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ACL injury and reconstruction affect control of ground reaction forces produced during a novel task that simulates cutting movements

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ACL injury and reconstruction affect control of ground reaction forces produced during a novel task that simulates cutting movements

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ABSTRACT

After anterior cruciate ligament (ACL) injury and reconstruction, biomechanical and neuromuscular control deficits persist and 25% of those who have experienced an ACL injury will experience a second ACL rupture in the first year after returning to sports. There remains a need for improved rehabilitation and the ability to detect an individual's risk of secondary ACL rupture. Nonlinear analysis metrics, such as the largest Lyapunovexponent (LyE) can provide new biomechanical insight in this population by identifying how movement patterns evolve over time. The purpose of this study was to determine how ACL injury, ACL reconstruction (ACLR), and participation in high-performance athletics affect control strategies, evaluated through nonlinear analysis, produced during a novel task that simulates forces generated during cutting movements. Uninjured re-creational athletes, those with ACL injury who have not undergone reconstruction (ACLD [ACL deficient]), those who have undergone ACL reconstruction, and high-performance athletes completed a task that simulates cutting forces. The LyE calculated from forces generated during this novel task was greater (ie, force control was diminished) in the involved limb of ACLD and ACLR groups when compared with healthy uninjured controls and high-performance athletes. These data suggest that those who have experienced an ACL injury and subsequent reconstructive surgery exhibit poor force control when compared with both uninjured controls and high-performance athletes. Clinical significance: significantly larger LyE values after ACL injury and reconstruction when com-pared with healthy athletes suggest a continuing deficit in force control not addressed by current rehabilitation protocols and evaluation metrics that could contribute to secondary ACL rupture.

KEYWORDS:
ACL, biomechanics, injury, kinematics and kinetics, knee, nonlinear, reconstruction, variability

1 | INTRODUCTION

Anterior cruciate ligament (ACL) ruptures are a common sport-related injury which affect both recreational athletes and high-performance athletes. Approximately 250,000 ACL ruptures occurannually[1,2] and most who intend to return to sport undergo ACL reconstruction. Conservative estimates of surgery costs exceed a $1billion annual price tag for treating ACL injury.[3]Unfortunately, 25% or more of young patients experience a second ACL rupture in the first year after returning to sports,[4]which often funnels them back into surgery and rehabilitation.

After ACL injury and reconstruction, biomechanical and neuromuscular control deficits persist. Proprioception in both the sagittal and transverse planes is also impaired.[5] ACL injuries often occur during running/cutting tasks where athletes initially decelerate prior to changing direction, and to do this they must generate significant anterior/posterior(AP) ground reaction forces.[6] Once deceleration is complete, they must then redirect the center of mass, hence producing greater medial/lateral(ML) ground reaction forces.[6] As speed and power increase, modulation of these multidirectional ground reaction forces (mGRFs) seen during cutting tasks are crucial in providing proper body support and positioning to protect against injury. Performance of running/cutting tasks, which require mGRF modulation, could be dangerous after ACL injury and a subsequent reconstruction and so safe methods that can elicit dynamic loads similar to cutting are needed.

Sports that require jumping, pivoting, and cutting tasks see the highest number of ACL ruptures.[7,8] In elite soccer, for example, athletes experience approximately 700 changes of direction during a single game.[9] Proper execution of this task is important not only to succeed as a player but for reducing injuries. Current training protocols focus on speed, power, and agility. These training protocols include activities like resisted printing and plyometrics, which themselves include different activities that focus on straight running and changes of direction. While these programs show improvement in jumping height and sprinting times, there are no clear improvements to change of direction performance.[10] Studying cutting mechanics in a high-performance cohort utilizing innovative analysis techniques may identify optimal control strategies and potentially better inform those who care for ACL injured and re-constructed patients.

Nonlinear analysis may be a pathway to gain additional insight into the neuromuscular control needed to perform cutting tasks in ACL injured and reconstructed patients. Two nonlinear parameters, the largest Lyapunov exponent (LyE) and approximate entropy (ApEn), capture smalltime-varying changes unseen with linear analyses (eg, standard deviation, range) and may prove valuable in understanding injury, recovery, andperformance.[11,12] LyE and ApEn have been used in a number of different biomechanical applications including postural control,[13] amputee gait,[14,15] as well as ACL injury[16] and ACL reconstruction.[17] Higher LyE values indicate greater variability and are associated with poorer motor control. For this study, we focused on the LyE, which measures the divergence of movement trajectories, by measuring the change in distance between trajectories over time. While successful in exploring kinematic variability, this investigative approach has yet to be applied to kinetics. Understanding changes to participants' ability to control mGRFs, as measured by LyE, after ACL injury, ACL reconstruction, and in high-performance athletes may provide additional valuable insight into the control strategies used to inform rehabilitation and improve surgical outcomes.

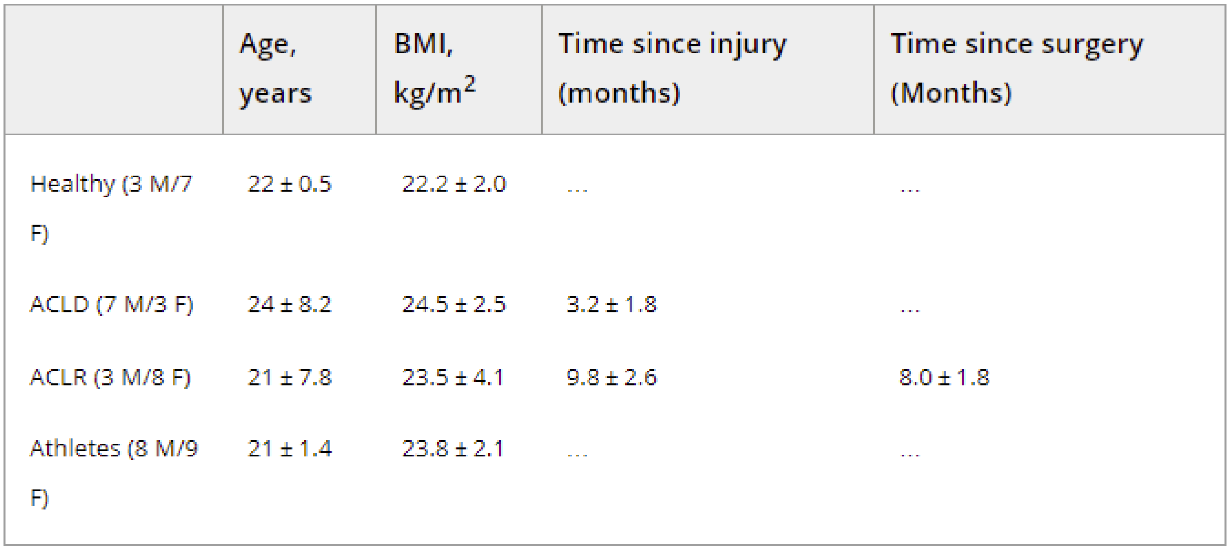
The purpose of this study was to determine how ACL injury, ACL reconstruction, and participation in high-performance athletics affects control strategies produced during a novel task[18] that simulates forces produced during cutting movements. Control strategies were evaluated using the LyE as calculated from the time series of them GRFs produced during this task. Overall, we hypothesized a difference in variability between groups in mGRF control, based on LyE values, with the lowest variability observed in high-performance athletes, and the greatest variability observed in ACL deficient (ACLD). Furthermore, we hypothesized that our injured populations, ACLD and ACL reconstructed (ACLR) would demonstrate a difference in mGRF control between limbs, with the involved limb demonstrating decreased control when compared with the uninvolved limb. Based on previously reported results,[18] we hypothesized no difference between limbs in the uninjured populations (high-performance athletes and uninjured recreational athletes). Finally, we hypothesized that there would be no difference in mGRF control between the AP and ML directions.

2 | METHODS

2.1 | Participants

A total of 47 participants (Table1) were recruited for this case-control study (level of evidence: III). Ten participants (mean age 22 ± 0.5 years, range 21- 23years) who were active in more than 50hrs/year of level I and II sports and no history of ACL injury or other major lower limb injuries were recruited from the local community and served as recreational athlete controls. Twenty-one participants (10 ACL deficient and11 after ACL reconstruction; ACLD mean age 24 ± 8.2 years, range 14-46years; ACLR mean age 21 ± 7.8 years, range 15-40 years) also active in more than 50 hrs/year of level I and II sports were recruited from the University of Delaware physical therapy clinic. ACLD participants included patients who had experienced an isolated unilateral ACL rupture. ACLR participants included patients who had undergone ACL re-constructive surgery in the last5.7 to 10.5 months (mean 8.0 ± 1.8months). A portion of participants experienced concomitant meniscal damage at the time of ACL rupture; participants received no treatment, partial meniscectomy, or meniscal repair. As meniscal damage is very commonly associated with ACL rupture, these participants were not excluded from the study. All patients were at a specific functional level before participating. All patients had quadriceps limb symmetry indexes of more than 80%. All ACLR patients met criteria to return to running and were cleared for weight-bearing activity. Seventeen athletes from the University of Delaware men's and women's soccer teams were recruited to serve as high-performance athletes (Table1). There were no statistically significant differences between groups regarding age or body mass index (BMI; Table1). This study was approved by the institutional review board of the University of Delaware and all the participants provided informed consent.

TABLE 1. Participant demographic data (average ± standard deviation) for the healthy recreational athletes, ACLD, ACLR, and high-performance athletes who participated in this study



	Age, years	BMI, kg/m^2	Time since injury (months)	Time since surgery (Months)
Healthy (3 M/7 F)	22 ± 0.5	22.2 ± 2.0	...	...
ACLD (7 M/3 F)	24 ± 8.2	24.5 ± 2.5	3.2 ± 1.8	...
ACLR (3 M/8 F)	21 ± 7.8	23.5 ± 4.1	9.8 ± 2.6	8.0 ± 1.8
Athletes (8 M/9 F)	21 ± 1.4	23.8 ± 2.1	...	...

Abbreviations: ACLD, anterior cruciate ligament deficient; ACLR, anterior cruciate ligament reconstruction.

2.2 | Force control task

All participants completed a force control task that has been publishedelsewhere[18] and described here in brief. Participants stood on two separate force platforms (AMTI OR-6, Watertown, MA) and placed a single limb on each platform. Prior to testing, participants were verbally in-structed to control a slider and align it with two indicators using forces generated at the foot via a single limb. They were instructed to generate force in a back and forth manner, continuously, and to the beat of a metronome set at 60 beats per minute. The goal was to alternatively align the movable slider with each stationary indicator. The force control task was two minutes in duration. During testing, participants received real-time visual feedback of their AP or ML force production as they con-trolled the slider corresponding to force production. Visual feedback was presented on a screen in front of participants and included one slider that responded to force production and two stationary indicators that served as goals for the participants (see Lanier et al[18] for images of visual feedback). Data obtained during a calibration trial were used to set the two stationary indicators at 50% of the participants' maximum strength in that direction. To calibrate the force control task, and set the two stationary indicators to each participant's strength, participants per-formed maximal force production trials. In these trials, participants pushed maximally on the force plates in the anterior, posterior, medial, and lateral directions with both feet. Four tests were completed: right limb anterior-posterior (AP), left limb AP, right limb medial-lateral (ML), and left limb ML. Test order was randomized and three trials of each test were completed. During the force control task motion capture and force profile, data were collected. For motion capture, we used an 8-camerasystem (Qualisys Motion Capture Systems, Gothenburg, Sweden), retro-reflective markers were placed on bony landmarks to define the lower limbs. Motion capture data were collected at 50 Hz.

At the conclusion of testing and prior to data processing, force profiles were visually inspected to assess data quality. Visual inspection was conducted to insure that off direction force, forces not purely in the AP/ML directions, did not show a similar cyclic force profile as the direction of interest, which suggested that the subject's force production was primarily in the task direction.

2.3 | Data processing

The largest LyE was calculated for both the AP and ML force control tasks, as detailed in Lanier et al,[18] using the time series of the AP and ML force profiles generated during their respective tasks. LyE is defined as the rate of divergence of a trajectory and is determined through a multistep process. Briefly explained, LyE calculations require two input paraments: time lag (τ), calculated through the minimization of average mutual information19and embedding dimension (m), calculated through the global false nearest neighbor algorithm,[19] which convert our signal of interest into state space. Once the signal of interest is converted to state space, the Euclidean distance between trajectories is measured.[20] Changes to trajectory distance forward in time provides the LyE or rate of divergence. Higher LyE values indicate greater variability and are associated with poorer motor control. More detailed information regarding LyE calculations can be found in Lanier et al.[18]

2.4 | Statistical analysis

To determine significant differences in the LyE between groups, direction, and limb, a 4 × 2 × 2 (group × direction × limb) mixed-design analysis of variance (ANOVA) was used (SPSS). Based on the results of our initial ANOVA, a Bonferroni post hoc comparison was used to determine individual differences in group, limb, and direction. In the case that no differences were found between limbs in our uninjured groups, limb assignment was randomly selected for comparison to the involved limb of ACLD and ACLR participants. Significance was set at $P< .05$ for the initial ANOVA with the Bonferroni post hoc testing set at $P< .0125$.

3 | RESULTS

3.1 | Across all participant groups

Overall, the LyE values measured from the involved limb of ACLD and ACLR groups were greater than that of healthy uninjured controls and high-performance athletes and there was no difference between uninjured controls and high-performance athletes. In addition, across groups, a main effect of direction was observed ($P= .009$, partial $\eta^2= 0.15$), with AP LyE greater than ML LyE (5.45 ± 2.45 vs4.97 ± 2.32 bit/s). Bonferroni post hoc comparisons revealed that the LyE of the involved limb of those who have experienced an ACL rupture or undergone ACL reconstruction (ACLD and ACLR groups) were greater than the healthy uninjured controls and high-performance athletes

(Figure1,P< .001) in both the AP and ML directions. There is no significant difference in LyE values when comparing the involved limb of ACLD and ACLR participants (Figure1,P= 1.00). We found no statistically significant difference in LyE measured between healthy uninjured individuals and high-performance athletes (Figure1,P= 1). This indicates that those with either ACL rupture or reconstruction exhibit diminished mGRF control when compared with uninjured populations, both recreational and high-performance athletes, and contrary to our hypothesis GRF control is affected by direction.

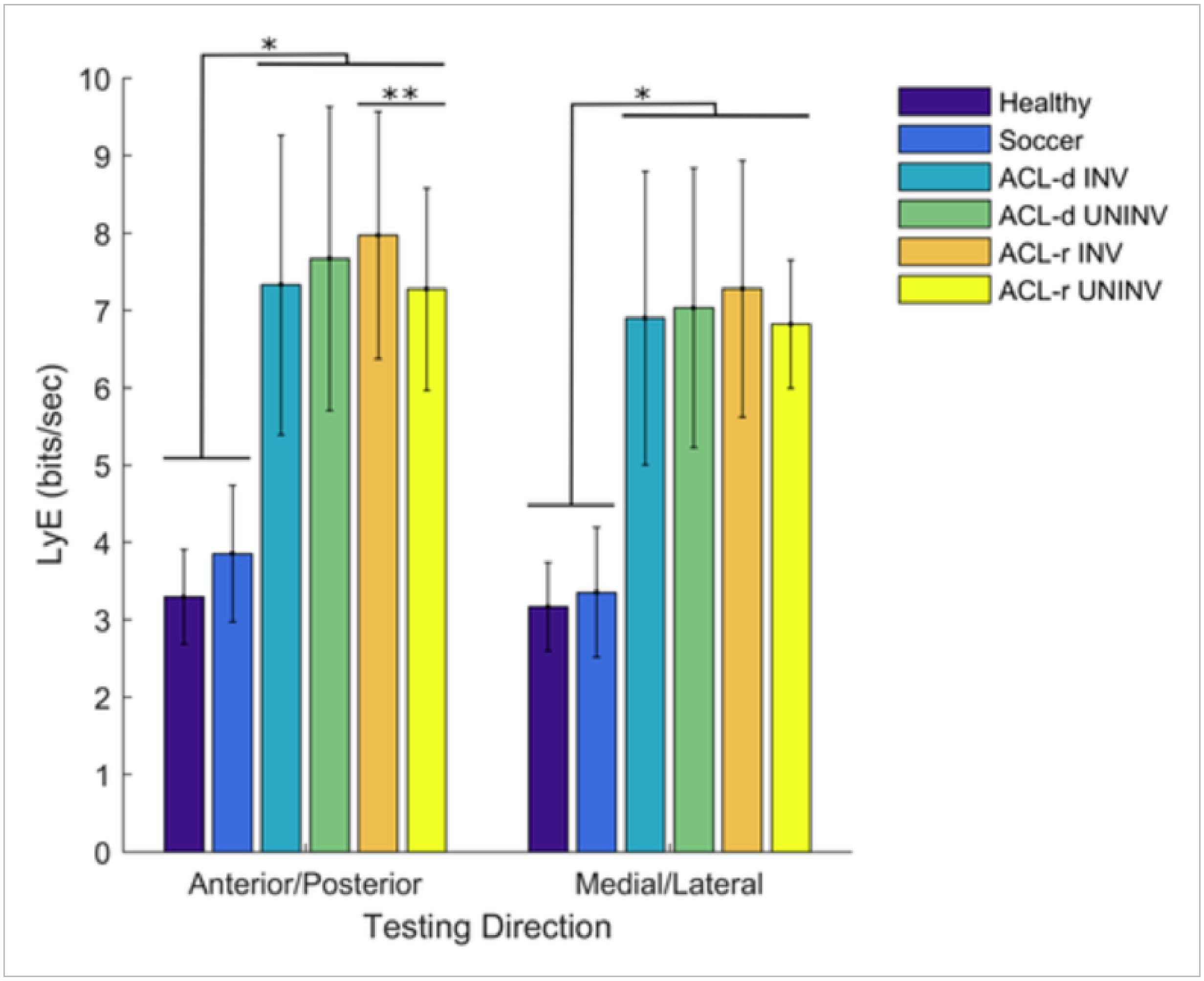


Figure 1

Average LyE (bit/s) values during the force control task for healthy control participants (blue), high-performance athletes (red), ACL deficient (ACLD) patients (green), and ACL reconstructed (ACLR) patients (orange). For ACLD and ACLR participants, the involved limb is solid while the uninvolved limb is striped. Data are reported for both the medial/lateral and anterior/posterior directions. *$P < .05$ ANOVA, **$P < .05$ paired *t* test. ACL, anterior cruciate ligament; ANOVA, analysis of variance; LyE, Lyapunov exponent [Color figure can be viewed at wileyonlinelibrary.com]

3.2 | Between limb and direction

Paired *t* tests revealed that for ACLD participants, there is no significant difference in LyE between the involved and uninvolved limbs in both the AP and ML directions (Figure1, AP:P= .31, Cohen's d= 0.34; ML:P= .64,d= 0.15). For these participants, we calculated average LyE values for the AP direction to be 7.33 ± 1.94 and7.68 ± 1.97 bit/s of the involved and uninvolved limb, respectively. LyE values calculated for the ACLD group in the ML direction were6.90 ± 1.90 and 7.03 ± 1.81 bit/s in the involved and uninvolved limbs, respectively. In the ACLR participants, our analysis revealed significantly greater LyE in the involved limb compared with the uninvolved limb in the AP direction, (Figure1,P= .007,d= 1.02) but no difference in the ML direction (Figure1,P= .97,d= 0.01). This suggests that the ACLR participants, but not ACLD participants, had diminished control in the involved limb in the AP direction only, which is counter to our hypothesis. Control was consistent between limbs in the ML direction for both groups (as hypothesized).

4 | DISCUSSION

The purpose of this study was to determine how ACL injury, ACL reconstruction, and participation in high-performance athletics can affect control strategies produced during a novel task18that simulates forces generated during cutting movements. Our study revealed significant differences in LyE values regarding the task direction and significant differences in LyE values when comparing those without ACL injury, those with ACL injury and those who have under gone ACL reconstruction.

There were significant group differences in LyE values when com-paring the ACLD and ACLR groups with our healthy and high-performance cohorts; larger LyE values of the ACLD and ACLR groups indicate less force control in both the AP and ML directions, which supports our first hypothesis. In the ACLD group, we found no difference in LyE values when comparing the involved and uninvolved limbs in both the AP and ML direction and thus no changes in force control. For the ACLR group, the involved limb exhibits significantly diminished mGRF control, or larger LyE values, when compared with the uninvolved limb in the AP direction, but not the ML direction. These results partially support our second hypothesis, diminished control in the involved limb, but partially contradict our third hypothesis, no difference in control based on direction. While there was a difference in LyE between the involved and uninvolved limbs, it is only present in ACLR participants and only in the AP direction. In summary, those who have experienced an ACL injury (ACLD) exhibit significantly larger LyE values, when compared with un-injured recreational athletes and high-performance athletes, indicating poor mGRF control, which is not resolved through ACL reconstructive surgery (ACLR).

We found no difference between involved and uninvolved limbs in a majority of comparisons within ACLD and ACLR participants. Deficits to mGRF control, as noted through larger LyE values when compared with uninjured recreational athletes, were consistent in both the involved and uninvolved limbs. This global pattern of poor mGRF control indicates an upper level neuromuscular error, at the spinal or cortical level, may be at play. Animal models of ACL injury indicate deficits to fine motor control and altered regulation of motor reflexes, which highlights both motor and spinal dysfunction resulting from ACL injury.[21] In addition, in vivo studies found that post-ACL injury, there is a reorganization of the central nervous system measured by functional MRI,[22] and diminished corticospinal excitability measured by transcranial magnetic stimulation.[23,24] Disruption to the sensory inputs and alterations to the central nervous system caused by ACL injury may influence force control in both the involved and uninvolved limbs of patients.

Our data also suggest that the LyE values calculated from high-performance athletes were slightly greater than those of healthy uninjured recreational athletes (Figure1), which may suggest a level of optimal control. In sports, athletes must be consistent yet flexible and adaptable in their movements to avoid injury in such a fast-paced sport. This is reflected in the slightly higher LyE values as compared with healthy uninjured recreational athletes. The theory of optimal movement variability posits that there exists a preferred band width of variability for healthy and mature motor skills.[25] Movements should not be too rigid to limit adaptability but not too unstable to limit predictability. This theory has been supported through case studies that explore postural control in children with cerebral palsy and athletes who have experienced a concussion.[12,25,26] Because high-performance athletes participate in intense training and high skill play, they are ideal candidates to present a state of optimal movement variability.

Our results identified significantly larger LyE values, indicating greater variability, in both the involved and uninvolved limbs of the ACLD and ACLR participants when compared with our uninjured cohort (healthy uninjured participants and high-performance athletes). One-quarter of those who experience an ACL injury will experience a second injury in the first year they return to sports. Contralateral reinjury is equally if not more likely than an ipsilateralreinjury.[4] Biomechanical changes occurring bilaterally, to both the involved and uninvolved, may be contributing to this phenomenon. Current research highlights bilateral changes to both dynamic and static balance after ACL injury.[27,28] Importantly, postural stability is predictive of second ACL injury.[29] Significantly larger LyE values of the injured cohort (ACLD and ACLR) when compared with the un-injured cohort (healthy controls and high-performance athletes) that are present in both the involved and uninvolved limbs may identify this measure as an important method to identify risk to reinjury seen in both ipsilateral and contralateral limbs.

We found a significant difference between involved and uninvolved limbs when generating force in the AP direction for ACLR participants. More specifically, ACLR participants had larger LyE values in the involved limb when compared with the uninvolved limb in the AP direction. Recovery after ACL injury and reconstruction is multifactorial. Strength and pain are important considerations in this population and may influence the differences we see in LyE between limbs. All participants were at a specific functional level, in an effort o minimize the effects of muscle weakness and preliminary testing correlating quadriceps limb symmetry index to LyE yielded no significant relationships. And so the reduced mGRF control in the re-constructed limb may be a result of surgery as it significantly alters the knee joint, affecting both joint stability and joint sensation. Tibial tunneling during reconstructive surgery significantly reduces meniscal attachment area and ultimate strength, which risks further injury as it may mechanically destabilize the joint.[30,31] In addition, removal of the ligament remnant may eliminate important mechan-oreceptors.[32] After surgery, research indicates reduced propriocep-tion,[5] reduced coordination variability,[33] altered muscle activation,[34] and altered joint kinematics.[35,36] The combination of these deficits caused by surgery may translate to poor control of mGRFs at the foot, noted by larger LyE values for the involved limb.

This is the first study to evaluate dynamic ML force production inACLD and ACLR patients prior to returning to sports. Generating this type of loading has been previously unattainable as cutting maneuvers can risk further injury. Our results demonstrated a large difference in force control, as measured by LyE, between our injured and uninjured cohorts. LyE values in the ACLD and ACLR participants were larger than healthy controls and high-performance athletes by almost twofold. The large group differences may be indicative of lack of ability to control the magnitude of forces generated at the foot which may not only affect a person's ability to successfully complete cutting and running maneuvers but also increase the likelihood of enduring a second ACL injury.

There are a few limitations to this study. This study was limited in the number of participants because we focused on including healthy participants who were active in jumping, pivoting, and cutting sports, injured and reconstructed participants who intended to re-turn to jumping, pivoting, and cutting sports, and high-performance athletes. While these specifications limited the number of eligible participants, it does provide a cohort more related to and at risk for ACL injury. We were unable to control for type and frequency of rehabilitation provided to those participants who had experienced an ACL rupture or undergone ACL reconstruction. Evaluating rehabilitation was beyond the scope of this study; however, we hope that by including participants acutely following injury and re-constructive surgery, we were able to capture force control at ap-propriate time points reflecting different levels of recovery. Overall, we believe that none of these limitations grossly affect our results.

5 | CONCLUSION

In conclusion, those who have experienced an ACL injury and those who have undergone reconstructive surgery exhibit poor mGRF control when compared with both uninjured controls and high-performance athletes by almost twofold. This is noted by significantly larger LyE values calculated during a force control task. Poor control in the ACLD and ACLR groups occurs in both the AP and ML directions when compared with the un-injured cohort. For the ACLR group, we found that the involved limb exhibited significantly greater LyE values when compared with the un-involved limb in the AP but not the ML direction. Most importantly, significantly larger LyE values by almost twofold after ACL injury and reconstruction may identify an aspect of recovery in terms of force control that is not addressed by current rehabilitation protocols that could contribute to the high rates of reinjury in both ipsilateral and contralateral limbs. Addressing this deficit both prospectively and during rehabilitation may be beneficial to those at risk for secondary ACL ruptures and current rehabilitation protocols may benefit from a significant focus on biofeedback tasks, single limb stability during both squatting and jumping, and dynamic multidirectional force production tasks, for ex-ample pushing a sled.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

ASL provided substantial contribution to the research design, data acquisition, and data interpretation, and also prepared, revised, and finalized the submitted manuscript. BK provided contributions to data processing, data interpretation, and manuscript revision. NS provided contributions to data interpretation and manuscript revision. L S-M provided contributions to data acquisition, data interpretation, and manuscript revision. TSB provided significant contributions to research design, data acquisition, data interpretation, and manuscript revision. All authors have read and approved the final submitted manuscript.

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