

Original Research

# Isokinetic Quadriceps Strength at Slower Speeds Following ACLR More Strongly Influences Hop Test Performance in Adolescent Athletes.

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### Background

Return-to-play (RTP) criteria remains inconsistent for adolescents following anterior cruciate ligament reconstruction (ACLR). Isokinetic strength testing (ISKT) and functional horizontal hop testing are commonly used to assess readiness, but the optimal ISKT testing protocol for predicting functional performance in adolescents has yet to be defined.

### Hypothesis/purpose

The purpose of this study was to examine the relationship between quadriceps peak torque at multiple isokinetic testing speeds and functional hop test symmetry. It was hypothesized that strength measured at 60°/sec would demonstrate a stronger association with hop performance than measures obtained at 180°/sec and 300°/sec.

### Study design

Prospective cohort study

### Methods

One hundred pediatric and adolescent patients (15.1 ± 2.0 yrs) completed a standard RTP assessment at a mean of 6.3 ± 0.4 months following ACLR. ISKT was assessed at 60 °/sec, 180 °/sec, 300 °/sec. Hop testing included the single hop for distance, triple hop for distance, crossover hop for distance, and 6-meter timed hop. ISKT values were examined as limb symmetry indices (LSI) and as normalized values (Nm/KG). Multiple linear regression analyses were used to assess the influence of ISKT speed on hop test performance.

### Results

ISKT LSI at 60 °/sec was significantly associated with single hop ( $\beta = 0.508$ , 95% CI [.18,.75],  $p = 0.001$ ), triple hop ( $\beta = 0.437$ , 95% CI [.09,.48]  $p = 0.001$ ), and crossover hop ( $\beta = 0.448$ , 95% CI [.09,.55]  $p = 0.006$ ). These results were consistent when examining that data as normalized at 60 °/sec for the single hop ( $\beta = 0.641$ , 95% CI [27.4,81.7]  $p = 0.001$ ), triple hop ( $\beta = 0.579$ , 95% CI [59.9,202.51]  $p = 0.001$ ), and crossover hop ( $\beta = 0.529$ , 95%

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CI [46.0,205.8]  $p = 0.006$ ). ISKT at 180 °/sec and 300 °/sec did not significantly influence hop performance.

## Conclusion

In adolescents following ACLR, quadriceps strength assessed at 60 °/sec, demonstrates the strongest relationship with functional hop test performance.

## Level of Evidence

Level 3

## INTRODUCTION

Anterior cruciate ligament (ACL) injuries and rehabilitation after surgical reconstruction have been well studied for many decades. However, a rise in injury rates at 147.8% and re-injury rates at 24.3-29.5% in the adolescent population have been reported.<sup>1-3</sup> Guidelines to establish when an athlete is appropriate for unrestricted return to sport remain unclear. Although recent adolescent-specific consensus guidelines provide a practical rehabilitation framework, universally accepted criteria for unrestricted return to sport remain variable.<sup>4,5</sup>

Readiness for return to sport is typically assessed using a multifactorial battery that may include balance, neuromuscular control, landing mechanics, and performance with strength and hop testing.<sup>5-7</sup> Although the adolescent population accounts for a large number of ACL injuries, this population is relatively understudied compared to the adult population.<sup>1</sup> Most research focuses on the adult population (>18 years of age), and attempts have been made to extrapolate these findings to the adolescent population; however, there are obvious limitations to this approach. Adolescents present with distinct biological differences compared to the adult population characterized by ongoing growth, maturation, and neuromuscular development.<sup>5</sup> These developmental differences necessitate age- and maturation-specific considerations in clinical management, rehabilitation, and return-to-sport decision-making.

Quadriceps strength is a key factor when recovering from an ACLR, and isokinetic testing is considered the gold standard for quadriceps strength assessment. Historically, the threshold for return to sport for isokinetic strength testing (IKST) is to reach a limb symmetry index (LSI) of at least 90% between the involved and uninvolved limb.<sup>5,8</sup> ISKT has been shown to be a valid measure of assessing muscle performance of the quadriceps muscles.<sup>9,10</sup> Additionally, in the adolescent population, ISKT has been shown to accurately predict patient's subjective report of knee function.<sup>11</sup> However, there is no consensus on what ISKT speed or group of speeds best predict functional outcomes following ACLR. Commonly used testing speeds traditionally range from 60 °/sec to 300 °/sec. Limited research is available to understand what speed offers the most useful information for assessment of recovery.

Hop testing is often used alongside ISKT because it is inexpensive, time-efficient, and provides complementary data on lower extremity performance. Hop testing has also been shown to be reliable for both patients and testers.<sup>12</sup> Historically, the clinical benchmark for hop testing is to

reach a >90% LSI for single, triple, crossover, and timed 6m hop tests. However, hop testing can inaccurately assess recovery when used alone and should continue to be paired with ISKT to better understand a patient's progress following ACLR.<sup>13</sup> Previous studies in adults and young adults have shown mixed correlations between results of hop testing and ISKT at speeds >90 °/sec, but results remain limited for slower speeds within the adolescent population.<sup>14,15</sup>

The purpose of this study was to examine the relationship between quadriceps peak torque at multiple isokinetic testing speeds and functional hop test symmetry. It was hypothesized that strength measured at 60°/sec would demonstrate a stronger association with hop performance than measures obtained at 180°/sec and 300°/sec.

## METHODS

This was a retrospective study of pediatric and adolescent patients undergoing ACL reconstruction at a single institution by a single surgeon (JJN). Institutional Review Board approval was granted. All patients 18 years of age or younger who underwent a standardized RTP assessment at 6 months postoperatively (range 5.5-7.5 months) were included. Exclusion criteria included: patients younger than 9 or older than 18; those who underwent multiligament reconstruction or revision surgery; missing RTP data; and patients with a history of contralateral ACL reconstruction. Patients were not excluded based on meniscal pathology. All patients underwent the same standardized ACL reconstruction physical therapy rehabilitation protocol. RTP assessment was performed in a standardized fashion at a single location.

The Biodex Multi-Joint Testing and Rehabilitation System (Biodex Medical Systems, Shirley, NY) was used to perform ISKT of the quadriceps and hamstrings. During testing, subjects were placed on the Biodex system and secured as previously described.<sup>16,17</sup> Subjects then performed contractions at 60 °/sec, 180 °/sec, and 300 °/sec per second for the uninjured and injured limbs. As per the Biodex recommendations, 5 repetitions were performed for the 60°/sec test, 10 repetitions for 180 °/sec test, and 15 repetitions for the 300 °/sec test.<sup>7</sup> Contractions at 60 °/sec and 180 °/sec are classically used to assess strength, while 300 °/sec is used to assess endurance.

Hop testing included the single hop, the triple hop, the crossover hop, and the timed hop over a 6-meter distance.<sup>7</sup> To be considered a valid trial, the landing had to be on one limb and under control for at least 2 seconds. The trial was repeated if the patient landed with an early touchdown

on the contralateral limb, had loss of balance, or had additional hops after landing. After two successful trials, the distances were averaged, and the mean value was used for analysis. During the single hop test (SHOP), participants were instructed to jump as far as possible on a single leg, without losing balance upon landing. Similarly, the triple hop (THOP) consisted of three consecutive hops on one leg, and the distance was measured in centimeters from the start line to the heel of the landing leg. For the crossover hop test (CHOP), patients were instructed to stand on one leg, then hop as far as they could three times, while alternating sides along a marked strip on the floor. Patients began the timed hop (6-M) by standing on one leg, then hopped as fast as possible over a 6-meter distance marked by a line on the floor at the start and finish points. A standard stopwatch was used to record the time and was started when the patient's heel left the floor and stopped when they crossed the finish line.

The LSI was calculated as  $LSI = (Involved / Uninvolved) \times 100$ . For timed hop testing, the LSI calculation was inverted to allow all LSI measurements less than 100% to represent a deficit. In addition to LSI calculations, ISKT data were also analyzed as normalized ISKT (Nm/Kg) and hops were analyzed using normalized hop distance as a percentage of the subject's leg length.

## STATISTICAL ANALYSIS

Statistical testing was performed utilizing SPSS (version 22.0, IBM Corp, Chicago, IL). Descriptive statistics were calculated for participant characteristics, quadriceps and hop test performance of all participants. Data distribution was assessed using Q-Q plots, along with measures of skewness and kurtosis, to evaluate normality.

Prior to the regression analysis, data were screened for violations of key regression assumptions, including normality, linearity, homoscedasticity, and multicollinearity. Examination of variance inflation factors (VIFs) and tolerance values indicated substantial multicollinearity between predictor variables for the normalized regression model. To address this issue and improve the stability and interpretability of the regression estimates, normalized quadriceps strength at 180°/sec was removed from the model. Following its removal, all remaining predictors met acceptable multicollinearity thresholds, and the regression assumptions were adequately satisfied for both regression models.

Next, four separate regression models were conducted (one for each hop test). The three ISKT testing speeds (60°/sec, 180°/sec, 300°/sec) were entered simultaneously into each model for the LSI regression (Table 2). The two ISKT testing speeds (60°/sec, 300°/sec) were entered simultaneously into each model for the normalized regression (Table 3). As there was no consistent way in which to normalize the timed hop tests, the normalized regression models did not include this test.

Coefficients of determination ( $R^2$ ) were interpreted as small (~0.02), medium (~0.13), and large (~0.26) effect sizes, while standardized beta coefficients ( $\beta$ ) were inter-

preted as small (~0.10), moderate (~0.30), and large (~0.50) associations. Statistical significance was set at  $p < 0.05$ .

## RESULTS

The study cohort consisted of 100 patients undergoing ACL reconstruction (51 males, 49 females) with return to play assessment at a mean of  $6.3 \pm 0.4$  months postoperatively. Participants completed a standardized RTP assessment including ISKT and hop testing. Table 1 presents demographic information for the subjects. Tables 2 and 3 present descriptive outcomes of RTS testing variables.

**Table 1. Patient Demographic Information**

|                          |                            |
|--------------------------|----------------------------|
| Age (years)              | 15.1 ± 2.0                 |
| BMI (kg/m <sup>2</sup> ) | 23.8 ± 5.2                 |
| Graft                    | BTB: 74<br>HS: 19<br>QT: 7 |

BTB: Bone-Patellar Tendon-Bone; HS: Hamstring; QT: Quadriceps Tendon

**Table 2. RTP Testing Descriptive Statistics as LSI Values**

| Test          | LSI Values |
|---------------|------------|
| ISKT 60       | 68.30±15.4 |
| ISKT 180      | 74.4±14.4  |
| ISKT 300      | 78.4±13.3  |
| SHOP          | 89.9±14.2  |
| THOP          | 92.3±9.9   |
| CHOP          | 92.3±10.0  |
| 6-M timed Hop | 94.2±10.8  |

IKST: Isokinetic Strength Testing; SHOP: Single Hop; THOP: Triple Hop; CHOP: Crossover hop; RTP: Return to Play; LSI: Limb Symmetry Index.

\*All values listed as LSI %

**Table 3. RTP Testing Descriptive Statistics as Normalized Values**

| Test                 | Normalized Values |
|----------------------|-------------------|
| ISKT 60 (NM/KG)      | 1.33±.42          |
| ISKT 180 (NM/KG)     | 1.04±.29          |
| ISKT 300 (NM/KG)     | .830±.22          |
| SHOP (Percent of LL) | 121.50±36         |
| THOP (Percent of LL) | 413.46±94         |
| CHOP (Percent of LL) | 371.55±96         |

IKST: Isokinetic Strength Testing; SHOP: Single Hop; THOP: Triple Hop; CHOP: Crossover hop; RTP: Return to Play; LL: Leg length

**Table 4. Regression Results for Each Hop Test using LSI**

| Single Hop Symmetry     | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p</i> -value |
|-------------------------|----------|-------------|-----------------------|---------|-----------------|
| <b>Constant</b>         | 53.94    | 7.43        | .305                  |         |                 |
| ISKT 60                 |          |             |                       | .508    | .001            |
| ISKT 180                |          |             |                       | .055    | .749            |
| ISKT 300                |          |             |                       | -.004   | .977            |
| Triple Hop Symmetry     | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p</i> -value |
| <b>Constant</b>         | 64.10    | 5.32        | .335                  |         |                 |
| ISKT 60                 |          |             |                       | .437    | .001            |
| ISKT 180                |          |             |                       | .172    | .749            |
| ISKT 300                |          |             |                       | -.014   | .977            |
| Cross Over Hop Symmetry | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p</i> -value |
| <b>Constant</b>         | 65.15    | 6.38        | .231                  |         |                 |
| ISKT 60                 |          |             |                       | .448    | .006            |
| ISKT 180                |          |             |                       | -.040   | .821            |
| ISKT 300                |          |             |                       | .106    | .401            |
| Timed Hop Symmetry      | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p</i> -value |
| <b>Constant</b>         | 69.25    | 7.05        | .150                  |         |                 |
| ISKT 60                 |          |             |                       | .222    | .180            |
| ISKT 180                |          |             |                       | .129    | .483            |
| ISKT 300                |          |             |                       | .078    | .549            |

IKST: Isokinetic Strength Testing; LSI: Limb Symmetry Index.

LSI at 60°/sec was the only speed significantly associated with hop test performance. Specifically, 60°/sec demonstrated significant associations with the SHOP ( $\beta = .508$ ,  $p = 0.001$ ), THOP ( $\beta = .437$ ,  $p = 0.001$ ), and CHOP ( $\beta = .448$ ,  $p = 0.006$ ), while no significant associations were observed for 180°/sec or 300°/sec across these outcomes (Table 4). For the THOP, no isokinetic testing speed was significantly associated with performance (60°/sec:  $\beta = .222$ ,  $p = 0.180$ ; 180°/sec:  $\beta = .129$ ,  $p = 0.483$ ; 300°/sec:  $\beta = .078$ ,  $p = 0.549$ ).

Three separate regression models were conducted for normalized hop performance (SHOP, THOP, CHOP), with ISKT speeds of 60°/sec and 300°/sec entered simultaneously. Strength at 60°/sec was significantly associated with all normalized hop outcomes, including the SHOP ( $\beta = .594$ ,  $p = 0.001$ ), THOP ( $\beta = .600$ ,  $p = 0.001$ ), and CHOP ( $\beta = .570$ ,  $p = 0.001$ ). In contrast, no significant associations were observed for 300°/sec for the SHOP ( $\beta = .167$ ,  $p = 0.162$ ), THOP ( $\beta = .185$ ,  $p = 0.113$ ), or CHOP ( $\beta = .162$ ,  $p = 0.191$ ) (Table 5).

## DISCUSSION

This study examined the relationship between ISKT speed and hop test performance within an adolescent population. At approximately 6 months postoperatively, knee extension strength measured at 60°/sec showed moderate associations with performance on the SHOP, THOP, and CHOP, and these findings were consistent across both LSI and normalized data. In contrast, testing at 180°/sec and 300°/sec did not demonstrate significant associations with hop per-

formance. ISKT measures were not significantly related to 6-m timed hop performance when calculated using LSI at any testing speed. Due to the inability to normalize the timed hop variable, it remains unclear whether normalized strength at 60°/sec influences timed hop performance.

Overall, the findings confirm the original hypothesis that performance at 60°/sec would have a stronger relationship with functional hop testing than IKST at other speeds. However, it is important to note that the overall contribution of ISKT testing results on hop performance was relatively low with  $R^2$  values for the LSI analysis ranging from 23% to 33% and  $R^2$  values for the normalized data ranging from 49% - 57%. These findings suggest that additional factors likely influence hop test performance, including neuromuscular control, balance, coordination, power and psychological components such as confidence or fear of reinjury. Furthermore, technique and movement strategy during the hop task may also contribute substantially to performance outcomes beyond isolated strength measures.

The findings indicating that the relationship between slower testing speeds and hop test performance differs from correlations at higher speeds contrasts with results from studies in adult populations that have shown stronger correlations at higher angular velocities when paired with hop testing.<sup>14,15,18,19</sup> However, this difference is not unexpected, as strength is a fundamental contributor to hop performance, particularly in tasks requiring rapid force production and propulsion. While isokinetic strength testing provides important foundational information, hop performance is a complex, multifactorial task that also depends

**Table 5. Regression Results for Each Hop Test, using normalized data**

| Single Hop      | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p-value</i> |
|-----------------|----------|-------------|-----------------------|---------|----------------|
| <b>Constant</b> | 31.63    | 9.58        | .543                  |         |                |
| ISKT 60         |          |             |                       | .594    | 0.001          |
| ISKT 300        |          |             |                       | .167    | .0162          |
| Triple Hop      | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p-value</i> |
| <b>Constant</b> | 163.35   | 25.32       | .574                  |         |                |
| ISKT 60         |          |             |                       | .600    | 0.001          |
| ISKT 300        |          |             |                       | .185    | 0.113          |
| Cross Over Hop  | <i>b</i> | <i>SE B</i> | <i>R</i> <sup>2</sup> | $\beta$ | <i>p-value</i> |
| <b>Constant</b> | 123.12   | 29.72       | .497                  |         |                |
| ISKT 60         |          |             |                       | .570    | 0.001          |
| ISKT 300        |          |             |                       | .162    | 0.191          |

IKST: Isokinetic Strength Testing;

on adequate neuromuscular coordination, rate of force development, proper movement strategies, and psychological readiness.

The current findings suggest that, in this population, additional variables beyond isolated strength may play a more prominent role in influencing hop performance. Results of previous studies of subjects aged 16-19 years of age indicate a clear relationship between ISKT and hop testing.<sup>20-22</sup> Schmitt et al.<sup>20</sup> reported that quadriceps symmetry was a significant predictor of SHOP ( $R^2$  change = 0.141,  $p$  = 0.004) and THOP performance ( $R^2$  change = 0.092,  $p$  = 0.029). Collectively, these findings reinforce the expected relationship that as quadriceps strength increases, hop test performance improves.<sup>20,23,24</sup> However, the relatively modest variance explained by strength measures in the current study highlights that strength alone does not fully account for performance outcomes, emphasizing the contribution of other functional and neuromuscular factors in this task.

Thorough return to play testing allows for a more complete understanding of the athlete's current ability and helps to identify continued areas of deficiency. A variety of isokinetic speeds are commonly utilized in literature.<sup>22, 25,26</sup> Utilizing different speeds during ISKT allows for the assessment of torque production across varying velocities, providing a comprehensive understanding of muscle performance. At slower speeds patients can create more concentric torque compared to higher speeds.<sup>17</sup> When assessing peak torque output, differences are clearly detectable at higher testing speeds (e.g., 180°/sec and 300°/sec); however, these velocities may reflect different neuromuscular qualities than those captured at slower speeds. Assessing slower isokinetic speeds is critical in the return to play process as it helps to illuminate potentially more meaningful deficits than those seen at faster speeds given its relationship to maximal force output which has been shown to be diminished in this population. Culiver et al.<sup>23</sup> evaluated college-aged participants (20–24 years old) and utilized ISKT speeds of 20°/sec, 60°/sec, 120°/sec, 240°/sec, and 400°/sec, comparing 20 individuals following ACL reconstruction to 20 healthy controls.<sup>27</sup> They concluded that

slower isokinetic velocities (reported as normalized values) are better at discriminating between the ACLR limb and both the uninvolved limb and a matched healthy control limb. Overall, their findings show that as testing speeds increased, the peak torque difference between the ACLR limb and the uninvolved limb and control limb decreased. These findings potentially support the need for slower testing speeds in the ACL-R population.

IKST testing in the adolescent ACL population frequently includes a range of speeds. When completing return to play testing in the adult population Gokeler et al.<sup>24</sup> reported that 60 °/sec is the hardest speed to reach <10% LSI when compared to 180, and 300 °/sec. Similar findings have been reported in the meniscal literature. Several studies in the adult population reported on strength recovery at speeds ranging from 60 °/sec up to 300 °/sec. The findings from these studies demonstrate that when testing at speeds faster than 60 °/sec, strength “normalized” between limbs much sooner, while significant difference at 60 °/sec continued to be reported as far out as six months to one year.<sup>28-30</sup>

Although isokinetic testing (ISKT) provides objective, valid, and reliable measures of isolated muscle performance, its clinical value extends beyond the assessment of strength alone.<sup>16</sup> ISKT allows for the identification of torque production deficits in specific muscle groups that contribute to overall functional capacity and movement quality. Knee extensor strength, in particular, has been shown to demonstrate a moderate positive relationship with hop test distance and performance, highlighting the important role of quadriceps strength in this dynamic task.<sup>23,24</sup>

However, hop testing alone may overestimate functional recovery, as limb symmetry indices (LSI) can be artificially elevated despite persistent strength deficits. This limitation has been consistently reported across studies, with similar findings observed at both 8 and 12 months postoperatively.<sup>13,19</sup> For example, pass rates for hop testing (LSI<10%) have been reported as high as 78.5% at 6 months post-operative whereas corresponding ISKT pass rates may

be as low as 39.3%.<sup>31</sup> Collectively, these findings underscore the importance of incorporating both strength-based and functional assessments to more accurately evaluate readiness for return to play.

Return to play testing continues to be a critical tool for clinicians to objectively measure athletes as they progress. Robust testing is key as ACL injuries continue to rise with a 147% increase in incidence rate for 5–14-year-olds and retear rates approximately at 25%.<sup>1–3</sup> It is important to delineate which combination of tests will help identify a patient's true readiness for return to sport, especially in adolescent athletes. Findings from this current study demonstrate that ISKT at 60 °/sec can be utilized as an important tool as results at that speed were related to functional performance. However, it is important to note that ISKT test performance only explained a small percentage of overall hop performance.

This study should be applied and interpreted with its limitations in mind. The normalized strength value at 180°/sec was removed from the normalized regression model due to multicollinearity violations. As a result, the potential unique contribution of this measure could not be examined independently, which may limit the overall interpretation of the findings. The study focused specifically on an adolescent sample from a single center with a single surgeon, which may limit the generalizability of the results. Within this cohort, multiple graft types were included, including bone–patellar tendon–bone (BTB), quadriceps tendon, and hamstring tendon. Future studies may benefit from examining outcomes from each graft type independently using larger sample sizes to better understand potential differences in ISKT and hop performance between

graft types. The cohort also included patients with surgical meniscal involvement, which may have influenced the results. Future research should consider comparing patients with and without meniscal involvement.

An additional limitation was the inability to normalize the timed hop variable; therefore, it remains unclear whether normalized ISKT at 60°/sec influenced timed hop performance. Lastly, the study focused on patients approximately 6 months postoperatively, and the findings are limited to adolescent patients at this stage of recovery. Outcomes may differ at other postoperative time points. Future research examining patients across a broader recovery timeline (e.g., 4 to 24 months postoperatively) is warranted.

## CONCLUSION

In adolescents following ACLR, quadriceps strength assessed at 60 °/sec, was significantly associated with performance on all of the functional hop tests. ISKT testing results were only able to explain 23–57% of hop performance. These findings support the use of combined isokinetic strength and functional testing when evaluating recovery. Given the study's limitations, results should be interpreted cautiously. Future research should examine these relationships across different time points and patient subgroups to better inform return-to-sport decisions.

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