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Original Research

An Exploratory Analysis of Countermovement Jump Variables Between Higher and Lower Performers on the LESS and Y-Balance Tests

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Background

Identifying movement dysfunction is critical for optimizing training and injury risk. While functional movement assessments like the Y-Balance Test (YBT) and the Landing Error Scoring System (LESS) are widely used, they require dedicated personnel, time, and testing space. The relationship between performance on movement assessments and the countermovement jump (CMJ) variables is unknown.

Hypothesis/Purpose

The purpose of this study was to explore the relationship between CMJ force plate metrics and performance on the YBT and LESS in collegiate athletes. It was hypothesized that CMJ variables would differ between high- and low-performing athletes on the YBT and LESS.

Study Design

Prospective observational cross-sectional study.

Methods

Male and female NCAA Division I athletes aged 18-21 years (n = 109) completed the YBT and LESS using standard protocols, and the CMJ on a validated portable force plate during the off-season as part of routine performance monitoring. Movement assessments independently stratified athletes into high- and low-performing groups. Group differences in CMJ metrics of jump height, Left/Right (L/R) peak propulsive force, landing stiffness, peak landing force, L/R average landing force, L/R landing impulse, reactive strength index modified (mRSI), and propulsive phase duration were analyzed using t-tests or Wilcoxon signed-rank tests.

Results

Athletes with LESS scores >5 demonstrated significantly greater landing stiffness (mean = -9757.73 ± 16231.15 N/m) compared to those scoring ≤5 (mean = -6555.38 ± 3515.67 N/m) ($p = 0.01$). Athletes with an anterior limb reach difference > 4 cm on the YBT had higher mRSI ($p = 0.004$), propulsive phase ($p = 0.004$), and peak landing force ($p = 0.002$).

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Conclusion

Some CMJ metrics vary by performance on the YBT and LESS, offering insight into movement quality in collegiate athletes. While further research is needed to establish direct links to outcomes, these findings support CMJ testing as a practical, objective complement to traditional movement assessments.

Level of evidence

Level 3

INTRODUCTION

Lower extremity injuries, specifically anterior cruciate ligament (ACL) injuries, are one of the most prevalent and debilitating injuries sustained by athletes. Annually, there are between 100,000 and 200,000 ACL ruptures in the United States alone.[1] Previous research demonstrates return to sport rates of 63% to 87% after ACL reconstruction, with re-injury rates ranging from 12% to 30%.[2-4] Furthermore, it is estimated that nearly 79% of individuals who sustain an ACL injury will develop knee osteoarthritis within 15-20 years post-injury.[5] Consequently, research efforts have been directed towards identifying athletes at heightened risk of injury and implementing effective interventions to mitigate these risks and attempt to prevent subsequent injuries.

Non-modifiable risk factors for ACL injury include female sex, specific measures of bony geometry of the knee joint, knee laxity, and a previous history of ACL injury.[6] Modifiable biomechanical and neuromuscular factors such as hamstring weakness and under-recruitment, valgus angulation of knee in change of direction movements and during knee landing, as well weakness and under-recruitment of hip external rotators also contribute ACL injury risk.[7-9] Accompanying the understanding of these risk factors, the assessment of biomechanical and neuromuscular function associated with lower extremity injury has become integral to guiding treatment progression and informing decisions regarding the return to sports after injury.[10,11] Although there is currently no consensus on the "best" return to sport assessment, clinicians can employ several tests and measurements to assess muscle function and movement capabilities to identify at risk movement patterns in athletes and to inform return to return to performance process.

The Landing Error Scoring System (LESS) is a commonly used functional assessment that involves a 30-cm drop jump landing, with a trained professional assessing nine landing errors from video footage. The LESS has been widely used to assess jump-landing biomechanics and identify athletes at risk for ACL injury. While its interrater and test-retest reliability are well established,[12] the predictive validity of the LESS for injury remains a topic of ongoing investigation. A 2023 study in professional and semi-professional football players demonstrated that the LESS could help distinguish athletes at elevated risk for ACL injury when used as part of a multifactorial screening battery.[13] Similarly, a 2024 scoping review of LESS methodologies underscored its broad clinical adoption.[14]

Another commonly used assessment is the Y-Balance Test (YBT). The YBT is a dynamic balance assessment used to evaluate an athlete's neuromuscular control and functional symmetry. The YBT measures an athlete's reach in three directions while balancing on one leg, with a composite score calculated based on leg length, and asymmetry is assessed using the difference in reaches between the two lower limbs (inter-limb difference).[15] Within the literature the YBT has been shown possess strong inter- and intra-rater reliability (ICC = 0.84-0.99).[15] Additionally, it has been shown to have discriminative validity with athletes demonstrating a right/left reach difference greater than 4 cm being 2.5 times more likely to sustain a lower limb injury.[16,17] Although the LESS and the YBT are shown to be valid and reliable tests, their practicality in large group contexts such as collegiate athletic programs is limited due to time constraints in testing entire teams and the necessity of a trained clinical professional to administer them. Therefore, more efficient tests are needed for higher risk movement pattern screening for large groups of athletes at high exposure risk for ACL injuries.

In parallel with the advance in data-driven assessment of injury risk, force plate testing and associated metrics have become commonplace in sports science with evidence regarding their application in sports medicine growing.[18] A common assessment performed on a force plate is a countermovement jump (CMJ). A CMJ is an assessment of lower-limb muscle function and can be described as a vertical jump performed on a force plate, with the athlete's hands on their hips to isolate force production to the lower body. Variables derived from a CMJ have exhibited sensitivity in detecting changes in muscle function as result of training, neuromuscular fatigue and injury.[19,20] The force-time curve of a CMJ can be broken down into four key phases with the force characteristics within each phase providing unique insight into the athlete's force generating capabilities linked to performance and injury outcomes.[19] The specific phases of the CMJ include unweighting, braking, propulsive, and landing, and have been previously explained by McMahon et al.[21,22] Specific to injury risk CMJ measures of eccentric force production which occur during the braking phase of the movement and overall jump height have been associated with injury in collegiate athlete populations.[23]

Although a substantial body of evidence exists linking CMJ variables with sports performance-based outcomes, less is known about their relationship with movement quality and performance in functional movement tasks such as the YBT and the LESS. However, a 2019 study by Hart et al. assessed the effect of prior injury on bilateral lower limb force asymmetries during the CMJ in professional soccer players (17 with a history of severe lower limb injury and 17 uninjured). The authors reported that previously injured participants exhibited significantly greater inter-limb asymmetries in concentric and eccentric force production compared to non-injured players.[24] Additionally, Pontillo et al. studied the predictive potential of force-time variables from a vertical jump performed on portable dual force plates for ACL injuries in collegiate athletes.[25] Results from this study indicated that athletes who later suffered ACL injuries displayed significant differences in concentric and eccentric phase variables of a CMJ.[25] However, it is important to note that the jumps performed in the study by Pontillo et al. incorporated an arm-swing which means force production would have been influenced by the upper body and technical factors associated with jumping such as coordination.[26]

Incorporation of CMJ testing into the routine monitoring of high-performance athletes has become common practice due to the increased accessibility of portable force plate technology, the time efficiency associated with conducting the test, and the user-friendly nature of software.[22,27] In contrast to the time and expertise demands of the YBT and the LESS, force plate derived CMJ metrics can be captured rapidly, potentially offering a practical complement to traditional functional movement screenings.

Exploring the difference in the force plate-derived CMJ variables between higher and lower-level performers in the LESS and YBT will provide sports science and sports medicine practitioners with information that complements their commonly used movement assessments. The purpose of this study was to explore the relationship between CMJ force plate metrics and performance on the YBT and LESS in collegiate athletes. It was hypothesized that CMJ variables would differ between high- and low-performing athletes on the YBT and LESS.

MATERIALS AND METHODS

STUDY DESIGN

This prospective cross-sectional study included sixty-six male and forty-three female Division I collegiate athletes without recent lower extremity. All male participants were active members of the Yale University football team. Twenty-one of the female participants were active members of the Yale University women's soccer team and twenty-two were active members of the Yale University women's lacrosse team. Inclusion criteria were as follows: student-athletes of age 18 years or older, student-athletes cleared for unrestricted participation in varsity athletics training, and student-athletes on campus in their off-season of training. Exclusion criteria included any history of ACL injury and any other significant lower extremity injury within one year that limited full sports participation or required medical restriction, modified training, or formal rehabilitation, consistent with NCAA Division I clearance standards. All tests were completed at a Yale University Strength and Conditioning facility. Study protocol was approved by Yale University Institutional Review Board. Written informed consent was obtained from all participants. An a priori power analysis estimated that a sample size of 260 would be required to detect between-group differences in CMJ variables based on an assumed variance of 0.50 and a population of approximately 800 student-athletes. Given the exploratory nature of the current study, a smaller sample size was used with the aim of informing the design, feasibility, and methodological considerations of future large-scale investigations.

PROCEDURES

Between June 2023 and August 2023, male and female athletes present on campus for off-season training were recruited. Athletes were selected from teams with a high risk of experiencing ACL injuries related to the mechanics of movement involved in their respective sports. All participants were cleared for unrestricted training by their team physician. Upon obtaining informed consent, athletes completed a demographic form to screen for unreported current injuries that might limit sports participation. This screening process ensured participants were suitable for inclusion in the study and helped establish a baseline for injury history.

All participants completed a dynamic warm-up as part of their routine preparation for off-season weightlifting prior to testing. Following this warm-up, athletes completed the following battery in this order: countermovement jump testing, YBT, and LESS. Rest intervals between tests were 3-5 minutes and consistent across participants and reflected standard practice within the training environment, with the full testing battery generally completed within approximately 15-20 minutes per athlete. All tests were performed on a single day, with each athlete completing two countermovement jumps on portable dual force plates (Hawkin Dynamics, Westbrook, Maine, USA), which have been validated as an alternative to the industry gold standard of in-ground force plates for assessing vertical jumps,[28] three YBT reaches in each direction, and three LESS trials. While fatigue-related effects cannot be fully excluded, consistent testing conditions across the participants were intended to minimize systematic bias. To reduce measurement bias, all assessments were standardized with verbal and visual instructions and administered by three certified strength and conditioning coaches following literature established protocols. Testing occurred with the last four weeks of off-season training period. Athletes and their strength and conditioning coaches were asked to not modify usual training schedules or prepare specifically for the testing session, and participation did not represent a deviation from their typical off-season routines.

COUNTERMOVEMENT JUMP

Each participant performed two maximal effort countermovement jumps. After stepping onto the wireless portable force plates, the athlete assumed an upright position with fully extended hips and knees for at least one second before initiating their maximal effort jump. Participants were instructed to maintain their hands on their hips and to leap "as fast and as high as possible," emphasizing rapid execution of both the countermovement and propulsion phases. To reduce bias, these instructions were standardized to ensure consistency and were based on previous research recommendations.[29,30]

During the CMJ trials, ground reaction forces were captured at a sampling rate of 1000Hz, with calibration of the force platform preceding each trial. Participants were required to maintain an upright and motionless posture for the initial second of data collection, a practice established to aid in the calculation of body weight, measured in Newtons, averaged over one second, and subsequently, body mass in kilograms, derived by dividing body weight by gravitational acceleration.[18,31] Raw vertical force-time data were exported as text files and analyzed using Microsoft Excel (version 16.18, Microsoft Corp., Redmond, WA, USA). Prior studies endorse examination of raw CMJ force-time data.[32] Because CMJ force-time data are routinely collected and processed for performance monitoring, the extraction of additional movement-related variables of interest for this study was automated within the force plate software and required minimal additional time beyond standard workflows.

For the purposes of this study, force plate metrics related to limb asymmetry and bilateral force production were chosen, in addition to jump height. Specifically, left/right (L/R) peak propulsive force (%), landing stiffness (N/m), peak landing force (N), L/R average landing force (%), L/R landing impulse (%), Reactive Strength Index modified (mRSI), and propulsive phase duration and were selected. The mRSI, propulsive phase duration, landing stiffness, and peak landing force were derived from the bilateral CMJ force-time curve (sum of left and right force plates), whereas variables reported as L/R (%) represent inter-limb asymmetry outputs. These CMJ variables were selected based on their relevance to neuromuscular performance, force attenuation strategies, and asymmetry patterns associated with injury-related movement quality. Peak propulsive force has been shown to influence dynamic stability during hopping tasks.[33] Peak propulsive force also reflects an athlete's ability to rapidly generate force during concentric action and has been studied in the setting of neuromuscular performance and dynamic task execution.[19,22,34] Asymmetry in propulsive force was included to align with the inter-limb symmetry constructs emphasize by the YBT.

Peak landing force represents the maximal vertical ground reaction force encountered during landing, whereas landing force and landing impulse capture the magnitude and temporal distribution of force absorption across the landing phase.[22] While related, impulse reflects force applied over time, providing complementary information to peak and average force regarding shock attenuation strategies. Landing stiffness was calculated as the ratio of peak vertical ground reaction force to center-of-mass displacement during the landing phase and reflects the athlete's capacity to attenuate force through eccentric control.[35,36]

Additionally, Reactive Strength Index modified (mRSI) and propulsive phase (s) duration data, both time-based metrics potentially reflecting acute neuromuscular fatigue, were collected.[34] The mRSI is calculated by dividing the jump height obtained by the time to take-off, consistent with established force plate methodology.[34] Together, these metrics were selected to provide a multidimensional assessment of force production, temporal characteristics, and inter-limb asymmetry, constructs that conceptually overlap with movement quality deficits by the LESS and YBT. Specifically, the LESS primarily evaluates jump-landing mechanics related to sagittal frontal plane control and error patterns during a dynamic landing task while the YBT emphasizes dynamic postural control and inter-limb symmetry across multiplanar reach directions. Although CMJ force plate analysis is performed during a predominantly vertical task, it provides objective quantification of force production, force attenuation, temporal characteristics of movement, and inter-limb asymmetry. These shared constructs, particularly eccentric control, force absorption strategies, neuromuscular status, and asymmetry, support the rationale for examining CMJ variables in relation to performance on established movement assessments.

CMJ force-plate variables have demonstrated good to excellent between-session reliability when standardized testing protocols are used, including metrics related to jump height, force production, impulse, and asymmetry.[29] The wireless dual force plates used in this study have also demonstrated acceptable validity and consistency compared to in-ground force plates.[28]

Y-BALANCE TEST

In accordance with the protocol described by Plisky et al. the Lower Quarter YBT assessment was conducted using the Y-Balance Test Kit (Functional Movement Systems, Danville, VA, USA).[15,17] Before recorded trials, participants completed practice reaches to became familiar with the task and ensure proper technique in accordance with the standard YBT guidelines. Each participant had up to six attempts to achieve three successful trials for each reach direction. Participants positioned themselves on the center footplate, with the distal aspect of their right foot placed at the starting line. While maintaining a single-leg stance on the right leg, participants extended their free limb in the anterior (ANT), posteromedial (PM), and posterolateral (PL) directions by pushing the indicator box as far as possible. Attempts were discarded and repeated if a participant failed to maintain unilateral stance on the platform, failed to maintain contact of the reaching foot with the reach indicator while in motion, utilized the reach indicator for support, or returned the reaching foot to starting position without control.

Leg length was measured in supine position from the anterior superior iliac spine to the most distal portion of the medial malleolus. Composite scores were calculated by summing the reach distances for ANT, PM, and PL, dividing by three times the participant's leg length, and then multiplying by 100 to obtain a percentage. Limb symmetry was evaluated using the Limb Symmetry Index (LSI), calculated by dividing the composite score of one limb by that of the contralateral limb and multiplying by 100. An LSI value below 95% has previously been associated with increased injury risk.[17] Additionally, side-to-side asymmetries for each reach direction (anterior, posteromedial, posterolateral) were calculated as the absolute difference in reach distances between limbs. Athletes were categorized high or low risk based on their composite score from their left and right leg performance in the YBT. High risk classification reflected failure to meet literature-defined thresholds,[37,38] including right or left composite YBT score < 89 cm, inter-limb composite score difference > 4 cm, anterior reach difference > 4 cm, posteromedial reach difference > 9 cm, and posterolateral reach difference > 3 cm, whereas athletes not meeting these criteria were categorized as low risk.

LANDING ERROR SCORING SYSTEM

The LESS protocol was adapted from research done by Padua et al.[12] Participants began the test by standing atop a 30-centimeter-high box and were instructed to jump forward a distance equal to half their height, as indicated by floor marker. Upon landing from the drop jump, they performed a maximal vertical jump. Prior to testing, participants received verbal instructions and visual demonstrations and were allowed practice attempts to become familiar with the task. Each participant completed three successful trials of the LESS, recorded by two perpendicular video cameras, each positioned 136 inches from the landing area. Cameras were set at a height of 48 inches. Two raters, an orthopedic surgeon and a strength and conditioning specialist, independently scored the participants using the LESS instructions and scoring sheet developed by Padua et al.[12] Final scores were averaged from both raters' assessments. Based on their LESS score, participants were categorized into four groups: excellent (<4), good (4-5), moderate (5-6), and poor (>6) jump landing mechanics.

AT RISK FLAG COUNT

Although not previously reported in the literature, the authors created a cumulative "At-Risk Flag Count" to capture the spectrum of movement-related risk across the study population. This metric was intended as an exploratory composite measure and has not been formally validated. The At-Risk Flag Count ranged from zero to seven, with one flag assigned for each previously identified at-risk threshold met across the LESS and Y-Balance Test (YBT). Threshold values for YBT anterior, posteromedial, and posterolateral reach performance were defined based on prior literature.[37,38] Specifically, one risk flag was assigned for each of the following criteria: right extremity composite YBT score < 89 cm, left extremity composite YBT score < 89 cm, inter-limb composite score difference > 4 cm, anterior reach difference > 4 cm, posteromedial reach difference > 9 cm, and posterolateral reach difference > 3 cm. An additional risk flag was assigned for a moderate – poor LESS score, while participants with an excellent – good LESS score did not receive a flag. The goal of the At-Risk Flag Count was to explore association between the accumulation of the movement-based risk indicators and CMJ force plate variables. Given the exploratory nature of this metric, it was not intended to serve as a diagnostic or predictive tool until further validation studies have been performed.

STATISTICAL ANALYSIS

Prior to analysis, based upon their performance in the LESS, participants were categorized into two independent groups: excellent – good (scores ≤5) and moderate – poor (scores >5). Such data grouping in LESS evaluation has been utilized by a previous study.[39] Additionally, athletes were categorized high or low risk based upon their composite scores from the left and right leg performance in the YBT. High risk classification reflected failure to meet literature-defined composite and asymmetry thresholds.[37,38] Variables were checked for normality using skewness, kurtosis, and the Kolmogorov–Smirnov test. Most CMJ variables demonstrated acceptable normality (p > 0.05), including time to take off, mRSI, propulsive phase variables, relative and peak landing forces, landing impulse, and jump height. Landing stiffness, L/R peak landing force, and L/R average landing force did not meet normality assumptions (p < 0.05) and were analyzed using nonparametric methods. To determine statistically significant differences between higher- and lower-level performers in the LESS and YBT, normally distributed variables were analyzed using independent samples t-tests, while non-normal variables were analyzed using Wilcoxon rank-sum tests. Effect sizes were determined using Cohen's d and interpreted according to previously established thresholds: small (d = 0.2), medium (d = 0.5), and large (d = 0.8). The number of flags and their association with each variable was determined using linear regression analysis. All statistical analysis was performed STATA BE 18 (StataCorp LLC, College Station, TX). All p-values were determined significant if p < 0.05. No covariates or confounders were adjusted for in the primary analysis, as the aim was to examine direct associations between movement screen scores and CMJ metrics.

RESULTS

PARTICIPANTS CHARACTERISTICS

A total of 109 athletes met inclusion criteria and completed testing (66 male, 43 female; mean age 20.1 ± 2.4 years) from football, women's soccer, and women's lacrosse teams. All athletes were tested during the off-season and had no history of ACL injury within the prior year. Eligibility criteria, recruitment strategy, and testing protocols are detailed in the Methods section. Two additional participants were excluded from final count due to incomplete testing, which was attributed to personal reasons.

PRIMARY OUTCOME MEASURES

Athletes with moderate – poor LESS scores recorded significantly higher landing stiffness on force plate CMJ than those who recorded excellent – good scores (p = 0.01, *d* = 0.48). Table 1 presents the force plate derived metrics

Table 1. Countermovement jump metrics between higher- and lower-level performers using the Landing Error Scoring System. Values are reported as mean ± standard deviation, unless otherwise indicated.

Countermovement Jump Metric	Excellent - Good LESS Score Group (≤5)	Moderate - Poor LESS Score Group (>5)	p-value	Effect Size (Cohen's *d*)
mRSI	0.55 ± 0.17	0.51 ± 0.19	0.31	0.23
Propulsive Phase (s)	0.23 ± 0.04	0.23 ± 0.04	0.83	0.06
L/R Peak Propulsive Force (%)	-0.62 ± 4.25	0.57 ± 4.89	0.33	0.27
Landing Stiffness (N/m)	-6555.38 ± 3515.67	-9757.73 ± 16231.15	0.01*	0.48
Peak Landing Force (N)	4330.65 ± 1722.52	4136.80 ± 1625.61	0.72	0.11
L/R Average Landing Force (%)	13.03 ± 152.85	-8.37 ± 13.90	0.21	0.15
L/R Landing Impulse Index (%)	-6.59 ± 15.08	-9.04 ± 13.34	0.57	0.17
Jump Height (cm)	37.18 ± 9.30	34.54 ± 6.50	0.29	0.29

mRSI = modified reactive strength index
Propulsive phase = time taken to complete the propulsion phase
L/R = left/right limb asymmetry
*p-values < 0.05 considered statistically significant

obtained from CMJ in two LESS groups: excellent – good group (≤5) and moderate – poor group (>5).

Athletes who had an anterior limb reach difference between right and left lower extremity, defined as greater than 4 cm in previous literature,[15] recorded statistically greater mRSI (p = 0.004), propulsive phase duration (p = 0.004), and peak landing force (p = 0.002). The data were subsequently examined by male and female athletes. Male athletes with a right limb composite score defined as less than 89 cm demonstrated significantly greater scores on L/R peak propulsive force (p = 0.007) and landing impulse (p = 0.01). Male athletes with a high risk left composite score (less than 89 cm total) had statistically significant greater peak landing force (p = 0.04) and smaller jump height (p = 0.004) than athletes with low risk composite scores (greater than 89 cm total). Table 2 displays the differences in CMJ derived force plate metrics between high and low risk athletes according to the YBT results.

SECONDARY OUTCOME MEASURES

Considering the potential at-risk flags between the two tests, statistical regression demonstrated that athletes with a greater number of these at-risk flags had significantly greater values in propulsive peak force (p = 0.01), L/R peak propulsive force (p = 0.02), peak landing force (p = 0.01), L/R average landing force (p = 0.02), and L/R landing impulse index (p = 0.02).

DISCUSSION

The purpose of this study was to compare force plate-derived metrics from a CMJ to higher and lower-level performers in two commonly used tests to assess ACL injury risk, the YBT and the LESS in an NCAA Division I collegiate athlete population. These results offer valuable preliminary insights into the use of CMJ metrics to complement lower extremity movement quality assessments in collegiate athletes.

Consistent with previous research methodologies,[39] this study categorized participants into two groups based on LESS scores: excellent – good and moderate – poor. The results revealed that athletes with moderate – poor LESS scores exhibited significantly higher landing stiffness during CMJ compared to those with excellent – good scores. The elevated landing stiffness during the CMJ has been linked to reduced eccentric control resulting in lowered capacity to absorb force.[35] This finding is also consistent with motion capture analysis of young female basketball and floorball players, demonstrating that "stiff landings" are associated with an increased ACL injury risk.[36] From a clinical and sports performance perspective, increased landing stiffness may reflect suboptimal shock absorption strategies during dynamic tasks, which could result in greater joint loading during landing and cutting maneuvers. In applied settings, CMJ-derived stiffness metrics may therefore serve as a complementary tool to traditional movement screens by providing additional insight into how athletes manage eccentric loading during high-demand movements. High risk participants (> 4 cm anterior inter-limb reach difference) demonstrated significantly greater CMJ metrics, including modified Reactive Strength Index, propulsive phase duration, and peak landing force. Both mRSI and propulsive phase duration are linked to neuromuscular fatigue, while peak landing force reflects an athlete's deceleration ability.[22,40,41] Although mRSI is classically associated with rapid impulse generation and shorter force application times, prior work has demonstrated that similar jump outcomes can be achieved through different force–time strategies depending on neuromuscular coordination, limb symmetry, and task constraints. McMahon et al. have shown that athletes may achieve comparable jump heights using

Table 2. Countermovement jump metrics between low and high risk performers on the Y-Balance test. *Values are reported as mean ± standard deviation.

Countermovement Jump Metric	Right Composite High Risk	Right Composite Low Risk	Left Composite High Risk	Left Composite Low Risk	Anterior Limb Difference High Risk	Anterior Limb Difference Low Risk
mRSI	0.54 ± 0.18	0.55 ± 0.17	0.54 ± 0.17	0.55 ± 0.18	**0.55 ± 0.18**	**0.54 ± 0.18**
Male	0.64 ± 0.03	0.66 ± 0.02	0.61 ± 0.03	0.67 ± 0.02	0.66 ± 0.03	0.65 ± 0.02
Female	0.38 ± 0.02	0.38 ± 0.01	0.38 ± 0.01	0.38 ± 0.01	0.38 ± 0.01	0.38 ± 0.01
Propulsive Phase Duration (s)	0.23 ± 0.04	0.23 ± 0.04	0.23 ± 0.04	0.23 ± 0.05	**0.22 ± 0.06**	**0.24 ± 0.04**
Male	0.21 ± 0.01	0.22 ± 0.01	0.21 ± 0.01	0.21 ± 0.01	0.21 ± 0.01	0.21 ± 0.01
Female	0.27 ± 0.01	0.26 ± 0.01	0.26 ± 0.01	0.26 ± 0.10	0.26 ± 0.03	0.26 ± 0.01
L/R Peak Propulsive Force (%)	0.97 ± 4.38	-1.05 ± 4.20	0.24 ± 4.21	-0.71 ± 4.38	-0.32 ± 4.65	-0.56 ± 4.18
Male	**1.89 ± 0.91**	**-1.13 ± 0.59**	0.44 ± 0.89	-0.50 ± 0.64	-2.22 ± 1.59	0.23 ± 0.52
Female	-0.56 ± 1.3	-0.93 ± 0.81	-0.56 ± 1.51	-0.90 ± 0.78	0.12 ± 0.90	-0.87 ± 0.72
Landing Stiffness (N/m)	-7710 ± 1466	-6699 ± 6522	-6374 ± 11227	-7631 ± 574	-7335 ± 3999	-6750 ± 7940
Male	-9547 ± 1993	-7618 ± 591	-9516 ± 2021	-7646 ± 1084	-9644 ± 1340	-8549 ± 839
Female	-4.648 ± 433	-5337 ± 108	-794 ± 4106	-6463 ± 801	-5993 ± 1008	-5103 ± 1219
Peak Landing Force (N)	4480 ± 1894	4231 ± 1625	4658 ± 1876	4176 ± 1629	**4511 ± 1889**	**4148 ± 1670**
Male	5674 ± 289	5137 ± 215	**5839 ± 279**	**5065 ± 213**	5183 ± 400	5326 ± 196
Female	-5.89 ± 4.37	-9.78 ± 3.57	2540 ± 169	-3.52 ± 2.97	-4.91 ± 4.05	-3.92 ± 3.04
L/R Average Landing Force (%)	-2.39 ± 12.72	1.57 ± 15.25	-3.54 ± 12.47	1.05 ± 16.85	-1.58 ± 17.39	1.26 ± 17.65
Male	-0.5 ± 3.32	2.90 ± 3.22	-2.30 ± 3.29	2.90 ± 3.22	-4.19 ± 3.5	2.75 ± 4.72
Female	-5.50 ± 2.44	-1.95 ± 3.19	-6.53 ± 2.92	-4.77 ± 1.30	-3.11 ± 4.33	-5.28 ± 1.27
L/R Landing Impulse (%)	-10.48 ± 14.80	-5.22 ± 14.51	-9.47 ± 14.99	-6.01 ± 14.64	-2.78 ± 13.66	-8.90 ± 13.64
Male	**-11.3 ± 5.30**	**7.20 ± 3.60**	-6.77 ± 4.97	1.80 ± 5.52	-1.16 ± 13.83	-2.48 ± 3.70
Female	-8.84 ± 2.43	-8.84 ± 2.43	-11.64 ± 5.09	-8.37 ± 2.23	-5.72 ± 18.44	-9.30 ± 2.13
Jump Height (cm)	14.05 ± 3.44	14.68 ± 3.58	13.97 ± 2.98	14.39 ± 3.21	14.71 ± 4.44	14.21 ± 3.62
Male	38.10 ± 0.99	38.1 ± 0.76	**39.10 ± 1.32**	**43.94 ± 0.88**	44.50 ± 1.60	41.9 ± 0.93
Female	27.43 ± 0.99	28.4 ± 0.86	27.94 ± 1.21	27.94 ± 0.81	27.17 ± 2.64	28.7 ± 0.68

mRSI = modified reactive strength index
Propulsive phase = time taken to complete the propulsion phase
L/R = left/right limb asymmetry
This force plate variable was only collected for 60 out of the 109 participants.
Statistically significant differences ($p < 0.05$) are shown in **bold**

either higher-force–shorter-duration or lower-force–longer-duration propulsion strategies, particularly when instructed to prioritize jump height rather than movement efficiency.[21,22] Bishop et al. further emphasize that time-based CMJ metrics should be interpreted in the context of movement strategy rather than as isolated markers of neuromuscular performance or fatigue.[34] In the present, the concurrent observation of higher mRSI and longer propulsive phase duration in athletes with anterior YBT asymmetry may therefore reflect compensatory bilateral force strategy rather than optimal neuromuscular efficiency. Athletes with inter-limb asymmetry may rely on prolonged force application to achieve sufficient impulse during bilateral jumping tasks, masking asymmetries that remain evident during unilateral balance assessments such as the YBT. It is also important to note that these findings are derived from group-level comparisons within an exploratory cohort spanning multiple sports and sexes, rather than from within-subject mechanistic analyses, and should therefore be interpreted as hypothesis-generating rather than causal. Despite this, overall findings from the current investigation may offer valuable insight regarding the potential utility of these metrics to also provide insight into movement quality in this athlete population and should be further studied.

Analysis stratified by gender revealed distinct patterns among male athletes with greater right and left limb composite scores. Specifically, those with greater right limb composite scores exhibited significantly higher scores on L/R peak propulsive force and landing impulse, indicating asymmetry between the right and left limb in the jump and greater force generation during propulsion and landing. Conversely, male athletes with greater left composite scores demonstrated greater peak landing force and lower jump height, suggesting challenges in landing force absorption and jump performance. These differences may stem from significant limb dominance, which can lead to preferential use of one limb for majority of strength generation and coordination, and therefore asymmetric force generation.[42] However, leg or hand dominance was not analyzed in our population, limiting exploration of this theory. No distinct patterns in CMJ metrics were observed among female athletes. This lack of differentiation may be due to insufficient sample size in female subgroup to detect subtle differences. It is also possible that at smaller absolute force generation capacities, as exhibited by the female athletes in this study as compared to the male athletes, there are less pronounced asymmetries. Lastly, the female athletes in this study may exhibit more balanced neuromuscular control and strength between limbs, potentially due to different training habits or physiological differences. Additionally, all male participants were football athletes, whereas female participants competed in lacrosse or soccer, which differ in movement demands, training exposures, and seasonal structure. These sport-specific factors may have contributed to the observed subgroup differences. Future research should employ longitudinal study designs with repeated testing across training phases within specific sports and sexes to better delineate sex- and sport-related influences on CMJ performance and movement quality.

Utilizing the "At Risk Flag Count" criteria, an exploratory composite measure reflecting the cumulative presence of multiple movement-based risk indicators across testing modalities, several significant associations were found between at-risk biomechanics and specific force plate metrics. Athletes with a higher number of at-risk flags exhibited significantly higher scores on propulsive time, peak landing force, average landing force, and landing impulse index. Although further investigation is required to determine how these landing metrics relate to injury assessment over time, each of these describes aspects of a "stiff" landing, which is known to be associated with knee injury.[36] As this composite risk approach has not been previously validated, the findings should be interpreted cautiously. However, by aggregating multiple established risk factors into a single summary score, the "At Risk Flag Count" may offer a preliminary framework for capturing movement-related risk profiles in a more integrated manner than single-factor assessments. Future research is needed to evaluate the reliability, validity, and potential clinical or performance utility of this approach in larger and longitudinal cohorts.

In addition to the unvalidated novel "At Risk Flag Count" tool discussed above, other limitations of this study must be considered. Stratifying data by sex, limb dominance, and composite scores allowed the researchers to explore more nuanced biomechanical differences, but it also introduced greater variability and complexity in interpretation. Subgroup sizes, particularly among female athletes, were limited, which may have masked subtle trends. Given the exploratory nature of this pilot study and the limited sample sizes within individual sport and sex subgroups, covariates such as sex and sport were not included in the regression models. Future larger-scale studies with adequate subgroup representation should incorporate these variables to allow for more robust multivariable analyses and better account for potential confounding across sports. Moreover, testing occurred in a single session, using only two CMJs per athlete, which may not fully capture an individual's typical mechanics or account for day-to-day variability. Repeating these assessments over time, or during different states of fatigue and training load, may provide more robust and representative data. Despite these limitations, the present findings support the feasibility of leveraging CMJ force plate metrics for purposes outside of performance to characterize movement asymmetries and neuromuscular patterns, warranting further investigation in larger longitudinal studies.

From a practical standpoint, force plate testing is already routinely implemented in many sports' performance settings for monitoring training load, jump performance, and neuromuscular status with data collection and processing embedded within existing workflows. Because CMJ testing is already commonly performed on a regular basis the extraction of additional force-time variables requires minimal additional time on a daily or weekly basis per athlete. In contrast, field-based movement screens such as the LESS and the YBT require dedicated testing space, more trials per athlete, and trained personnel for real-time administration and scoring, making repeated daily and weekly assessment across entire teams, which can include greater than 70 athletes per team, substantially more time and resource-intensive. While CMJ testing should not at this time be viewed as replacement for established movement assessments, the ability to leverage existing force plate infrastructure for complementary movement quality insights may offer longer-term efficiency advantages in settings where force plates are already available and reduce the need for frequent resource-intensive screening sessions. Future work should further evaluate how CMJ-derived metrics could be integrated into athlete monitoring workflows, particularly in programs with limited staffing or logistical capacity to perform comprehensive screening batteries on a regular basis.

CONCLUSION

The findings of this study suggest that specific CMJ variables, particularly landing stiffness, modified Reactive Strength Index (mRSI), propulsive phase duration, and peak landing force may be associated with movement patterns flagged as high risk by traditional screening tools such as the LESS and the YBT. The LESS, YBT, and the CMJ assess different characteristics of movement and control in different planes of motion. The results of this exploratory study highlight the complementary nature of the CMJ variables. These results position the CMJ as a promising adjunct tool within a larger athlete testing battery.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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