INTRODUCTION
Anterior cruciate ligament (ACL) injury leads to significant reductions in patient function, and biomechanical asymmetries that frequently persist for two years or longer after ACL-reconstruction. [1] Recent reports indicate that as many as one in four ACL-reconstructed patients will suffer a second ACL injury to either the affected or contralateral limb within their first year of return to sport. [2] Furthermore, patients who suffer a second injury have significantly poorer short-to-long term outcomes.

Hip, knee, and ankle kinematics are critical modifiable factors that affect ACL injury risk. Previous research indicates that landing with the hip and knee near full extension, and reaching lower levels of peak hip and knee flexion increase the likelihood for injury. In addition, stiffer landings transmit greater forces and torques through the joints, and likely contribute to increased injury risk. Neuromuscular training (NMT) protocols that target high-risk biomechanics and impairments in neuromotor control effectively reduce rates of primary ACL injury. [3] Furthermore, subjects that participate in these training protocols demonstrate a number of associated improvements in functional biomechanical control. [4] Despite success in large, prospective analyses of healthy athletes, few studies have investigated the impact of NMT on functional biomechanics in ACL-reconstructed subjects. The goal of this study was to quantify lower extremity kinematics during unilateral and bilateral landing in ACL-reconstructed subjects prior to and after participation in NMT.

METHODS
Twenty-one (9 males, 12 females, 20.2±7.3 years old) ACL-reconstructed subjects who were recently discharged from supervised physical therapy participated in this study (37.1±17.2 weeks post-operative). Subjects underwent two biomechanical testing sessions: One prior to participation in a twelve (12) session NMT program (Pre-test), and one after training (Post-test). Biomechanical testing consisted of 3D motion analysis using a 12 camera motion analysis system with marker data sampled at 240 frames per second. Subjects were outfitted with fifty-five (55) retro-reflective markers in a modified Helen Hayes configuration.

Subjects performed three successful trials of a bilateral drop vertical jump (DVJ) task, and a single leg drop landing (SLD) task off a 30.5 cm box in the motion capture volume. Knee, hip, and ankle angles in all three planes were averaged over the three trials. The NMT protocol consisted of twelve (12) training sessions. The program consists of biomechanical feedback from a certified trainer, and a multi-phase progression of task difficulty. The program is described in detail by Di Stasi et al. [5]

Discrete values for maximum and minimum angles, alignment at initial contact (IC), and joint excursions in all three planes were calculated and utilized for statistical analyses using 2x2 (limb-by-session) repeated measures analysis of variance (ANOVA). Post-hoc t-tests were used to determine differences between limbs and effects of training.

RESULTS AND DISCUSSION
Nineteen (19) of the 21 subjects performed the DVJ task at both biomechanics sessions. Twenty (20) of the 21 subjects performed the SLD task at both the sessions.

Hip Kinematics: Subjects demonstrated greater hip flexion at IC on the involved limb compared to the uninvolved limb during both tasks (DVJ: INV: 33.9±9.4 deg, UNIN: 31.5±10.1 deg; p=0.006), (SLD: INV: 26.2±5.8 deg, UNIN: 21.9±6.3 deg; p<0.001). After training, peak hip flexion during SLD increased (Pre-Test: 50.1±12.0 deg, Post-Test: 55.4±10.5 deg; p=0.02), as did hip flexion
excursion (Pre-Test: 26.3±8.6 deg, Post-Test: 30.9±9.1 deg; p=0.02). Subjects also demonstrated a strong trend toward decreased hip frontal plane excursion (Pre-Test: 17.1±6.0 deg, Post-Test: 15.4±4.8 deg; p=0.056).

Knee Kinematics: Knee flexion at IC after training increased for both tasks (DVJ: Pre-Test: -17.1±7.2 deg, Post-Test: -23.9±8.9 deg; p=0.001, SLD: Pre-Test: -9.4±4.8 deg, Post-Test: -11.8±5.7 deg; p=0.014). Peak knee flexion increased significantly after training for the SLD task (Pre-Test: -60.6±10.8 deg, Post-Test: -66.3±8.4 deg; p=0.006), and demonstrated a similar, but statistically insignificant trend during the DVJ task (Pre-Test: -88.0±11.0 deg, Post-Test: -93.1±12.2 deg; p=0.077). During the SLD task, subjects also demonstrated increased knee flexion excursion after training (Pre-Test: 51.1±9.6 deg, Post-Test: 54.5±8.67 deg; p=0.036).

Ankle Kinematics: Subjects demonstrated a decrease in ankle plantar flexion at IC during the DVJ (Pre-Test: -46.1±7.7 deg, Post-Test: -40.2±8.5 deg; p<0.001) and the SLD tasks (Pre-Test: -54.6±7.8 deg, Post-Test: -48.7±12.6 deg; p<0.001). Ankle flexion excursion also decreased after training for DVJ (Pre-Test: 51.6±8.4 deg, Post-Test: 46.0±8.7 deg; p<0.001) and SLD (Pre-Test: 49.8±8.4 deg, Post-Test: 46.6±6.5 deg; p=0.01).

This study demonstrates that the primary kinematic effects of NMT after ACL-reconstruction occur in the sagittal plane. Unpublished pilot data from our group demonstrates that the reported Post-Test hip and knee flexion values for peak and IC are likely greater than those of untrained ACL-reconstructed subjects at one year post-operative. Importantly, the tasks performed during the biomechanics sessions were not the same as the tasks performed during training. Thus, the biomechanical feedback provided to subjects during training appears to carry over into other landing tasks to which the subjects may not be accustomed.

Approximately 70% of ACL injuries occur via a non-contact mechanism, and are most frequently characterized by near full extension of the knee and hip at the time of IC. [6] Landing with the hip and knee in greater initial flexion, reaching deeper peak flexion, and exhibiting greater sagittal plane excursion are all likely protective of the native ACL and/or graft. [7]

While NMT did not affect coronal or transverse plane landing mechanics, the standard physical therapy regimen for ACL-reconstructed subjects at Ohio State, where most subjects performed their formal rehabilitation, is highly focused on controlled landing mechanics. At the time of Pre-Test, the patients in this study, on average, landed with their knees in slight adduction at IC for DVJ (INV: 1.9±3.4 degrees, UNIN: 1.6±2.0 degrees) and exhibited low values for peak knee abduction (INV: -2.2±3.6 degrees, UNIN: -1.98±3.3 degrees). Similar values were observed after training, and for the SLD task. These are representative of generally low-risk frontal plane mechanics, thus our cohort may not exhibit the frontal and transverse-plane control issues commonly observed in ACL-reconstructed subjects.

CONCLUSIONS
ACL-reconstructed subjects who participate in NMT after completion of formal rehabilitation exhibit ACL-protective adaptations in sagittal plane kinematics at the hip and knee during unilateral and bilateral landing tasks. The effects of NMT in ACL-reconstructed subjects as they pertain to second injury rates and joint kinetics will be investigated further and training programs should be optimized to maximize safe return to sport.

REFERENCES

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