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# Hop Tests Can Result in Higher Limb Symmetry Index Values than Isokinetic Strength and Leg Press Tests in Patients following ACL Reconstruction

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## Abstract

**Purpose—**Quadriceps weakness is a common clinical sign following anterior cruciate ligament injury and reconstruction surgery (ACLR). The aim of this study was to compare strength deficits and the limb symmetry index (LSI) from three different types of functional tests: isokinetic dynamometry, hop test, and leg press.

**Methods—**A total of 26 subjects with ACLR (average 8.3 months post-operation) participated in the study. The peak knee extension torque was tested with isokinetic dynamometry at 60/180/300 degrees per second (ISO60/180/300). Hop distance was tested during single hop (SH) and triple hop (TH). Unilateral peak leg power (POWER) was tested during a bilateral leg press test. LSI was calculated as the ratio of the involved limb over the uninvolved limb values. Pearson correlation coefficients and paired t-tests were used to establish relationships among ISO60/180/300, SH/TH, and POWER values and compare these values between the limbs, respectively. Within-subject one-way analysis of variance (ANOVA) with *post-hoc* analyses were used to compare LSI values among different tests.

**Results—**ISO60/180/300 values were significantly positively correlated with SH/TH and POWER ($P < 0.05$), while SH/TH and POWER values were not significantly correlated. Significant limb differences were found in all tests ($P = 0.001 – 0.008$). ANOVA revealed significant LSI differences among different tests. Specifically, *post-hoc* analyses revealed that LSI during SH was significantly higher than LSI during ISO60. Similarly, LSI during TH was significantly higher than LSIs from ISO60, ISO180, and POWER tests.

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Authors' Contributions
TN and NS carried out all aspects of the study. EL and TE participated in the design and development of research aims. TN and TE were involved in interpretations of the results and discussion. All authors read and approved the final manuscript.

**Conclusions—**Peak knee extension torque values were positively associated with hop distance and leg power during the leg press test. However, LSI values should be interpreted with caution as hop tests provided significantly higher LSI values than isokinetic testing. Both isokinetic dynamometry and unilateral leg press machine could be used to isolate and strengthen the quadriceps in the involved limb. The current "gold standard" isokinetic testing at slow speed (ISO60) provided the lowest LSI value among all functional tests; therefore, the current study supported a continued use of isokinetic testing when examining individual's readiness and return-to-sport.

Level of Evidence III, Cross-sectional study

## Introduction

Quadriceps weakness is the most common hallmark of clinical presentation in individuals after anterior cruciate ligament injury and reconstruction surgery (ACLR). Quadriceps strength may never return to estimated pre-injury levels, even after post-operative rehabilitation and return-to-sport [15, 33]. This chronic condition of quadriceps weakness is likely caused by a neuropathological process – arthrogenic muscle inhibition – and is associated with several morphological and neuromuscular changes: smaller muscle size, loss of motor unit recruitment, and decreased motor unit firing rate [13]. Perhaps the most devastating clinical significance of quadriceps weakness is its association with an increased risk of secondary ACL injury [7, 16], decreased self-reported knee outcome/function [11], low psychological readiness [18], and early progression to osteoarthritis [24]. For obvious reasons, quadriceps muscular strength assessment plays an integral part of ACLR and musculoskeletal rehabilitation, and provides objective values that can be used for return-to-sport guidelines and long-term joint health.

The current "gold standard" for quadriceps muscular strength testing following ACLR is isokinetic dynamometry performed at slow speed (30–60 degrees/second) [32]. During isokinetic testing, quadriceps strength is reported as concentric knee extension torque [32]. In addition, the limb symmetry index (LSI) is calculated as the ratio of the peak knee extension torque in the involved limb over the peak knee extension torque in the uninvolved limb. Isokinetic testing at slower speed can detect larger quadriceps strength deficits (lower LSI value) than isokinetic testing at faster speed [10]. These isokinetic variables are utilized commonly in sports medicine literature to determine return-to-sport criteria following ACLR [32]. However, quadriceps strength testing with isokinetic dynamometry has limitations, including a non-weight bearing testing position (open-kinetic-chain as compared to weight-bearing or closed-kinetic-chain) and feasibility factors (cost and trained personnel to operate). For these reasons, other field-expedient and clinically-friendly tests have been developed. Single hop (SH) or triple hop (TH) tests for distance are two common tests and have been validated for clinical use in individuals following ACLR [25]. Several studies have compared isokinetic dynamometer quadriceps strength and hop tests and reported high and positive relationships between these two tests [12, 26, 34]. Contrarily, a recent study has reported higher LSI values during hop tests when compare to LSI values from isokinetic dynamometer quadriceps strength testing [1]. The authors cautioned when interpreting LSI values from hop tests.

A seated leg press machine is a common closed-kinetic-chain resistance training device during ACLR rehabilitation: it can also be used to test the lower extremity muscular strength, power, and LSI [23, 30]. Additionally, a seated leg press machine is easily accessible by patients and provides a mechanism to overload the quadriceps during eccentric actions and can improve quadriceps strength effectively [3]. Recent leg press machines have an option to separate right and leg footplate and perform a unilateral leg press during a bilateral explosive strength test. However, the lower extremity power and LSI during a seated leg press test has not been validated with the “gold standard” isokinetic dynamometry and common field-expedient hop tests. It is clinically relevant to explore additional field-expedient functional tests to examine quadriceps strength and LSI. Furthermore, the purpose of the current study was to examine relationships between the lower extremity muscular explosive strength (power output) from the leg press machine, peak knee extension torque from isokinetic dynamometry, and the maximum hop distance from hop tests. It was hypothesized that the leg press values would be positively correlated to isokinetic and hop test values. In addition, the secondary purpose of the study was to compare LSI values among different tests (leg press, isokinetic, and hop tests). It was hypothesized that there would be no difference in LSI among leg press, isokinetic, and hop tests.

## Materials and methods

A total of 26 individuals (15 females / 11 males, Age: 22.1 ± 9.1 years old; Height: 173.5 ± 11.6 cm; Weight: 77.6 ± 23.0 kg; Months from ACLR: 8.3 ± 2.6 months) participated in the study. All subjects sustained a primary ACL tear on one leg. Board-Certified orthopedic surgeons at the same institution performed all ACL reconstruction surgeries using the bone-patellar tendon-bone autograft (n = 18), hamstring autograft (n = 6), or gracilis/hamstring allografts (n = 2). Patients who had multiple ligament/meniscus reconstructions/repairs in the knee joint of the involved limb or uninvolved limb were excluded from the study. All subjects were at least 6 months post-operation (average: 8.3 ± 2.6 months post-operation) and were able to jog at a comfortable pace. Patients with residual pain, swelling, or discomfort from the surgery and those patients who were unable to perform any of isokinetic strength, hop, or leg press tests were excluded from the study. Rehabilitations after ACLR were provided by licensed physical therapists at the same institution and followed the same post-operation guidelines/protocols. All patients participated in a one-hour testing session that consisted of isokinetic strength, hop, and leg press tests.

For isokinetic strength testing, subjects were seated upright in the dynamometer (Humac Isokinetic Dynamometer, CSMI USA, Stoughton, MA) with their hip and knee comfortably bent at 90 degrees. The contralateral, uninjured leg was tested first. After familiarization, subjects were asked to kick into knee extension and then pull back as hard as they can in succession for five repetitions for knee extension (quadriceps) and knee flexion (hamstrings) muscular strength assessment. The speed of the machine was set at 60 degrees/second. After rest, the same procedures at faster speeds (180 [10 repetitions] and 300 degrees/second [15 repetitions]) were repeated. The average peak torque was expressed in Nm divided by body weight (Nm/kg), and the ratio of the peak torque on the ACLR limb over the contralateral limb was used as LSI and expressed in percentage (e.g., 85% LSI means that the average peak torque of the ACLR limb was 15% less than that of the contralateral limb). For the purpose of the study, only knee extension torque was analyzed. Excellent reliability (intraclass correlation coefficient [ICC] = 0.76 – 0.86) and precision (standard error of measurement [SEM] = 0.17–0.19 Nm/kg) was established with the same dynamometer and protocols [8].

For SH testing, subjects were asked to hop as far as they could for three times on the contralateral limb first. There was a tape measure on the floor, and the hop distance was read from the starting line to the front tip of their shoes in centimeters. If subjects failed to stick the landing (i.e. non-landing leg hits the floor or skipping during landing), those jumps were not counted and the same procedures were repeated until three successful jumps were performed. Similarly, TH testing was performed following SH testing. The average of three hops was used for statistical analyses. LSI for both SH and TH tests were calculated in the same manner. Excellent reliability (ICC = 0.88 – 0.92) and precision (SEM = 3.49–4.32% of the maximum distance) was reported [27].

For leg press testing, a commercially available air-pressured load leg press machine was used (Keiser Air 300 Leg Press, Keiser Corporation, Fresno, CA). Subjects were positioned in an inclined chair with their hip close to full flexion with their knee at approximately 100 degrees flexion. The leg press pedals were positioned directly in front of the chair for subjects to push horizontally. As a warm-up, subjects were asked to perform easy, medium, and hard leg press for 12, 8, and 3 repetitions with a rest in between sets. A rating of perceived exertion was used to define their perception of easy, medium, and hard leg press and amount of weight lifted. Using the same scale, an examiner adjusted target weight accordingly. After a rest, subjects were asked to perform the one repetition maximum (1RM), defined as the maximum weight one can lift only one time. Weight was gradually added until subjects no longer could move the pedal. The maximum weight for 1RM was used to calculate a default weight (70% of 1RM weight) for power assessment. During the power assessment, subjects were asked to push the pedals as fast and hard as they could. After practice trials, a total of five leg presses were performed with 10-second rests in-between repetitions. The average of 5 repetitions was used for analysis. Since there were two independent pedals with force/power outputs, the average power in watts for each limb was used to calculate LSI. Excellent reliability (ICC = 0.94) and minimal error (0.43 watts/kg) was reported previously with leg press power testing [23]. The study was reviewed and approved by the Mayo Clinic Institutional Review Board (ID:15-009007), and all subjects were consented prior to the testing.

## Statistical analyses

For the sample size calculation, *a priori* power analysis and a previous study [6] with similar outcome measurements revealed that at least 20 subjects were required to achieve an effect size of 0.30, alpha of 0.05, and a power of 0.80. Due to potential attritions, a total of 26 subjects were recruited and tested in the current investigation. For statistical analyses, descriptive statistics (means and standard deviations) of dependent variables were calculated. Normality of each variable was examined using Shapiro-Wilk tests. To statistically analyze side-to-side differences within-subjects, paired t-tests were used. For the first hypothesis, bivariate simple linear correlations were used to examine relationships between each variable from the leg press, isokinetic, and hop tests for the involved and uninvolved limb and LSI. Lastly, for the second hypothesis, one-way within-subject analysis of variance (ANOVA) with *post-hoc* analyses was used to compare LSIs among all tests. Significance was set at $P < 0.05$ *a priori*. All statistical analyses were run using the IBM SPSS Statistics Software version 22.0 (IMB Corporation, Armonk, NY).

## Results

Means and standard deviations were shown in Table 1. For within-subject analysis (between-limb comparison), paired t-tests revealed that there were significant differences between the involved and uninvolved limb in all test types ($P = 0.001 – 0.008$). Pearson correlation coefficient values are shown in Table 2. Actual values of isokinetic tests and power test within the same limb (involved limb or uninvolved limb) were significantly and positively correlated to each other ($r = 0.51 – 0.63$, $P = 0.001 – 0.023$). The SH and TH distance was also positively correlated in the involved limb ($r = 0.58$, $P = 0.009$) and the uninvolved limb ($r = 0.52$, $P = 0.023$); however, these hop test distances were not correlated with the power values from the leg press test in either limb ($r = 0.07 – 0.44$, n.s.). There were fewer significant relationships found in the LSI. The LSIs from the isokinetic tests were significant only in adjacent pairs: 60/180 degrees/second ($r = 0.51$, $P = 0.008$) and 180/300 degrees/second ($r = 0.46$, $P = 0.025$). In addition, the SH LSI was significantly correlated with the TH LSI ($r = 0.83$, $P < 0.001$). Despite some trends, there were no significant correlations between the power LSI and the isokinetic ($r = 0.25 – 0.38$, n.s.) or hop LSI ($r = 0.19 – 0.38$, n.s.).

For the second hypothesis, one-way within-subject ANOVA on LSI by test types (6 test types) was significant ($F = 9.419$, $P < 0.001$, *Partial* $\eta^2 = 0.344$). *Post-hoc* analyses revealed the following significant findings (Figure 1): 1) the LSI from the isokinetic testing at 60 degrees/second were significantly lower than the LSI from both SH and TH tests ($P < 0.001$); 2) the LSI from the isokinetic testing at 180 degrees/second was significantly lower than the LSI from TH test ($P = 0.017$); and 3) the LSI from power test was significantly lower than the LSI from TH test ($P = 0.025$). The rest of comparisons on the LSI were not significant (n.s.).

## Discussion

The current investigation examined unilateral lower extremity strength/power during a bilateral leg press test and compared it with common laboratory and functional field tests – isokinetic dynamometry and hop tests – in individuals with ACLR. Peak knee extension torque values and LSI values during isokinetic tests were similar to the previous studies [4, 30]. SH and TH test LSI (92.7% and 94.0%, respectively) were also similar to previously reported values (92.0% and 91.0%, respectively) at 7.8–11.9 months post-operatively [21]. These values were much higher compared to a previous study with SH and TH LSI values (88.4% and 89.5%, respectively) at 13.5 months post-operatively [26]. Differences in demographics, athletic background, months after reconstruction surgery, and surgical/rehabilitation protocols would likely explain mixed findings.

Overall, the hypothesis was that unilateral lower extremity power during a bilateral leg press test would identify strength deficits on the involved limb in ACLR patients and provide similar LSI values among test types. These hypotheses were largely supported in that the peak power in the reconstructed limb was significantly weaker than the contralateral/ uninjured limb. The peak power during leg press was positively correlated with knee strength values during isokinetic testing; however, the peak power was not correlated with the distance during hop tests. When LSIs were compared among all 6 tests, hop tests had much higher LSI than isokinetic or power tests. This finding was clinically applicable as LSI may show a false positive result. Instead, the current "gold standard" isokinetic testing at slow speed and its LSI values reflect true quadriceps strength deficits. The current investigation also confirmed that a novel test of unilateral power during a bilateral leg press could monitor individuals' single leg strength in a closed-kinetic-chain task. ACLR patients and their therapists can benefit from information regarding how much patients were favoring the uninvolved limb over the involved limb.

The current investigation is one of the first studies to compare LSIs among multiple tests. One study reported significant positive correlation between the peak isokinetic extension torque LSI at 180 degrees/second and SH distance LSI [35]. The current results were not in agreement with those and found no correlation between those LSI. These findings are almost paradoxical as the positive and significant correlations were found between the peak knee extensor torque values and hop test distance in each leg, but the magnitude of deficits in the reconstructed limb is specific to each task performed. In other words, isokinetic testing could detect greater strength deficits in the involved/reconstructed limb than hop tests. A possible explanation of this lack of correlations among LSIs is neuromuscular alteration to utilize the hip extensor muscles to generate the lost propulsion forces from the lower extremity. This contention is supported by the finding that individuals with weak quadriceps muscles after ACLR exhibited greater hip extensor strength [2]. It is interesting to note that rehabilitation exercises which target the strength of the quadriceps muscles might also contribute to improve the hip extensor and hip adductor muscle forces [29]. Furthermore, an earlier simulation study reported that simulated quadriceps weakness was compensated for by increased activity of the gluteus maximus and soleus [31]. One finding from the current results was that hop LSIs could result in overestimation of one's quadriceps strength and lower extremity function. In turn, hop LSIs could lead to return-to-sport too early and leave athletes at higher risk of secondary ACL injuries.

In order to countermeasure quadriceps weakness, a recent meta-analysis supports the use of cryotherapy and neuromuscular electrical stimulation to control pain and minimize quadriceps hypotrophy in the early stage of ACLR rehabilitation while other popular modalities such as whole-body vibration and blood flow restriction exercise have limited evidence [5, 9]. During the strengthening phase of ACLR rehabilitation, eccentric strength training has been shown to effectively improve quadriceps strength and minimize arthrogenic muscle inhibition in ACLR patients [19, 20]. Based on the current study, both isokinetic dynamometry and leg press could be used in eccentric strength training.

A unilateral leg press machine is a popular piece of equipment that can be used to train the neuromuscular system to enable patients to exert forces equally from each leg. However, its

LSI values failed to show any significant correlations when paired with the LSI values from isokinetic and hop tests. The current results were in agreement with a previous study: this study examined side-to-side differences during the isokinetic test and leg press test in healthy individuals and did not find significant relationship in side-to-side differences [14]. Although subject demographics (ACLR vs. healthy) were different, cumulative evidence support that the magnitude of side-to-side differences can largely depend on testing types. Compensatory neuromuscular adaptations of hip extensor and calf muscles post-ACLR have been previously discussed. Based on the current results on the LSI values during a bilateral leg press test, a unilateral leg press machine might be better suited for a training modality to improve single leg strength rather than used as a testing tool.

Future investigations should focus on intervention effects to improve quadriceps strength and increase LSI. The knee extension peak torque values and LSI from isokinetic dynamometry is still “gold standard” of the quadriceps muscle testing following ACLR [32]. It has also been determined at 12 month or longer follow-up visits that LSIs return to normal with time (usually 1 – 2 years) due to gradual strength reduction in the contralateral limb [30]. To further examine quadriceps strength compared to other non-injured athletes, a recent paper included actual peak torque values (> 3.0 Nm/kg) as a reference and as a return-to-sport criterion [6]. In the current study (average 8.3 months post-operation), not one subject scored a peak extensor torque greater than 3.0 Nm/kg. Recent evidence continues to support importance of normal quadriceps strength to avoid recurrent ACL injuries [7, 16]. Inevitably, for those patients with strength deficits, a delay of return-to-sport up to two years may be necessary to prevent second ACL injuries [22]. Given that quadriceps weakness is associated with early progression of osteoarthritis following ACLR [24], it is imperative to stop the vicious cascade of musculoskeletal health decline which affects an individual’s quality of life: progressive osteoarthritis which may lead to total knee arthroplasty, further reduction in quadriceps strength, and high risk of falls [36]. It is remarkable how decreased quadriceps strength is associated with so many musculoskeletal problems throughout one’s lifespan.

Limitations of this study should be acknowledged. First, the current investigation utilized each individual’s own limbs to calculate LSI. All comparisons were made within-subject; therefore, it was not deemed important to have sex/age/activity-matched control group. The current study is a part of an ongoing investigation to establish scoring criteria (threshold) for safe return-to-sports. Since athletes’ profiles and modifiable risk factors might differ between primary ACL injury and second ACL injury (graft tear or contralateral tear), the current results add new knowledge to the literature similar to a recent study with a similar research aim [6]. Another limitation is that subjects in the current investigation included individuals with both types of ACLR grafts (patellar tendon and hamstring grafts) and both sexes [28]. Although it is commonly known that female athletes have decreased normalized strength/power, the current study focused on within-subject design (both correlational analyses and within-subject one-way ANOVA) and had minimal effect on these two factors. Further analyses were conducted to evaluate the effect of graft types and sexes on LSI in the current data and there were no significant differences between graft types and sexes, which was also supported by previous studies [17, 23]. Another limitation is that the unilateral leg press test was a novel and unique test; therefore, it was the first time for several patients.

Despite practice trials, it was possible that some patients could have benefitted from longer familiarization and practice. Lastly, even within the same institution and facility, differing surgical technique and rehabilitation protocols provide confounding variables. Moreover, each participant's number of therapy visits and their at-home activities may also be different. A precise recording of actual exposures and training volume/type/intensity at home should be considered for future studies.

Clinical relevance of the current research was the fact that LSI values from field-expedient hop tests could overestimate individual's functional outcomes. Surgeons and therapists should not rely solely on hop tests results when examining patient's readiness and return-to-sport. On the other hand, isokinetic dynamometry and unilateral leg press machine could be used to target the quadriceps in the involved limb as well as to monitor quadriceps strength over the course of pre- and post-operation rehabilitation.

## Conclusion

The peak knee extension torque values were positively associated with hop distance and unilateral leg power during a bilateral leg press test. All tests were able to detect the side-to-side strength difference or significant functional reduction in the involved limb compared to the uninvolved limb. However, LSI values should be interpreted with caution as they were task-dependent, and hop tests provided significantly higher LSI values than isokinetic testing. Quadriceps strength deficits following ACLR should be examined with isokinetic dynamometry, the current "gold standard" to avoid a false positive and ensure safe return-to-sport. Both isokinetic dynamometry and the leg press machine could be used in strength training, especially eccentric training.

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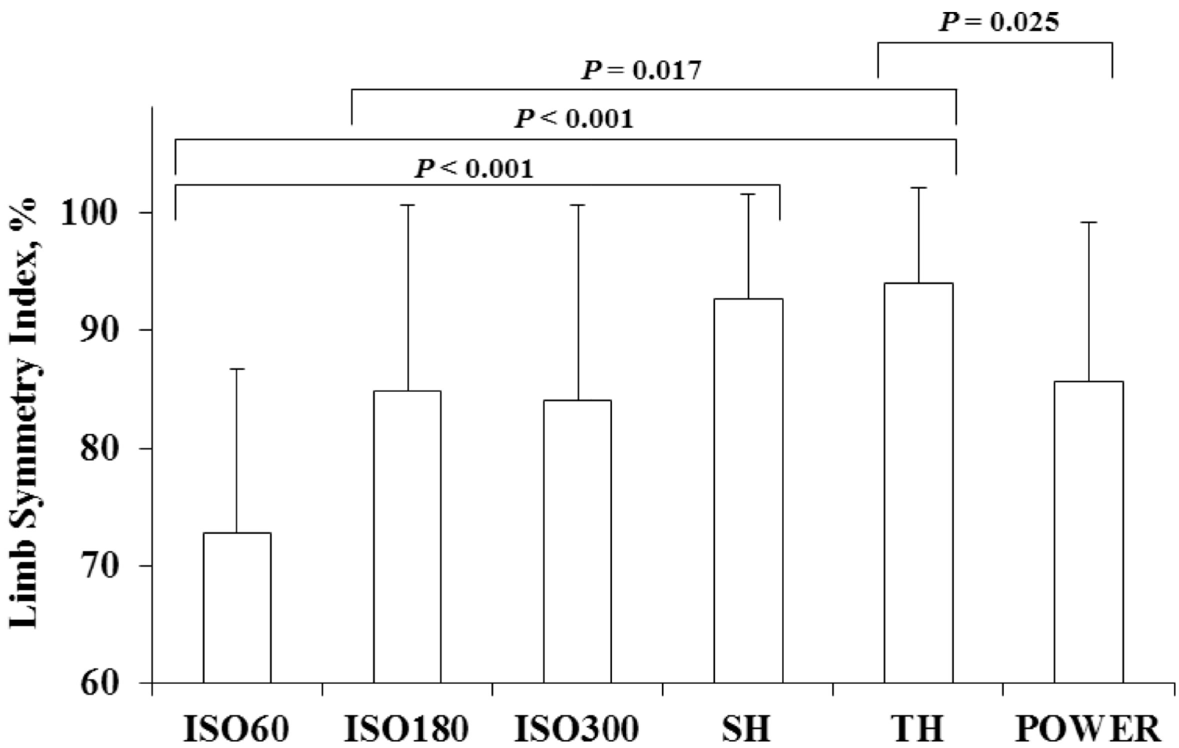


**Figure 1.**

Limb Symmetry Index (LSI) Differences between Types of Testing. ISO60/180/300 represents the LSIs of the peak knee extension torque during isokinetic dynamometry testing at the speed of 60/180/300, respectively. SH/TH/POWER represents the LSIs of single hop distance, triple hop distance, and unilateral power during a bilateral leg press, respectively.

**Table 1.**

Descriptive Statistics (Means ± Standard Deviations) and Between-Limb Comparison (Paired T-Tests) *P*-values.

| | Involved Limb | Uninvolved Limb | *P*-values | LSI |
|---|---|---|---|---|
| ISO60 (Nm/kg) | 1.6 ± 0.4 | 2.2 ± 0.5 | <0.001 | 72.8 ± 13.9% |
| ISO180 (Nm/kg) | 1.1 ± 0.3 | 1.4 ± 0.5 | 0.001 | 84.8 ± 15.8% |
| ISO300 (Nm/kg) | 0.8 ± 0.2 | 0.9 ± 0.3 | <0.001 | 84.0 ± 16.6% |
| Single Hop (cm) | 150.8 ± 35.9 | 162.4 ± 35.9 | 0.003 | 92.7 ± 8.8% |
| Triple Hop (cm) | 427.5 ± 130.6 | 454.1 ± 137.8 | 0.008 | 94.0 ± 8.1% |
| Peak Power (watts/kg) | 8.8 ± 3.3 | 10.6 ± 4.0 | <0.001 | 85.6 ± 13.5% |

ISO60/180/300 represents the peak knee extension torque during the isokinetic testing at 60/180/300 degrees per second, respectively. LSI represents Limb Symmetry Index.

**Table 2.**

Pearson Correlation Coefficients (*r*) for Each Variable in Involved Leg, Uninvolved Leg, and Limb Symmetry Index (LSI)

| Involved Leg | ISO180 | ISO300 | SH | TH | POWER |
|---|---|---|---|---|---|
| ISO60 | 0.83** | 0.82** | 0.36 | 0.36 | 0.57** |
| ISO180 | - | 0.76** | 0.59** | 0.55* | 0.61** |
| ISO300 | | - | 0.50* | 0.64** | 0.51* |
| SH | | | - | 0.58** | 0.23 |
| TH | | | | - | 0.44 |
| **Uninvolved Leg** | **ISO180** | **ISO300** | **SH** | **TH** | **POWER** |
| ISO60 | 0.81** | 0.66** | 0.50* | 0.58** | 0.63** |
| ISO180 | - | 0.71** | 0.38 | 0.40 | 0.47* |
| ISO300 | | - | 0.33 | 0.60** | 0.53* |
| SH | | | - | 0.52* | 0.07 |
| TH | | | | - | 0.39 |
| **LSI** | **ISO180** | **ISO300** | **SH** | **TH** | **POWER** |
| ISO60 | 0.51** | 0.27 | 0.14 | 0.31 | 0.25 |
| ISO180 | - | 0.46* | −0.11 | 0.16 | 0.38 |
| ISO300 | | - | −0.06 | −0.05 | 0.32 |
| SH | | | - | 0.83** | 0.19 |
| TH | | | | - | 0.38 |

ISO60/180/300 represents the peak knee extension torque during the isokinetic testing at 60/180/300 degrees per second, respectively. SH/TH represents the maximum distance during single hop and triple hop tests, respectively. POWER represents the lower extremity peak power during a leg press test.

* $P < 0.05$ (2-tailed).

** $P < 0.01$ (2-tailed).