uncorrected at 0.05 for all analyses.

Results: SLHOP for the injured and uninjured limb significantly decreased from pre-injury to RTP ($p<0.001$). Specifically, the injured limb decreased 23.95±15.60cm (Hedge's g=1.49) and the uninjured limb decreased 19.95±11.43cm (Hedge's g=1.69) at RTP. However, symmetry did not significantly decrease from pre-injury to RTP (99.90±8.31% pre-injury and 96.60±6.22% RTP; p=0.14). All KOOS subscales significantly improved over time between all time points ($p<0.05$). The largest differences were seen from time of injury to 3-months post on the KOOS-symptoms (mean difference=39.86±2.12) and KOOS-quality of life (mean difference 41.21±3.46).

Conclusions: Relative to pre-injury, bilateral SLHOP deficits remain at RTP following ACLR despite limb symmetry remaining unchanged. These data suggest using the contralateral limb may overestimate function and limb symmetry should be used with caution when executing RTP decisions after ACLR. Clinicians should consider using pre-injury data in order to track complete functional recovery following ACLR.

Abstract #34

Pass Rates Among Different Components of Return to Sports Test Batteries After ACLR in Adolescent Patients

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Context: Following ACL reconstruction (ACLR) clinicians utilize batteries of tests to guide return to activity decisions. Clinicians may have difficulty in determining which criteria to follow if there is disagreement in pass/fail outcomes from various tests.

Objective: There is evidence of disagreement between strength and hopping test outcomes in adults. The purpose of this study was to determine whether this relationship was similar in adolescents. We hypothesized that a greater proportion of participants would pass hop tests and fail strength tests.

Design: Descriptive Laboratory Study.

Setting: University Laboratory.

Patients or Other Participants: A total of 106 adolescent participants (50 males, 56 females) on average 6.7±1.39 months post primary, unilateral, and uncomplicated ACLR (16.1±1.46 years, 170.4±11.29 cm, 71.7±18.41 kg) completed the study procedures as a part of a larger research study.

Intervention(s): Participants completed 8 repetitions of isokinetic knee extension at 90°/s and 180°/s on a Biodex System 3 Dynamometer. Peak torque from each set was recorded bilaterally. Participants also completed three trials of the single leg hop (SLHOP) and the triple hop test was measured in cm. The average distance of each set of three hop tests was recorded bilaterally.

Main Outcome Measure(s): Primary outcomes were peak torque during isokinetic knee extension at each velocity and average distance during hop testing. Limb symmetry index for each measure was calculated using the following equation (LSI = (ACLR / contralateral side)/100). "Pass" was defined as 90% LSI or above for each test. Pass rates were compared between each combination of isokinetic strength tests and hop tests using chi square tests. Alpha was set at $p \leq 0.05$.

Results: Mean LSI for each test were as follows: 90°/s=0.7±0.16, 180°/s=0.8±0.15, SLHOP=0.9±0.12, and triple hop=0.9±0.10. Pass rates were non-uniformly distributed between isokinetic testing and SLHOP testing (90°/s X^2=4.93 p=0.03, 180°/s X^2=5.80 p=0.02). There was no significant association between isokinetic testing and the triple hop (90°/s X^2=1.27 p=0.26, 180°/s X^2=0.56 p=0.46). Disagreement between 90°/s and SLHOP test pass results occurred in 46.2% (46/106) of the patients. Specifically, 3 patients passed strength testing and failed the SLHOP whereas 43 patients failed strength testing and passed hop testing. Disagreement between testing at 180°/s and SLHOP results occurred in 40.6% (43/106) of the patients. For testing at 180°/s, 7 patients passed strength testing and failed the SLHOP whereas 36 patients failed strength testing and passed hop testing.

Conclusions: Conflicting information about patient readiness from different test types may challenge clinicians when making decisions. When findings disagree, patients are more likely to pass hop tests in the face of persistent weakness indicating that clinicians should be wary of interpreting hop testing in a vacuum as it is testing a capacity that is not directly related to muscular function following injury.

Abstract #35

Kids Are Not Adults; Sustainable Knee Health After a Pediatric ACL-Injury Warrants Reconsideration of Return to Sport Decision-Making. A Scoping Review

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Context: Up to 90% of pediatric athletes Return to sport (RTS) after anterior cruciate ligament reconstruction (ACL-R). However, less than 50% RTS at the same level. In addition, second ACL injury rates are up to 34%.

Objective: To study (1) which physical and psychological criteria currently guide clinical decision making on RTS in pediatric athletes after ACL-injury and (2) present a framework with insights from cognitive and neurophysiological domains to enhance rehabilitation outcomes.

Data Sources: PubMed, CINAHL, Embrase and Cochrane library databases and grey literature were systematically searched. Studies on pediatric (<18 years) ALC-injured patients (surgically or non-surgically), RTS tests and decision-making were included.

Study Selection: The search yielded 1214 results. Two authors independently reviewed titles, abstract, and full-text. Of all results 962 were excluded. Grey literature and cross-reference checking resulted in 7 extra studies. After full text screening of 259 studies 196 were excluded, thus 63 were finally included for data extraction. Disagreement was resolved by discussion.

Data Extraction: A data chart was created for structured data extraction. Details on study population, study aims, methodology, intervention type, outcomes measures and important results were

collected by one examiner. The included study types were Cohort (n=23,37%), Cross-sectional (n=7,11%), Case-series (n=27,43%) and (randomized) controlled trial (n=6,10%).

Data Synthesis: Patient numbers, their characteristics, type of sports, physical outcome measures (POMs) and patients reported outcome measures (PROMs) and both time and cut-off values for RTS clearance were extracted. Studies included a total of 4456 patients (mean age 14) and 7 POMS and 9 PROMS were identified. Quadriceps and hamstrings strength (n= 25, 40%), knee ligament arthrometer (n=24, 38%) and hop tests (n=22, 35%) were commonly assessed. These tests guided RTS decision making in <50% of studies. Strictest cut of scores in hop and strength testing were post-operative limb symmetry index (LSI) differences of >90% or arthrometer difference <3mm. Regarding PROMs the International Knee Documentation Committee (IKDC (n=24, 38%)), Lysholm (n=23, 37%) and Tegner (n=15, 24%) were most reported. Only the IKDC was RTS decisive for RTS with an 85% threshold.

Conclusions: RTS decision-making in paediatric ALC-reconstructed patients is in general not based on adherence of clear criteria. The LSI is often used for hop testing, but recent research suggests it overestimates knee function using the current thresholds. Hop testing biomechanics then are still impaired and these lack any context, which is more and more recognized as important rehab content. Stricter thresholds, clear biomechanical parameters, more contextual rehab and RTS guidance will likely improve clinical results after ACL-R.

Surgical Considerations: Abstracts #36–38

Abstract #36

Quadriceps Tendon Autograft in Pediatric Anterior Cruciate Ligament Reconstruction: Graft Dimensions and Prediction of Size on Preoperative MRI

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Context: There has been a growth of interest in quadriceps autograft anterior cruciate ligament (ACL) reconstruction in the pediatric population.

Objective: The goal of this study was to evaluate children and adolescents who underwent ACL reconstruction using a quadriceps autograft to determine the properties of the harvested graft and to assess the value of demographic, anthropometric, and MRI measurements in predicting the graft size preoperatively.

Setting: Referral pediatric sports referral hospital

Intervention(s): A retrospective IRB-approved database search was performed from January 2018 through October 2020 for patients undergoing ACL reconstruction.

Patients or Other Participants: Patients <18 years old at the time of surgery in whom a quadriceps tendon autograft was used were selected.

Main Outcome Measure(s): Demographic data and anthropometric measurements were recorded and graft measurements were abstracted from the operative note. Knee magnetic resonance images (MRI) were reviewed to measure the quadriceps tendon thickness on sagittal cuts. Linear regression models were used to correlate the graft length and diameter with anthropometric and radiographic data.

Results: A total of 169 patients (98 male) were included in the final analysis, with a median age of 15 years (range, 9-17). A tendon length of 65mm or more was harvested in 159 (94%) patients. The mean final graft diameter was 8.4 ± 0.7mm (range, 7 – 11mm). All patients had a graft diameter of 7mm or more, and 139 (82%) had a diameter of 8mm or larger. Preconditioning decreased the graft diameter by a mean of 0.68 ± 0.23mm. Age (P=0.04) and quadriceps thickness on MRI (P<0.001) were significant predictors of the final graft diameter. An MRI sagittal thickness of >6.7mm was 97.4% sensitive for obtaining a graft of ≥8mm in diameter. A linear regression model established that age and height were significant predictors of graft length and accounted for 18.3% of explained variability in graft length (F (2,166) = 18.6, P<0.001, regression equation: graft length = 47.01 + age*0.36 + height*0.10).

Conclusions: Our findings suggest that tendon-only quadriceps autograft is a reliable graft source in the pediatric ACL reconstruction, yielding a graft of ≥8mm in diameter in 82% of pediatric patients. Furthermore, preoperative MRI measurements can be reliably used to predict a graft of adequate diameter in children and adolescents undergoing ACL reconstruction, with a sagittal thickness of >6.7mm being highly predictive of a final graft size ≥8mm.

Abstract #37

Gait Biomechanics in Individuals With Quadriceps Tendon Autograft ACL Reconstruction

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Context: Anterior cruciate ligament reconstructions (ACLR) are frequent, especially in active populations. Growing evidence suggests the quadriceps tendon (QT) autograft viable for ACLR. Little information is available examining walking gait biomechanics following QT-ACLR.

Objective: To describe hip and knee joint biomechanics during the stance phase of walking gait in QT-ACLR patients. We hypothesized that these would be different between the QT-ACLR and healthy limb throughout the stance phase of gait.

Design: Descriptive laboratory study.

Setting: Research laboratory.

Patients or Other Participants: 14 participants (11M 3F, age= 25.9±9.8 years, height= 1.8±0.1 m, mass 83.2±16.3 kg) were recruited in a convenience sample from orthopedic offices.

Intervention(s): The independent variable was limb (QT-ACLR vs healthy). A biomechanics assessment was completed with an active marker set. Participants walked at a self-selected speed on a split-belt instrumented treadmill. Data were analyzed and time-normalized from 0-100% of the stance phase with a custom LabVIEW program.

Main Outcome Measure(s): Dependent variables were 3-dimensional hip and knee kinetics and kinematics during the stance phase. Curve analysis graphs with averages and 95% confidence intervals were created to identify statistically significant differences between limbs. Percentages represent periods during the stance phase where significant differences occurred between limbs. Cohen's *d* effect sizes with pooled standard deviations were calculated from the greatest difference between group means.

Results: The ACLR limb had reduced external moments: knee flexion (14-23% *d*=-1.1(-1.9,-0.3)); knee adduction (53-81% *d*=-1.8 (-0.9,-2.7)); knee internal rotation (55-84% *d*=-1.6(-0.7,-2.4)); hip flexion (60-67% *d*=-1.1(-1.9,-0.3)); hip abduction (31-35%, 71-76% *d*=-1.2(-0.4,-2.0)); hip internal rotation (56-88% *d*=-1.7(-0.9,-2.6)). The ACLR limb had reduced angles: knee flexion (1-8%, 58-85% *d*=-1.8(-2.6,-0.9)); knee abduction (9-32%, 92-100% *d*=-2.4(-1.5, -3.4)); knee internal rotation (0-100% *d*=-5.7(-4.0,-7.4)); hip abduction and adduction (0-100% *d*=-3.0(-4.1,-1.9)); hip external rotation (20-39% *d*=-1.7(-2.5,-0.8)). The ACLR limb had increased hip internal rotation angle (88-100% *d*=1.6(0.8,2.5)).

Conclusions: Biomechanical differences exist at the hip and knee during walking gait between ACLR and healthy limbs in participants who underwent QT-ACLR. Despite returning to physical activity, deficits persisted in lower extremity function. These findings are similar to previous research examining other ACLR graft types and walking gait, specifically, unloading of the ACLR limb and quadriceps avoidance gait patterns. These

asymmetries should be addressed when designing rehabilitation programs following ACLR.

Abstract #38

Differences in Gait Biomechanics Between Individuals With Quadriceps Versus Patellar Tendon Autograft Reconstruction

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Context: Lower extremity dysfunction commonly persists following anterior cruciate ligament reconstruction (ACLR) regardless of graft type. Bone patellar-tendon bone (PT) autografts are most commonly used for ACLR. Preliminary evidence examining strength and functional outcomes following quadriceps tendon (QT) autografts is favorable. Research comparing walking gait between PT-ACLR and QT-ACLR patients is lacking.

Objective: To compare walking gait biomechanics between those who underwent PT- and QT-ACLR. We hypothesized that biomechanics would be similar between groups throughout the stance phase.

Design: Descriptive laboratory study

Setting: Research laboratory.

Patients or Other Participants: 24 participants were recruited in a convenience sample from orthopedic offices with PT autografts (n=10, 5M, 5F, age=21.1±5.4 yrs, height=1.7±0.1 m, mass=75.3±14.7 kg) and QT autografts (n=14, 11M, 3F, age=25.8±9.8 yrs, height=1.8±0.1 m, mass=83.2±16.3 kg).

Intervention(s): The independent variable was graft type (PT vs QT). A biomechanics assessment was completed with an active marker set. Participants walked at a self-selected speed on a split-belt instrumented treadmill. Data were analyzed and time-normalized from 0-100% of the stance phase with a custom LabVIEW program.

Main Outcome Measure(s): Dependent variables were 3-dimensional hip and knee kinetics and kinematics during the stance phase. Curve analysis graphs with group means and 95% confidence intervals were created to identify statistically significant differences between PT- and QT-ACLR limbs. Percentages represent periods during the stance phase where significant differences occurred between graft types. Cohen's *d* effect sizes with pooled standard deviations were calculated from the greatest difference between group means.

Results: The QT group had reduced external moments: knee flexion (73-92% *d*=-1.2(-2.1,-0.3)); knee adduction (29-91% *d*=-2.0(-1.0,-3.0)); hip flexion (11-75% *d*=-2.2(-3.2,-1.1)). The QT group had increased angles: knee abduction (0-95% *d*=4.3(5.7,2.8)); hip extension (81-89% *d*=1.3(2.1,0.4); hip abduction (0-12% *d*=1.5(2.4,0.6)); hip external rotation (0-2% *d*=1.2(0.3,2.1)). The QT group had reduced hip flexion (0-30% *d*=-2.6(-3.7,-1.5)) angles.

Conclusions: In individuals previously cleared for return to physical activity, differences in hip and knee biomechanical patterns are present between PT and QT ACLR limbs during self-selected walking gait. QT-ACLR had reduced external moments during propulsion possibly associated with decreased muscle force production. These results indicate that PT-ACLR and QT-ACLR may not produce equitable functional outcomes.

Early Markers of Posttraumatic Osteoarthritis: Abstracts #39–42

Abstract #39

Adolescent and Adult Participants Differ in the Change in the Prevalence of Early Knee Osteoarthritis Symptoms After ACL Reconstruction

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Context: Patients with ACL reconstruction (ACLR) report a high prevalence of symptoms that meet a patient-reported classification criteria for early knee osteoarthritis (OA) at ~6 months post-ACLR. It is unclear how prevalence of early knee OA symptoms changes during the first year post-ACLR and whether the change in prevalence is different between adolescent and adult participants post-ACLR.

Objective: To compare the change in prevalence of early knee OA symptoms post-ACLR in adult and adolescent participants.

Design: Cohort study.

Setting: Laboratory.

Patients or Other Participants: Participants 13-35 years of age were recruited from a sports medicine clinic if they had undergone primary unilateral ACLR. We included participants with: 1) initial visit between 5 and 9 months post-ACLR and 2) a follow-up visit ≥ 2 months later.

Intervention(s): Adolescent participants were 13-17 years old (n=30). Adult participants were 18-35 years old (n=32).

Main Outcome Measure(s): At both study visits, participants completed the Knee Injury and Osteoarthritis Outcomes Score (KOOS) subscales: activities of daily living, symptoms, pain, and quality of life. The presence of early OA symptoms was operationally defined using validated, patient-reported classification criteria described by Luyten et al. (i.e., scoring ≤85% on at least 2 of the KOOS subscales). Participants were grouped based on the classification criteria from both study visits: 1) no early OA at both visits, 2) early OA at visit 1 but not 2, 3) early OA at visit 2 but not 1, 4) early OA at both visits. We used a Fisher's Exact test to compare the change in prevalence of early knee OA symptoms between adolescent and adult participants post-ACLR.

Results: Time post-ACLR was similar between adult and adolescent participants at visits 1 (adults=6.5±1.0, adolescents=6.6±1.3 months) and 2 (11.5±2.8, 11.5±3.0 months). There was a difference between adult and adolescent participants for the change in prevalence of early knee OA symptoms post-ACLR (p=0.004). The following percentages of adult and adolescent participants were classified as: no early OA at both visits (adults=3%, adolescents=30%), early OA at visit 1 but not 2 (13%, 23%), early OA at visit 2 but not 1 (3%, 0%), and early OA at both visits (81%, 47%).

Conclusions: Only 17% of participants had resolution of early knee OA symptoms from ~6 to ~12 months post-ACLR. The majority of adult (81%) and adolescent (47%) participants post-ACLR met a classification criteria for early knee OA symptoms at both post-ACLR visits, but the prevalence was significantly greater in adult participants. Future research needs to identify interventions that target these symptoms early post-ACLR to prevent persistent disability and maintain long-term knee joint health, especially for adult patients.

Abstract #40

Between-Limb Changes in Femoral Articular Cartilage Composition in Adolescent and Young Adult Females Following ACL Reconstruction: An Exploratory Analysis

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Context: Decreased tibiofemoral articular cartilage proteoglycan density (PGD) is an early compositional change reflective of osteoarthritis development in individuals with an anterior cruciate ligament reconstruction (ACLR). T1ρ magnetic resonance imaging (MRI) provides an *in vivo* estimate of PGD which has been used to longitudinally track tissue health post-ACLR. While incidence of ACL injury is increasing for adolescent females, it remains unknown if

changes in tibiofemoral articular cartilage PGD differs between adolescent and young adult females.

Objective: To determine between-limb effect sizes for PGD in 3 groups of female patients between 6 and 9 months post-ACLR who are: 1) ≤17; 2) 18-20; 3) 21-35 years old.

Design: Cross-sectional, case-comparison analysis

Setting: Laboratory

Patients or Other Participants: We retrospectively stratified females who underwent primary, unilateral ACLR testing into 3 groups: 1) ≤17 years old (n=5; 23.42±0.42 kg/m^2; 16.64±0.60 years old), 2) 18-20 years old (n=5; 23.18±0.93 kg/m^2,19.40±0.89 years old); 3) 21-35 years old (n=5; 23.2±1.75 kg/m^2; 23.78±2.97 years old). Groups were matched on body mass index (±3kg/m^2) and months post-ACLR (±2).

Intervention(s): T1ρ MRI was collected in both the ACLR and contralateral limbs during a single session.

Main Outcome Measure(s): MRI T1ρ images of the tibiofemoral articular cartilage were collected with either a Siemens Magnetom TIM Trio 3T scanner or a Siemens Magnetom Prisma 3T Power-Pack scanner on both limbs. Femoral articular cartilage was segmented into medial and lateral femoral (MFC, LFC) weightbearing regions. Mean T1ρ relaxation times (ms) calculated for each region, where greater T1ρ relaxation times were interpreted as lower estimated PGD. Hedge's g effect sizes and associated 95% confidence intervals (CI) were calculated between the ACLR and contralateral limb for MFC and LFC T1ρ relaxation times in each group (strong=0.8; moderate=0.5; weak=0.2).

Results: Individuals who were ≤17 years old demonstrated strong between-limb effect sizes in the MFC (ACLR=54.73±2.57ms vs Uninjured=51.46±0.59ms; g=1.58; 95% CI= 0.07, 3.09) and LFC (ACLR=55.97±2.33ms vs Uninjured=50.61±1.99ms; g=2.24; 95% CI= 0.55, 3.92). Individuals between 18-20 years old displayed weak between-limb effect sizes in the MFC (ACLR=53.44 ± 4.60ms vs Uninjured=53.37 ± 1.67ms; g=0.02; 95% CI=-1.30, 1.34) and LFC (ACLR=53.76 ± 2.33ms vs Uninjured=52.16 ± 3.22ms; g=0.30; 95% CI= -1.02, 1.63). In individuals 21-35 years old, moderate effect sizes were observed between-limbs in the MFC (ACLR=52.69±4.49ms vs Uninjured=50.37±2.57ms; g=0.57; 95% CI= -0.77, 1.92) and LFC (ACLR=53.78±5.37ms vs Uninjured=50.20±3.37ms; g=0.72; 95% CI= -0.64, 2.08).

Conclusions: Tibiofemoral PGD changes may differ by age following ACLR, with the most deleterious between-limb effects observed in the youngest female ACLR patient group. Future studies should consider the impact of age on compositional tissue outcomes following ACLR.

Abstract #41

Adolescents Demonstrate Increases in Joint Tissue Metabolism Preoperatively to 6 Months After Anterior Cruciate Ligament Reconstruction

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Context: Serum cartilage oligomeric matrix protein (sCOMP) is an important biomarker of cartilage metabolism and has been associated with knee joint health in patients with anterior cruciate ligament reconstruction (ACLR). Previous studies have reported that greater adult age is associated with greater sCOMP, but the effects of age on biomarkers of cartilage metabolism have not yet been explored in younger individuals post-ACLR. Many studies include ACLR patients between 16 and 35 years, yet it remains unclear if sCOMP trajectories early post-ACLR differ between adolescent and young adult ACLR patients.

Objective: Determine differences in sCOMP between adolescents (≤18 years old) and young adults (19-31 years old) preoperatively to 6 months post-ACLR.

Design: Case-control study

Setting: Laboratory

Patients or Other Participants: Twenty-two participants with primary unilateral ACL injury planning to undergo ACLR participated. Adolescents (n=11, 64% female, 17.09±1.64 years old, BMI=25.69±6.20 kg/m^2) were identified from a larger cohort. Young adults (n=11, 63% female, 22.64±4.23 years old, BMI=25.99±6.51 kg/m^2) from the same study were matched based on BMI and sex.

Intervention(s): All participants underwent resting serum blood draws from the antecubital vein preoperatively and 6 months post-ACLR.

Main Outcome Measure(s): Serum samples were placed in a centrifuge for 30 minutes after collection to allow for clotting and spun at 3000 rpm for 10 minutes at 4°C for serum separation. All samples were stored in a -80°C freezer until samples were batch-processed after study completion. sCOMP concentrations (ng/mL) were analyzed using commercially available enzyme-linked immunosorbent assays (intra- and inter-assay variability <10%). We conducted a 2x2 repeated measures analysis of variance to determine differences in sCOMP between groups and time points. In the presence of a significant interaction, Bonferroni adjusted independent and dependent t-tests (p-value=0.025) were utilized for *post hoc* analyses.

Results: There was a statistically significant group-by-time interaction (F(1,20)=6.27 p=0.02). Adolescents demonstrated increases in sCOMP preoperatively (130.01±24.35 ng/mL) to 6 months post-ACLR (155.53±59.40 ng/mL, p=0.02) while young adults demonstrated decreases in sCOMP preoperatively (154.99±57.80 ng/mL) to 6 months post-ACLR (132.34±30.45 ng/mL, p=0.02). There were no differences between adults and adolescents at each timepoint (p=0.21-0.27).

Conclusions: Adolescents demonstrate increased sCOMP over the first 6 months post-ACLR. This change may be a product of multiple factors, including known inherent changes in skeletal maturation involving cartilage turnover during adolescence, but should be confirmed in future work by comparing biomarkers of joint tissue metabolism between adolescents with and without ACLR. Our data suggest that future work should account for age when evaluating sCOMP changes post-ACLR, as different trajectories between adolescent and adult patients may be masked if all ages are studied in combined groups. Furthermore, future work should determine if changes in sCOMP 6 months post-ACLR are similarly predictive of poor knee joint health development in adolescents as reported in adults.

Abstract #42

Open-Sourced Semi-Automatic Program for Ultrasound Assessments of Femoral Trochlea Cartilage Thickness

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Context: Osteoarthritis (OA) develops in more than 50% of anterior cruciate ligament (ACL) injured patients, predisposing young-injured athletes to a high risk for OA. B-mode ultrasound imaging has been adopted by many as a quick, cost-effective, and clinically practical method for the assessment of cartilage health. Though pragmatic, ultrasound imaging is highly susceptible to errors and the field lacks advanced and standardized data collection and processing schemes that severely limits its utility. To address this critical need, we developed an open-sourced program that rigorously accounts for widespread ultrasound limitations and expands the clinical utility of ultrasound imaging for assessments of femoral trochlear cartilage health.

Objective: To develop a reliable, open-sourced program that can easily be adapted by researchers, accounts for common ultrasound limitations, and expands the clinical utility of ultrasound imaging for the early detection of changes in femoral trochlea cartilage health.

Design: Cross-sectional.

Setting: Research laboratory.

Patients or Other Participants: 18 participants (22±6years, 9m/9f, 175±9cm, 72±12kg) with a history of ACL reconstruction.

Intervention(s): B-mode ultrasound images were collected in the suprapatellar view at 140 degrees of knee flexion with a GE LOGIQe system to: 1) test the reliability of our application, 2) demonstrate the influence of ultrasound refraction and the effect of not including the near interface on thickness, 3) show the variability of single location and traditional thickness measurement techniques compared to a more comprehensive assessment and, 4) highlight the value of sub-region of interest (ROI) analyses.

Main Outcome Measure(s): Two-way random effect inter- and intraclass correlation coefficients for absolute agreement of cartilage thickness were used to determine the reliability of two raters. Paired t-tests were used to determine the degree that segmentation errors, ultrasound refraction, ROI overgeneralizations, and sub-ROI analyses influence outcomes.

Results: Inter and intra-rater reliability were excellent (.958-.991). By not including the near quadriceps tendon-cartilage interface or accounting for refraction, cartilage thickness was underestimated by 26-27% and overestimated by 0-4%, respectively ($p < 0.001$). Comprehensive thickness measurements achieved by measuring the Euclidean distance between every point (resolution = .09mm/pixel) on the interfaces were significantly different than thickness measurements taken a single location (lines drawn at 10mm, or the midpoint) or by using a cross-sectional area/length of ROI technique in the injured and uninjured limbs ($p<0.01$). Sub-ROIs within a compartment were found to be significantly different than all whole ROIs ($p=0.001$-0.012).

Conclusions: Ultrasound is a promising cost-effective imaging modality for cartilage health. The fields lack of consistency in data processing schemes make it difficult to interpret and compare findings across studies. To address this issue, here we release a new open-sourced tool that can be easily adapted by researchers to collectively standardize data processing schemes and expand the clinical utility of B-mode ultrasound imaging.

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