ABSTRACT

Background: Although functional tests including the single leg hop (SLH), triple hop (TH), cross over hop (COH) for distance, and the tuck jump assessment (TJA) are used for return to play (RTP) criteria for post anterior cruciate ligament (ACL) injury, sport-specific baseline measurements are limited.

Purpose: The purpose of this study was to examine differences in SLH, TH, and COH distance and limb symmetry index (LSI), as well as total scores, number of jumps, and individual flaws of the TJA in 97 injury-free Division I (DI) collegiate female student athletes participating in ACL injury prone vs. non ACL injury prone sports. The hypothesis was that significant mean differences and asymmetries (LSI) would exist between the two groups in SLH, TH, COH and TJA.

Study Design: Cross sectional.

Methods: Due to research suggesting inherent ACL injury risk associated with specific sport involvement, participants were grouped into high (HR, n=57) and low (LR, n=40) ACL injury risk based on participating in a sport with high or low ACL injury rates. The HR group was composed of athletes participating in soccer, basketball, and volleyball, while the LR group athletes participated in diving, cross country, and track and field. Participants performed all standard functional tests (SFT) and side-to-side differences for each participant as well as between group differences were assessed for the hop tests. The LSI, a ratio frequently used to gauge athletes' readiness for RTP post injury, was also assessed for between group differences. The TJA was compared between the groups on individual flaws, overall scores, and number of jumps performed.

Results: No between group differences for hop distances were found, with medium to large effect sizes for SLH, TH, and COH. The HR group had a higher TJA score, number of jumps, and higher proportion of the flaw of ‘foot placement not shoulder width apart’.

Conclusion: Although most SFT’s showed no significant differences between athlete groups, some differences were seen in the TJA; the HR group showed an increase in ‘foot placement not shoulder width apart’ flaw, higher overall flaw scores, and overall jumped more times compared to the LR group. These results may warrant caution in relying solely on SFT for RTP decisions, due to potential asymmetries seen in an uninjured population with baseline testing.

Level of Evidence: 4

Key Words: Asymmetry, knee, return to play
INTRODUCTION
Anterior cruciate ligament (ACL) injuries are physically, financially, and emotionally devastating sport-related knee trauma, leading to over 134,000 ACL reconstructions per year in the United States. The majority of ACL injuries are due to non-contact mechanisms. There is a substantial difference by sex, with females up to four times more likely to sustain an ACL injury compared to males, depending on sport participation. Sports associated with most ACL injuries often require sidestepping, pivoting, landing, deceleration, and cutting maneuvers, which place the knee in valgus positions under high loads and rotational forces. Furthermore, sports played on courts, such as basketball and volleyball, may have an increased ACL injury occurrence, compared to other types of playing surfaces.

After ACL injury, proper reintroduction to sport is vital to prevent re-injury and long-term consequences. To provide measurements for assessment for safe return to play (RTP) post-ACL injury, standard functional tests (SFT) have been developed. Most SFTs measure distances hopped during complex multi-planar movements as a surrogate for strength and power assessment when evaluating neuromuscular control of athletes. Myer, et al reported that hopping tests could be used to identify female athletes who are at risk for ACL re-injury. Differences between injured and uninjured limbs are one criteria used to assess readiness for RTP and may also be used to document improvements in athletes' strength symmetries throughout progression of rehabilitation protocols; the Limb Symmetry Index (LSI) is commonly used to measure such differences. LSI is the mean hop test score of one limb divided by the mean score of the contralateral limb, multiplied by 100.

Participating in sports may facilitate pre-programed neuromuscular strategies that are sport-specific, which may predetermine functional asymmetries. Superior motor functioning on dominant limbs, including strength and power, may exist in athletes of various sports. Specifically, lower limb imbalances and asymmetries during cutting and pivoting have been observed in sports such as basketball, soccer, and volleyball. It is important to determine if such potential pre-programmed movement patterns of specific sports influence baseline performance on hop tests and the tuck jump assessment (TJA).

The purpose of this study was to examine differences in single leg hop (SLH), triple hop (TH), and cross over hop (COH) distance and LSI, as well as total scores, number of jumps, and individual flaws of the TJA in 97 injury-free Division I (DI) collegiate female student athletes participating in ACL injury prone vs. non ACL injury prone sports. The hypothesis was that significant mean differences and asymmetries (LSI) would exist between the two groups in SLH, TH, COH and TJA.

METHODS
This cross-sectional study included 97 healthy and injury free Division I (DI) female student athletes (n=97) between 18 and 22 years of age (mean ± standard deviation: 19.3 ± 1.2 years). Athletes participated in soccer, basketball, volleyball, diving, cross-country, and track and field. Potential participants were cleared to play by the team physician during the pre-participation exam prior to being given a health questionnaire. Positive responses on the questionnaire were reviewed by a physical therapist (mw) prior to performance of any of the functional tests. Participants were excluded if they had a history of concussion in the prior six months, any current injury or illnesses that would limit ability to participate in the testing, or if improper attire (i.e., non-athletic shoes) was worn. Data were collected at Northern Arizona University's athletic facilities throughout the 2014-2016 sport seasons.

Before data collection, participants were given verbal information about the purpose, risks, benefits, and expectations of the study as well a chance to ask questions. All participants signed an informed consent, which was approved by the Institutional Review Board at Northern Arizona University.

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Participants were categorized into two groups based on ACL injury risk from sport participation. The high ACL injury risk group (HR) was composed of participants in soccer, basketball, and volleyball (n=57). The low ACL injury risk group (LR) included participants in diving, cross country, and track and field (n=40).

Each participant completed four tests – SLH, TH, and COH for distance, and the TJA. The order of the
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The tuck jump assessment (TJA) has been suggested as a useful tool to identify lower extremity flaws seen with plyometric movements and can, along with hop tests, document improvements in an athlete’s progression through rehabilitation protocols. With the TJA, clinicians identify movement patterns associated with ACL injury, such as excessive knee valgus and target impairments with neuromuscular training to help lower injury risk. Good inter- and intrarater reliability for the TJA have been published, however, conflicting research exists. Dudley et al found poor interrater reliability and poor to moderate intrarater reliability, and further suggested a possible learning curve to scoring the TJA and resultant improvements with interrater reliability with repeat scoring. To help achieve consistent scoring, two independent assessors were trained and underwent practice sessions before scoring; consensus was achieved between the two independent assessors on videos from 25 athletes not associated with this study.

The SLH, TH, and COH for distance are the most frequently reported functional tests used post-ACL reconstruction, thus these were chosen for this study. Literature shows a correlation between hop tests and knee function, as measured by self-reported questionnaires post ACL injury. Furthermore, the distance hopped for the SLH test may predict low back pain and lower extremity injuries. Hop tests can reveal differences between injured and uninjured limbs when determining a measure for safe RTP, the literature supports a LSI threshold of 90%. Reduced LSI asymmetry is associated with the promotion of improved RTP rates and lower rates of re-injury. Hop tests have also shown good reliability (intraclass correlation coefficients [ICCs] 0.84 to 0.97). The SLH, TH, and COH required participants to stand with the tips of one shoe on a piece of tape on the ground. For the SLH, the participant hopped forward in a straight line as far as possible, landing on the same foot. For the TH, the distance measured included three consecutive hops on one leg in a straight line, with no recovery allowed between hops. For the COH, each participant performed three hops, crossing a one-foot wide area marked off with tape with each hop. The distance was measured from the starting tape to the back of the heel upon landing. For each test, participants had to demonstrate no loss of balance at landing before the hop distance was measured and recorded; having to put down the second foot at any time during the hop or landing or any aberrant movement that caused the plant foot to move upon landing was recorded as a failed attempt. Failure to perform the hop properly required repeated attempts until a proper hop was completed. The hops were performed two times per limb with a short rest break between attempts. One practice attempt was allowed before each of the hop tests.

STATISTICAL METHODS

Independent t-tests of means were used to compare continuous demographic variables between the two groups. For each hop test (i.e., SLH, TH, COH), the participant’s average distance of two hops was normalized to height. The LSI was calculated by the ratio of right to left limb, versus injured vs. non-injured, due to the population being healthy. Because there were significant differences in weight between those in high and low ACL risk sports as well as a significant association between hop tests and weight, differences between the groups from...
the hop tests were analyzed using linear regression, adjusting for body weight. For the TJ A score and number of jumps, between group differences were assessed with independent t-tests. The association of each flaw by group was analyzed using Chi Square. Bonferroni’s correction was used to minimize the risk of Type 1 error due to multiple tests; alpha of 0.003 was used for statistical significance. Cohen’s d were calculated as effect sizes and categorized (<0.29 = small, 0.3-0.49 = medium, >0.5 = large) to aid in interpretation of clinical relevance of the tests. SAS 9.4 (SAS Institute, Inc., Cary, NC) was used for statistical analysis.

**RESULTS**

There were 97 participants in this study with 57 in the HR group and 40 in the LR group. The two groups were similar in age (p=0.95); however, the HR group participants were taller and heavier (p = 0.004 and 0.005, respectively) (Table 1).

Ninety-five (HR=57, LR=38) participants completed the right SLH, TH, and COH, while 94 (HR=56, LR=38) completed the left SLH, TH, and COH. There were no significant differences in average SLH, TH, COH distances between groups (p-values: SLH R = 0.05 L = 0.02, TH R = 0.05 L = 0.005, COH R = 0.1 L = 0.04) (Figure 1). Effect sizes ranging from 0.35 to 0.62 (RSLH = 0.42, LSLH = 0.49, RTH = 0.43, LTH = 0.62, RCOH = 0.35, LCOH = 0.46) were found for both right and left SLH, TH, and COH, showing a moderate to large clinical relevance, despite lack of statistical significance. In general, the participants hopped equal distances on the right and left leg (LSI close to 100% for all). No between-group differences were found with LSI with any of the hop tests (Table 2).

Ninety-seven participants completed the TJ A with 57 in the HR group and 40 in the LR group; however, only data from 90 participants (HR = 50, LR = 40) were analyzed due to video malfunctioning. The HR group had a higher TJ A score, (HR: 5.86±1.51 vs. LR: 4.68±1.29, p <0.001) indicating worse performance, as well as a greater number of jumps (HR: 103.3%±1.0% vs. LR: 100.3%±1.2%).

### Table 1. Demographic Characteristics by Group

<table>
<thead>
<tr>
<th></th>
<th>High Risk ACL, n=57</th>
<th>Low Risk, n=40</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years (mean ± standard error [SE])</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>0.95</td>
</tr>
<tr>
<td>Height, cm (mean ± SE)</td>
<td>170.9 ± 0.01</td>
<td>166.5 ± 0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Weight, kg (mean ± SE)</td>
<td>68.3 ± 1.2</td>
<td>61.2 ± 2.1</td>
<td>0.005</td>
</tr>
</tbody>
</table>

### Table 2. Average Adjusted Limb Symmetry Index (LSI) by Group

<table>
<thead>
<tr>
<th>Hop Test</th>
<th>High Risk, n = 56</th>
<th>Low Risk, n = 38</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Leg Hop LSI (mean ± standard error [SE])</td>
<td>100.5% ± 0.95%</td>
<td>99.1% ± 1.1%</td>
<td>0.33</td>
</tr>
<tr>
<td>Triple Hop LSI (mean ± SE)</td>
<td>103.3% ± 1.0%</td>
<td>100.3% ± 1.2%</td>
<td>0.006</td>
</tr>
<tr>
<td>Crossover Hop LSI (mean ± SE)</td>
<td>100.8% ± 1.1%</td>
<td>99.6% ± 1.4%</td>
<td>0.52</td>
</tr>
</tbody>
</table>
and showed a close relationship with asymmetry measurements (LSI). Above 90% threshold was observed for all participants with the LSI regardless of group. This may suggest that hop tests are not affected by pre-programmed motor programs associated with sport performance and may be used for RTP measurements independent of the participant's sport. However, this sample may not reveal significant differences between the groups due to post hoc analysis (power = 0.31-0.57) showing some comparisons (hop tests) were underpowered. With medium to large effect sizes, there may be important differences between the two sport groups for the hopping tests that the sample size may have limited the ability to uncover. It would be clinically important to know of such possible discrepancies prior to injury, otherwise it would not be of clinicians' best interests to use hop tests as RTP criteria.

**DISCUSSION**

This study examined whether or not Division I collegiate female athletes in high ACL injury risk sports performed similarly to counterparts in low ACL injury risk sports during testing of functional hop tests and the tuck jump assessment. The hypothesis was that differences would be observed due to specific sport participation facilitating pre-programed lower extremity biomechanical maladaptions, resulting in performance differences between groups and asymmetries (LSI). No significant differences in hop test distances and LSI were found; however, clinically relevant differences may exist. Further, the TJA did reveal differences between the high risk and low risk groups.

In regards to the SLH, TH, and COH, the two groups hopped similar distances with left and right limbs and showed a close relationship with asymmetry measurements (LSI). Above 90% threshold was observed for all participants with the LSI regardless of group. This may suggest that hop tests are not affected by pre-programmed motor programs associated with sport performance and may be used for RTP measurements independent of the participant's sport. However, this sample may not reveal significant differences between the groups due to post hoc analysis (power = 0.31-0.57) showing some comparisons (hop tests) were underpowered. With medium to large effect sizes, there may be important differences between the two sport groups for the hopping tests that the sample size may have limited the ability to uncover. It would be clinically important to know of such possible discrepancies prior to injury, otherwise it would not be of clinicians' best interests to use hop tests as RTP criteria.

The TJA showed a significant difference between the two groups on the ‘foot placement not shoulder width apart’ flaw with an increase in the flaw seen in the HR group. Participants in the HR group also performed significantly more jumps and pre-

<table>
<thead>
<tr>
<th><strong>Table 3. Tuck Jump Assessment Flaws in Percent of Occurrence</strong></th>
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<tbody>
<tr>
<td><strong>Flaw</strong></td>
</tr>
<tr>
<td>Lower Extremity Valgus at Landing</td>
</tr>
<tr>
<td>Thighs Do Not Reach Parallel (Peak of Jump)</td>
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<tr>
<td>Thighs Not Equal Side-to-Side (During Flight)</td>
</tr>
<tr>
<td>Foot Placement Not Shoulder Width Apart</td>
</tr>
<tr>
<td>Foot Placement Not Parallel (Front to Back)</td>
</tr>
<tr>
<td>Foot Contact Timing Not Equal</td>
</tr>
<tr>
<td>Excessive Landing Contact Noise</td>
</tr>
<tr>
<td>Pause Between Jumps</td>
</tr>
<tr>
<td>Technique Declines Prior to 10 Seconds</td>
</tr>
<tr>
<td>Does Not Land in Same Footprint (Excessive In-Flight Motion)</td>
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* = Significant (p-value < 0.003)
may explain the greater number of jumps recorded. The LR group sports expose athletes to less frequent jumping activities, leading to potential decreased jump rates due to inexperience with the task. This may have caused the discrepancy between jump rates and thus total jumps performed from each group. Therefore it may be beneficial to provide participants with a way to practice the jumps or control jumping rates in the TJA in future studies to help standardize the procedure and minimize possible fatigue discrepancies between athletes.

Because the TJA is often used for RTP progression,9,14,47 as well as for identifying females at risk of injury,13 understanding performances on this test pre-injury is important for proper analysis of results. The HR group performed worse on the TJA, suggesting that female athletes in soccer, volleyball, and basketball may be at an increased risk of ACL injury compared to female athletes in track and field, cross country, and diving. The results also suggest possible differences in the biomechanical motor programs between the groups. This may be present in a healthy population and be related to their respected sport participation, with HR ACL injury risk sport participants presenting with decreased neuromuscular control and increased asymmetries.

The results of this study show similar performances on hop tests, but significantly different TJA performances between female athletes participating in HR and LR sports; thus, in part rejecting the original hypothesis. Due to some significant differences found, caution is warranted when using the TJA for RTP post injury, due to possible pre-injury differences, which may exist as a result of pre-programmed motor programs. Such differences may be the result of functional asymmetries witnessed due to participation in sports such as soccer, volleyball, and basketball and the biomechanical loads and demands of these sports. Further research investigating such differences among healthy athletes of different sports is needed. Knowledge of pre-injury differences on performances between various sports may lead to development of sport specific RTP protocols.

If rehabilitation clinicians rely on hop tests or the TJA results for RTP decisions, caution is warranted as asymmetry and performance differences may exist

sent with a higher number of total flaws. Linginger et al42 and Myer et al38 have suggested grouping individual TJA flaws into various categories, with the ‘foot placement not shoulder width apart’ flaw being grouped into the ‘proximal control’ and ‘ligament dominance’ categories, respectively. Ligament dominance refers to difficulty maintaining a stable knee with dynamic tasks due to imbalances found between muscular and ligamentous knee influences, leading to inability to control lower extremities during jumping tasks.38 Furthermore, hip weakness may result in participants shifting their feet to minimize forces on a weaker limb.38 If the HR group did have asymmetries in muscle strength, this may be manifested in the TJA performance, which may explain the increased number in the “foot placement not shoulder width apart” flaw. This flaw may represent lack of proximal control due to hip weaknesses. Further, if the HR group demonstrated increased occurrences of hip weakness and lack of proximal control, other flaws will be more likely to be observed in the jumps, especially the ‘excessive knee valgus’ flaw as hip weakness is also associated with increased valgus moments.43 This may potentially explain the increase number of total flaws seen in this group and may suggest that certain uninjured athletes perform functional tests with increased asymmetry and decreased LE control compared to others, depending on type of sport performed.

It is also possible that the increase in number of flaws seen with the HR group may be due to the increased number of jumps performed and thus increased fatigue that occurred during the 10 second test. Lininger, et al42 suggested faster jumping rates lead to increased fatigue, compared to slower jumping rates, where there is increased time spent on the ground and thus potentially less fatigue during the 10 second TJA. Fatigue onset has been shown to occur in male and female track athletes under 10 seconds on the Wingate test with resulting decrease in postural control and hip mechanics.44 Furthermore, fatigue has been shown to affect quality of jumps.45,46 A slower rate of jumps may be witnessed in a population not trained in jumping, and thus taking a longer time to control the new skill. This is consistent with the findings of this study. Since jumping is a frequent activity seen with the HR group sports, it may explain the greater number of jumps recorded. The LR group sports expose athletes to less frequent jumping activities, leading to potential decreased jump rates due to inexperience with the task. This may have caused the discrepancy between jump rates and thus total jumps performed from each group. Therefore it may be beneficial to provide participants with a way to practice the jumps or control jumping rates in the TJA in future studies to help standardize the procedure and minimize possible fatigue discrepancies between athletes.

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If rehabilitation clinicians rely on hop tests or the TJA results for RTP decisions, caution is warranted as asymmetry and performance differences may exist
because of pre-programmed motor programs established through sport participation. Clinicians may want to focus on a multi-planar approach instead and this should be the focus of further research. Furthermore, if differences do exist between athletes of various sports, more specific and, thus, effective interventions and RTP protocols could be developed.

Limitations to this study include a small sample of convenience, with all 97 female participants of this study playing for one Division I university, potentially limiting external validity; practical application to males and different levels of competition cannot be assumed. Also, participants were not screened for a history of previous ACL injuries. This could be a limitation due to research that describes the possibility of long term deficits between involved and uninvolved limbs on strength and functional tests post ACL injury. However, Hartigan et al reported that the mean scores on four hop indices (SLH, TH, COH, and six-meter timed hop) were above 90% in males and females at six months post ACL reconstruction. It also remains unclear whether such post-surgical neuromuscular limitations in hopping tests are purely the result of ACL injury, or if pre-injury asymmetries existed as studies designed to assess field tests in ACL injury have only been retrospective, not prospective, in nature. Despite the limitations, this is the first study that examined differences in functional tests based on type of sport.

Further research should examine performances on SFTs with larger samples and in male athletes to extend findings across sexes and to minimize the possibility of type II error. Comparing dominant and non-dominant, versus left and right, limbs between groups in a healthy population may also be of benefit. Further research should also evaluate the ability of functional hop tests and TJA in predicting incidence of ACL injury in female athletes participating in high ACL injury risk sports compared to females participating in low ACL injury risk sports.

**CONCLUSION**

The results of this study showed no differences between hop test scores in Division I female athletes of high and low ACL risk sports, however differences were observed between groups for the TJA. Due to the differences seen between baseline performance in normal subjects examined in this research, caution should be used when interpreting the TJA for RTP decisions. Due to the medium effect sizes, showing clinically relevant differences for the hop tests, future research with increased sample sizes is warranted to help lower the risk for potentially committing Type II errors. Performances on the TJA might vary due to the inherent nature of different and asymmetrical biomechanical movements associated with specific sports. More research is needed to verify the observed differences of this study.

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