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original research

Measures of Functional Performance and Their Association With Hip and Thigh Strength

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Context: Insufficient hip and thigh strength may increase an athlete's susceptibility to injury. However, screening for strength deficits using isometric and isokinetic instrumentation may not be practical in all clinical scenarios.

Objective: To determine if functional performance tests are valid indicators of hip and thigh strength.

Design: Descriptive laboratory study.

Setting: Research laboratory.

Patients or Other Participants: Sixty-two recreationally athletic men (n = 30, age = 21.07 years, height = 173.84 cm, mass = 81.47 kg) and women (n = 32, age = 21.03 years, height = 168.77 cm, mass = 68.22 kg) participants were recruited.

Intervention(s): During session 1, we measured isometric peak force and rate of force development for 8 lower extremity muscle groups, followed by an isometric endurance test. During session 2, participants performed functional performance tests.

Main Outcome Measure(s): Peak force, rate of force development, fatigue index, hop distance (or height), work (joules), and number of hops performed during the 30-second lateral-hop test were assessed. The *r* values were squared to calculate r^2. We used Pearson correlations to evaluate the associations between functional performance and strength.

Results: In men, the strongest relationship was observed between triple-hop work and hip-adductor peak force ($r^2 = 50$, $P \leq .001$). Triple-hop work also was related to hip-adductor ($r^2 = 38$, $P \leq .01$) and hip-flexor ($r^2 = 37$, $P \leq .01$) rate of force development. For women, the strongest relationships were between single-legged vertical-jump work and knee-flexor peak force ($r^2 = 0.44$, $P \leq .01$) and single-legged vertical-jump height and knee-flexor peak force ($r^2 = 0.42$, $P \leq .01$). Single-legged vertical-jump height also was related to knee-flexor rate of force development ($r^2 = 0.49$, $P \leq .001$). The 30-second lateral-hop test did not account for a significant portion of the variance in strength endurance.

Conclusions: Hop tests alone did not provide clinicians with enough information to make evidence-based decisions about lower extremity strength in isolated muscle groups.

Key Words: peak force, rate of force development, strength endurance

Key Points

- In general, hop work accounted for a greater percentage of variance in peak force and rate of force development than did hop distance.
- In men, the strongest relationship was between triple-hop work and hip-adductor peak force.
- In women, the strongest relationship was between single-legged vertical-jump height and knee-flexor rate of force development.

Strength, defined as the ability of a muscle to create force through active tension,[1] consists of multiple attributes or aspects: maximum strength, rate of force development (RFD), and strength endurance.[2,3] Although each factor reflects a similar phenomenon (ie, muscular strength), each targets a unique function (or ability) of the muscle group over a unique interval of time.[2,4–6] Deficits in 1 or more of these attributes of strength may increase injury susceptibility.[7–13] To help identify strength-related deficits and aid in clinical decision making about an athlete's readiness to return to sport participation, instrumentation such as portable isometric or isokinetic dynamometry may be used. However, using these devices to collect data on all 3 attributes of strength at multiple hip and thigh muscle groups may not be cost effective or time efficient in all clinical settings (eg, high school) or scenarios (eg, large-scale preparticipation examinations and sideline evaluations).

One approach to addressing clinical feasibility may be the substitution of functional performance tests for strength tests. Functional performance testing, although not traditionally used as a sole indicator of strength, does include an element of strength[14,15] along with other components critical to successful sports performance such as power[14,15] and agility.[15] Furthermore, measures of functional performance (eg, hop tests) require minimal equipment and costs.

The distance hopped in centimeters during single-hop and triple-hop-for-distance tests are strong predictors of isokinetic maximum strength at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, particularly in the knee flexors and extensors.[14,16] In addition, compared with distance alone, the magnitude of these relationships between isokinetic strength and measures of functional performance is greater when the body weight is incorporated into the jump- and hop-distance measures.[17–19] Incorporation of body weight into the jump and hop measures of distance produces a measure of work (joules = body weight [N] multiplied by distance hopped [m]). The work performed during a single hop for distance accounted for a greater percentage of variance (77% versus 40%) of isokinetic average peak knee-extension torque at $60°\cdot s^{-1}$ than did distance hopped.[19] Comparisons of vertical-jump work performed and height jumped with isokinetic hip, knee, and ankle strength at $60°\cdot s^{-1}$, $120°\cdot s^{-1}$, and $180°\cdot s^{-1}$ demonstrate similar findings.[17] Including the performer's weight in the evaluation of horizontal-hopping or vertical-jump height accounts for strength abilities that distance alone fails to explain.[17,19]

Although researchers have reported strong relationships between functional performance and maximum strength, the use of these measures to provide valid information about other attributes of muscular strength (ie, RFD and strength endurance) at the hip and thigh remains largely unexplored. In sports and other strenuous activities, the ability to rapidly produce adequate levels of strength (ie, RFD) or to sustain it (ie, strength endurance), or both, may be as important as maximum strength in reducing injury susceptibility or the risk of reinjury. For example, fatigue of the lower limb musculature (specifically the hip abductors) can limit an athlete's ability to attenuate the normal force associated with landing mechanics.[20,21] Using functional performance tests (eg, 30-second lateral-hop test for endurance) to assess an athlete's resistance to fatigue would help clinicians make better evidence-based decisions during sideline evaluations.

Also, we need to further evaluate these relationships separately in men and women. Analyzing men and women together without considering sex may overestimate the variance accounted for by the specific functional performance test. A better understanding of these relationships separately in men and women will enhance the clinical usefulness of hop tests in detecting deficits in maximum strength, RFD, and strength endurance at the hip and thigh. Finally, using functional performance tests as indicators of other aspects of athletes' muscular strength will help to provide a more comprehensive strength profile and better guide clinicians in determining readiness to return to sport. Therefore, the purpose of our experiment was to assess if functional performance tests were valid indicators of hip and thigh strength in men and women. We hypothesized that the hop tests, emphasizing distance hopped and work performed, would have a strong correlation ($r \geq 0.50$) with isometric maximum strength and RFD in both men and women. Second, we hypothesized that the number of repetitions performed during a 30-second lateral-hop test for endurance would be strongly correlated ($r \geq 0.50$) with isometric strength endurance at the hip and thigh in both men and women.

METHODS

Study Design

Our study was a correlational design involving 2 test sessions separated by 7 days. The first session consisted of isometric assessments: (1) maximum strength, which identified peak force (PF), (2) RFD, and (3) strength endurance, which resulted in a fatigue index (FI) for the hip abductors, hip adductors, hip flexors, hip extensors, hip external rotators, hip internal rotators, knee flexors, and knee extensors. Peak force and RFD were collected simultaneously before the assessment of strength endurance. The main outcome measures were PF, RFD, and FI for each muscle group evaluated.

The second session consisted of the following measures of functional performance: 30-second lateral hop for endurance, triple hop for distance, crossover hop for distance, single hop for distance, and single-legged vertical jump. The measures of interest were work (joules) performed for each functional performance test (except for the crossover hop for distance and 30-second lateral-hop test for endurance), distance (centimeters) hopped for each test (except the 30-second lateral-hop test for endurance), and the total number of hops performed during the 30-second lateral-hop test for endurance.

Participants

Sixty-two recreationally athletic men (n = 30, age = 21.07 ± 2.83 years, height = 173.84 ± 12.82 cm, mass = 81.47 ± 12.91 kg) and women (n = 32, age = 21.03 ± 2.82 years, height = 168.77 ± 7.70 cm, mass = 68.22 ± 13.67 kg) were recruited. Post hoc power calculation indicated that a sample population of 30 men and 32 women was sufficient to detect r^2 of 0.25 for any 2 compared variables, representing a large effect size. A *recreational athlete* was defined as an individual who engaged in moderate activity, such as tennis, biking, jogging, or weight lifting, 2 or 3 times a week for at least 30 minutes. Individuals were excluded if they had any of the following conditions: (1) restriction within the last 6 months by an athletic trainer or team physician from participating in any practice or competition for longer than 2 days because of a lower extremity injury, (2) a neurologic disorder, or (3) a history of anterior cruciate ligament injury. Participants were asked not to perform a rigorous lower extremity workout at least 24 hours before testing. All measures were collected on the *dominant limb*, which was determined by asking participants which leg they would use to kick a soccer ball with maximal force.[22] Participants read and signed a consent form that was approved by the institutional review board, which also approved the study.

Instrumentation

We collected isometric strength data using a commercial dynamometer (model LCR; OmegaDyne, Inc, Stamford, CT). The data were sampled at 1000 Hz (PF and RFD) and 100 Hz (FI) using a 1-MHz, 24-bit USB Data Acquisition Module (model NI-DAQ 9237; National Instruments Corporation, Austin, TX) and logged using LabVIEW Signal Express (National Instruments Corporation). All logged data were stored on a laptop computer for offline processing and analysis. A power spectrum density analysis was performed using a custom MATLAB program (The MathWorks, Inc, Natick, MA) to determine the optimum cutoff frequency of 50 Hz. The data were filtered postlog using a digital low-pass, fourth-order Butterworth filter with the 50-Hz cutoff frequency developed within LabVIEW Signal Express. The dynamometer was calibrated

Figure 1. Standing strength evaluation.

Figure 2. Seated strength evaluation.

daily within 1% of a known weight (178 N). In-laboratory intraclass correlation coefficient (3,1) intrarater intrasession reliability values ranged from 0.78 (SEM = 29.81 N) to 0.91 (SEM = 11.26 N) for PF and 0.80 (SEM = 145.50 $N \cdot s^{-1}$) to 0.92 (SEM = 58.63 $N \cdot s^{-1}$) for RFD. For the isometric endurance measure, the intraclass correlation coefficient (3,1) ranged between 0.43 (SEM = 3.03 FI) and 0.88 (SEM = 3.87 FI).

Testing Procedures

Session 1. Anthropometric measures were obtained for mass, height, lower leg length, and total leg length. The lower leg length was measured from the lateral joint line of the tibiofemoral joint to the lateral malleolus. The leg length was measured from the greater trochanter to the lateral malleolus. The leg-length measurements were obtained with a standard cloth tape measure.

After the anthropometric measurements, participants were instructed to warm up for 10 minutes on an exercise bicycle. After warm-up, participants performed 3 simultaneous trials of a PF and RFD strength assessment. Each trial was 5 seconds in duration, with a 60-second rest period between trials. For each trial, the participants were instructed to contract the muscles as hard and as fast as possible. Scripted instructions and prompts were used for consistency across trials and participants. The muscle groups were evaluated in a counterbalanced order.

After the PF and RFD strength analyses, the participant was given a 10-minute rest. Immediately after the rest period, we conducted isometric strength-endurance testing, which evaluated the same muscle groups tested during the PF and RFD analyses, in the same testing positions as the PF and RFD analyses in a counterbalanced order. For the strength-endurance testing, participants performed two 30-second isometric contractions[6,23–25] separated by a 2-minute rest. For each trial, the participants were instructed to contract as hard and as fast as possible. The scripted instructions and prompts were similar to the maximum strength and RFD script except that participants were asked to "keep pulling" approximately every 5 seconds until the task was completed.

For a trial to be valid, the participant had to reach a minimum of 95% of maximal isometric PF (as determined by the previous PF analyses) within 5 seconds of the start signal. If the participant did not meet this criterion within the initial 5 seconds, testing was halted and the participant was given an additional 2-minute rest period. After the rest period, the tester instructed the participant to repeat the trial. We adopted this 95% minimum PF requirement to ensure that the participants were giving maximal effort at the start of each contraction.

Hip-abductor, hip-adductor, hip-flexor, and hip-extensor strength were assessed in standing position (Figure 1). Knee-extensor, knee-flexor, hip–external-rotator, and hip–internal-rotator strength were assessed in an upright, seated position with an ankle cinch strap (11.4 cm wide by 37.5 cm long) positioned immediately proximal to the malleoli (Figure 2), as previously described.[26] The reliability of the seated and standing protocols was also previously reported.[26]

Session 2. The participants performed a 10-minute warm-up on an exercise bicycle before the functional performance test battery. All functional performance tests used in the present study were proven to be reliable.[27–31] Each functional performance test (except for the 30-second lateral-hop test for endurance) consisted of 3 test trials separated by a 30-second rest period.[27] There was a 2-minute rest period between functional performance tests. At the final landing of each trial (except for the 30-second lateral-hop test for endurance), participants had to maintain balance on the test limb until prompted to relax. Failure to maintain balance resulted in an invalid trial. The participants were prompted to relax once they demonstrated control (ie, quiet stance) in an upright position. If the participant took an extra hop on the landing, the trial was deemed invalid.[29] A toe-to-toe measure was used for all tests requiring measurements of the total distance hopped.[32] The functional performance test battery was administered in a counterbalanced order.

Thirty-Second Lateral-Hop Test for Endurance. The participant was instructed to stand on 1 foot with the arms behind the back and to hop side to side between 2 parallel lines (40 cm apart) for 30 seconds. Hops in which the participant touched the tape counted as errors. If 25% or more of the hops were counted as errors, the test was performed again after a 3-minute rest period.[28] The participant performed 2 valid trials, with a 3-minute rest between trials. The higher number of repetitions from the 2 trials was recorded.

Triple Hop for Distance. Each participant stood on 1 leg and hopped as far as possible 3 times, landing on the same leg at completion. The total distance was recorded.[29,30] The participant's arms were free from restraint and could be used to propel the body and aid in balance upon landing.

Crossover Hop for Distance. The participant hopped forward 3 consecutive times while alternately crossing over

Table 1. Strength Measures by Muscles, Mean ± SD

Muscles	Men	Women
Strength measure		
Hip abductors	196.40 ± 42.90	139.85 ± 31.69
Hip adductors	202.75 ± 54.75	136.19 ± 28.58
Hip extensors	193.93 ± 58.43	126.13 ± 36.39
Hip flexors	189.27 ± 43.80	137.68 ± 31.03
Hip external rotators	160.39 ± 49.19	112.43 ± 22.07
Hip internal rotators	152.36 ± 41.76	117.32 ± 35.50
Knee extensors	505.83 ± 136.20	328.79 ± 71.12
Knee flexors	303.88 ± 91.71	224.73 ± 57.12
Rate of force development, $N \cdot s^{-1}$		
Hip abductors	804.32 ± 201.88	538.95 ± 151.07
Hip adductors	799.90 ± 239.69	529.51 ± 156.84
Hip extensors	748.69 ± 283.58	430.82 ± 146.27
Hip flexors	724.41 ± 187.12	514.18 ± 155.97
Hip external rotators	586.42 ± 219.23	375.72 ± 107.69
Hip internal rotators	558.99 ± 195.54	400.38 ± 164.71
Knee extensors	2042.22 ± 548.64	1306.89 ± 320.64
Knee flexors	1218.57 ± 404.61	870.48 ± 252.46
Strength endurance (fatigue index)		
Hip abductors	27.50 ± 4.63	29.70 ± 7.27
Hip adductors	27.15 ± 9.16	22.38 ± 8.33
Hip extensors	33.46 ± 8.57	33.50 ± 9.99
Hip flexors	30.49 ± 8.31	27.15 ± 8.66
Hip external rotators	34.97 ± 8.36	33.15 ± 8.25
Hip internal rotators	24.79 ± 10.63	25.08 ± 10.77
Knee extensors	24.45 ± 11.98	23.81 ± 11.33
Knee flexors	30.38 ± 9.34	25.79 ± 10.94

a measuring tape on the floor. The participant was positioned so that the first of the 3 hops was lateral to the direction of the crossover.[29,30] The total distance hopped was recorded.

Single Hop Test for Distance. The participant hopped as far as possible with hands behind the back.[16,31] The distance hopped was recorded.

Single-Legged Vertical Jump. The participant was positioned with the right shoulder 6 in (15.24 cm) away from a Vertec vertical-jump testing apparatus (Sports Imports, Hilliard, OH). The participant raised the right hand and touched a plastic vane on the measuring device. After the reach height was recorded, the participant was instructed to lower the hand and stand on 1 leg. The participant was instructed to jump with maximal effort as high as possible, strike a plastic vane with the right hand, and land on the takeoff foot. The height reached was recorded to the nearest 1.27 cm.

Data Reduction

Force was recorded in newtons and the highest value of the 3 isometric attempts was used to determine the PF (N) and RFD ($N \cdot s^{-1}$). The initial 200 milliseconds after the onset of the contraction were used to calculate the RFD.[4,33] The point at which the torque was 7.5 Nm greater than the baseline value was defined as the *onset of the muscle contraction*.[4]

Strength endurance was determined through an FI ratio score: $FI = (1 - [AUFC/HAUFC]) \times 100$,[6,23–25] where FI is equal to 1 minus the quotient of the area under the torque-time curve (AUFC) divided by the hypothetical area under the force-time curve (HAUFC). The AUFC is the integral

Table 2. Functional Performance Test Results, Mean ± SD

Functional Performance Test	Men	Women
30-s Lateral hop, repetitions	76.33 ± 9.46	69.66 ± 13.02
Triple hop for distance, cm	541.15 ± 85.78	417.81 ± 88.50
Triple hop for work, J	4312.29 ± 852.21	2795.16 ± 811.88
Crossover hop, cm	486.63 ± 104.46	358.31 ± 95.72
Single hop for distance, cm	171.48 ± 25.56	132.70 ± 24.21
Single hop for work, J	1371.16 ± 276.13	882.20 ± 208.17
Single-legged vertical jump for distance, cm	38.61 ± 6.94	29.88 ± 7.14
Single-legged vertical jump for work, J	306.56 ± 67.95	200.27 ± 61.42

of force for a 30-second trial time, whereas the HAUFC is the PF value observed between 0 and 5 seconds of the 30-second trial time. A lower FI score indicates greater resistance to fatigue. For the single-legged vertical-jump, triple-hop-for-distance, and single-hop-for-distance tests, the work performed was calculated by multiplying the distance hopped in meters by the mass (kilograms) of the participant and gravity: work (joules) = participant's mass × gravity (9.81 $m \cdot s^{-2}$) × distance hopped.[18,19]

Statistical Analysis

We recorded descriptive data (means and standard deviations) for all variables. Because this was a within-subjects correlational design, the data were not normalized by height and weight.[14] Separate Pearson product moment bivariate correlations were calculated to evaluate the association between isometric muscular performance and functional performance. Before the analyses, the data were separated by sex. Correlation coefficients were described as *trivial* (0.0), *small* (0.1), *moderate* (0.3), *strong* (0.5), *very strong* (0.7), *nearly perfect* (0.9), and *perfect* (1.0).[34] We squared all coefficient correlations (r values) to calculate the coefficient of determination (r^2) and evaluate the percentage of common variance between any 2 variables. A coefficient of determination (r^2) equal to or greater than 0.50 was considered *clinically meaningful* because it indicated there was a high-level generality between the 2 measures.[35] The α level was set at .05. All statistical analyses were performed using SPSS (version 21; IBM Corporation, Armonk, NY).

RESULTS

Functional Performance and PF

Means and standard deviations are reported in Tables 1 and 2. In men, the strongest relationship was between triple-hop work and hip-adductor PF ($r^2 = 50$, $P \leq .001$; Table 3). In women, the strongest relationships were between single-legged vertical-jump work and knee-flexor PF ($r^2 = 0.44$, $P \leq .01$) and between single-legged vertical-jump height and knee-flexor PF ($r^2 = 0.42$, $P \leq .01$; Table 3).

Functional Performance and Rate of Torque Development

In men, the strongest relationships were between triple-hop work and hip-adductor RFD ($r^2 = 38$, $P \leq .01$) and

Table 3. Coefficient of Determination (r^2) Indicating Amount of Common Variance Explained by Functional Performance Test by Sex

	Hip												Knee			
	Abductors		Adductors		Extensors		Flexors		External Rotators		Internal Rotators		Extensors		Flexors	
Functional Performance Test	PF	RFD	PF	RFD	PF	RFD	PF	RFD	PF	RFD	PF	RFD	PF	RFD	PF	RFD
Men (n = 30)																
Triple hop for distance, cm	0.08	0.06	0.23	0.22	0.09	0.04	0.23	0.14	0.11	0.08	0.03	0.02	0.16	0.11	0.14	0.18
Triple hop for work, J	0.36[a]	0.27[b]	0.50[c]	0.38[a]	0.18	0.15	0.36[a]	0.37[a]	0.21	0.20	0.08	0.06	0.26[b]	0.15	0.19	0.20
Crossover hop, cm	0.02	0.01	0.06	0.09	0.03	0.01	0.08	0.06	0.01	0.00	0.02	0.03	0.09	0.09	0.10	0.15
Single hop for distance, cm	0.12	0.09	0.20	0.20	0.11	0.09	0.29[b]	0.18	0.07	0.06	0.01	0.01	0.12	0.10	0.08	0.12
Single hop for work, J	0.36[a]	0.28[b]	0.41[a]	0.31[b]	0.17	0.18	0.35[b]	0.36[a]	0.14	0.15	0.05	0.04	0.18	0.12	0.12	0.12
Single-legged vertical jump for distance, cm	0.00	0.00	0.05	0.03	0.01	0.00	0.08	0.04	0.10	0.08	0.03	0.06	0.14	0.05	0.16	0.16
Single-legged vertical jump for work, J	0.18	0.14	0.31[b]	0.18	0.10	0.10	0.25[a]	0.28[b]	0.24	0.23	0.12	0.14	0.31[b]	0.12	0.30[b]	0.25[b]
Women (n = 32)																
Triple hop for distance, cm	0.05	0.03	0.06	0.04	0.01	0.00	0.13	0.05	0.22	0.18	0.20	0.20	0.14	0.17	0.24	0.30[b]
Triple hop for work, J	0.27[b]	0.18	0.08	0.07	0.25[b]	0.13	0.29[b]	0.12	0.20	0.24	0.23	0.28[b]	0.08	0.10	0.30[b]	0.28[b]
Crossover hop, cm	0.03	0.03	0.10	0.05	0.00	0.00	0.20	0.10	0.12	0.07	0.08	0.08	0.17	0.21	0.18	0.23
Single hop for distance, cm	0.01	0.04	0.11	0.08	0.00	0.04	0.06	0.04	0.16	0.06	0.12	0.14	0.07	0.18	0.11	0.17
Single hop for work, J	0.22	0.21	0.14	0.14	0.13	0.04	0.25[b]	0.14	0.18	0.14	0.20	0.27[b]	0.04	0.11	0.21	0.22
Single-legged vertical jump for distance, cm	0.10	0.07	0.18	0.20	0.00	0.05	0.14	0.05	0.19	0.12	0.18	0.22	0.18	0.25[b]	0.42[a]	0.49[c]
Single-legged vertical jump for work, J	0.29[a]	0.20	0.18	0.20	0.13	0.01	0.27[b]	0.12	0.19	0.18	0.23	0.30[b]	0.12	0.15	0.44[a]	0.44[a]

Abbreviations: PF, peak force; RFD, rate of force development.

[a] $P \leq .01$.
[b] $P \leq .05$.
[c] $P \leq .001$.

between triple-hop work and hip-flexor RFD ($r^2 = 37$, $P \leq .01$; Table 3). For women, the strongest relationship was observed between the single-legged vertical-jump height and knee-flexor RFD ($r^2 = 0.49$, $P \leq .001$; Table 3).

Functional Performance and Strength Endurance

All coefficient determinations describing the relationship of the 30-second lateral-hop test for endurance to isometric strength endurance are reported in Table 4. The number of repetitions of the 30-second lateral-hop test for endurance did not account for a significant portion of the variance of any measure of isometric strength endurance (FI).

DISCUSSION

The main findings of our study were that, in women, the single-legged vertical jump test (both distance and work) provided a strong to very strong indicator of knee-flexor maximum strength and RFD, whereas triple-hop work resulted in a strong to very strong indicator of maximum strength and RFD at the hip abductors, adductors, and flexors in men. Additionally, the 30-second lateral-hop test for endurance was not a strong indicator of lower extremity strength endurance in the muscle groups we assessed. To our knowledge, we are the first to explore these relationships separately in men and women. These results suggest that in the context of large-scale screenings or return-to-play evaluations, the interpretation of results on performance tests may need to be based on the sex of the athlete. Further, although a statistically significant relationship may exist between certain measures of functional performance (eg, single-legged vertical jump and triple hop) and strength, many of the relationships are not clinically meaningful.[19,35] Only 2 relationships were close to meeting the criterion ($r^2 \geq 0.50$): (1) triple-hop work and hip-adductor PF and (2) single-legged vertical-jump height and knee-flexor RFD. The large percentage of unaccounted-for variance (in some cases $\geq$75%) means that other physiologic factors (eg, muscle fiber characteristics, stiffness of the muscle-tendon complex, or muscle cross-sectional area)[36–40] play a greater role in isometric PF and RFD than in hop performance. Therefore, hop tests alone may not provide clinicians with the necessary information to make evidence-based decisions about the strength of an isolated muscle group. Future researchers should continue to explore the relationship between hop tests and strength with other factors, such as muscle fiber characteristics, stiffness of the muscle-tendon complex, or muscle cross-sectional area, incorporated into the study design.

Single-Hop Distance and Isometric PF and RFD

Investigators previously evaluated these relationships between functional performance and maximum lower limb strength via isokinetic instrumentation.[14,16,22] However, only 1 group[19] explored the relationship between single-hop work and lower limb strength, and this study was limited to knee-extensor and knee-flexor peak torque and total work.

For our study, we hypothesized that measures of functional performance tests emphasizing distance and work would be strong indicators of PF and RFD at the hip and thigh. However, the results did not fully support these

Table 4. Coefficient of Determination (r^2) Indicating Amount of Variance in Isometric Endurance Explained by the 30-s Lateral-Hop Test by Sex

Sex	Hip Abductors	Hip Adductors	Hip Extensors	Hip Flexors	Knee Extensors	Knee Flexors	Hip External Rotators	Hip Internal Rotators
Men (n = 30)	.00	.12	.02	.00	.02	.05	.00	.00
Women (n = 32)	.01	.00	.00	.02	.00	.02	.01	.01

hypotheses. The single-hop distance was the only factor that accounted for a significant portion of the variance for hip-flexor PF in men. In women, the single-legged vertical-jump distance was the only factor that explained a significant portion of the variance in knee-flexor PF and RFD.

Because of the lack of research in this area, it was difficult to compare our findings between single-hop distance and RFD with those of previous authors, but our findings between single-hop distance and PF do allow for comparison with the literature. Earlier investigators reported that single-hop distance predicted 40% to 44% and 50% of the variance in knee-extensor peak torque at the isokinetic velocities of $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, respectively,[16,19] and the triple-hop distance predicted 43% to 49% and 52% to 58% of the knee-extensor peak torque at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, respectively.[14,16] The association between the triple-hop distance and knee-flexor PF we observed was less than the values reported by investigators[14] using isokinetic instrumentation. In past reports, researchers[14] noted that triple-hop distance predicted 57% and 56% of the variance of isokinetic knee-flexor peak torque at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, respectively. However, 2 of the aforementioned investigations[14,22] represent a grouped analysis (ie, analysis not separated by sex). For comparison, we grouped the men and women in our study and found that the triple-hop distance accounted for 36% and 31% of the variance in knee-extensor and -flexor PF, respectively. For further comparison with earlier research, we also pooled and analyzed data for the single-hop distance and single-legged vertical-jump height. Single-hop distance explained 33% of the variance in isometric knee-extensor PF, which was closer to an earlier report[19] of 40%, using isokinetic instrumentation at $60°\cdot s^{-1}$. Investigators[41] who conducted a pooled analysis reported the single-legged vertical jump accounted for 42% of the variance in isokinetic knee-extensor peak torque at $180°\ s^{-1}$. When we pooled men and women, single-legged vertical-jump height accounted for 34% of the variance in knee-extensor PF in the present study.

These findings highlight the need to analyze data for men and women separately. Grouping men and women without accounting for sex in the model appears to result in overestimation of the variance accounted for by the specific measure of functional performance. Thus, the strength of the relationships in prior studies may have reflected the difference between men and women, with women representing lower values and men representing higher values.

The magnitude of the relationships between hop tests (single and triple hop for distance) and knee-extensor strength has previously been reported to increase as velocity increases.[14,16] This was observed[17] when comparing double-legged jump tests with isokinetic hip-extensor and knee-extensor torque at $60°\cdot s^{-1}$, $120°\cdot s^{-1}$, and $180°\cdot s^{-1}$. Thus, it is likely that the strength of the relationship is a function of velocity, such that stronger relationships occur at higher velocities. Future researchers should explore this hypothesis further.

In attempting to compare our results observed at the hip with the previous literature, we identified only 1 study.[22] The investigators[22] reported that in recreationally active women (N = 32), triple-hop distance accounted for 31%, 7%, 52%, and 42% of the variance in isokinetic hip-abductor, hip-adductor, hip–external-rotator, and hip–internal-rotator eccentric peak torque, respectively, at $30°\cdot s^{-1}$ when both the hop distance and strength were normalized to body weight in kilograms. For comparison with this study,[22] we normalized the triple-hop distance and PF data in our study to kilograms of body weight and analyzed the data for the recreationally active women (N = 32). Normalized triple-hop distance explained 10%, 13%, 26%, and 27% of the variance in normalized isometric hip-abductor, hip-adductor, hip–external-rotator, and hip–internal-rotator PF, respectively. In comparison with the prior study,[22] except for hip-adductor PF, the values for the relationships between PF and triple-hop distance are relatively low. Arguably, the differences between the 2 studies may reflect greater similarity in neuromuscular firing patterns for the triple-hop and eccentric-strength testing as compared with those for the triple-hop and isometric tests.

In general, the values between distance hopped (specifically, single hop and triple hop) and isometric PF at the hip and thigh were less than those reported by investigators using isokinetic dynamometry.[14,16,22] Our results most likely vary from those of earlier isokinetic reports because of the difference in neural recruitment patterns between static and dynamic tasks.[18,42] Because neural recruitment[18,42] and rate coding[18] differ between static and dynamic tasks, it is plausible that neural recruitment patterns elicited by isokinetic mode contractions more closely resemble those of hop tests.

Single-Hop Work and Isometric PF and RFD

Consistent with previous literature,[17–19] hop work accounted for a greater percentage of the variance in PF and RFD than did distance hopped. Inclusion of participant weight in the evaluation of single-hop distance appeared to account for strength abilities in a way that distance alone was not able to explain.[17,19] Because work is determined by multiplying force and distance moved, including body weight in the evaluation of hopping tests may provide a better indicator of muscle function.[19] The results from this study were in agreement, suggesting that work performed during these tests provided clinicians with a better indicator of maximum strength and RFD than did distance hopped.

In men, triple-hop work accounted for 36% and 50% of the variance in hip-abductor and -adductor PF, respectively. In addition, it accounted for 27% and 38% of hip-abductor and -adductor RFD, respectively. To our knowledge, we are the first to report these findings separately in men and women within the same study. This finding is important given the reports[7,10,20,43] indicating the contribution of hip-abductor strength to lower limb movement mechanics and injury-free athletic participation and the need for an effective method to evaluate these muscle groups before participation.

Overall, hop work in men explained a significant portion of the variance only in frontal-plane hip RFD and hip-flexor RFD, with the best measure of functional performance being triple-hop work. In women, hop work accounted for a significant portion of the variance in knee extensor, knee-flexor, and hip–internal-rotator RFD. Previously, double-legged vertical-jump work accounted for 11% of the variance of a seated unilateral leg-extension test in men with weight-training experience.[18] In the present study, we found that single-legged vertical-jump work accounted for a similar portion of the variance (12%) of knee-extensor RFD in male recreational athletes.

The 30-Second Lateral-Hop Test for Endurance and Isometric Strength Endurance

Our second hypothesis proposed that the number of repetitions performed during the 30-second lateral-hop test for endurance would demonstrate a strong correlation with isometric strength endurance. However, the results did not support this hypothesis. The relationship between the 30-second lateral-hop test for endurance and the isometric strength-endurance test may be a result of the individual task requirements. The more functionally integrated performance tests may have allowed participants to compensate for fatigue because the muscles were able to act synergistically across the entire lower limb to accomplish the task. During the isometric endurance task, isolation of a single muscle group may have caused participants to be more susceptible to peripheral fatigue mechanisms. Although 30 seconds may be sufficient to fatigue a muscle group under isolated conditions, longer time durations (eg, 45–50 seconds) could be required to elicit the notable effects of fatigue during functional integrated tasks, such as the 30-second lateral-hop test for endurance, in healthy, recreationally active individuals.

Clinical Relevance

Clinically, the use of functional performance tests represents a more time-efficient and cost-effective method of assessing muscle function than isometric or isokinetic instrumentation.[14,44] Functional performance tests and single-joint isometric and isokinetic testing procedures represent uniquely different methodologic approaches (ie, integration versus isolation) to evaluating muscular function. Functional performance tests assess the function of the entire lower limb in an integrated manner, encompassing strength, power, neuromuscular coordination, and stability across multiple joints[14,15,45] at varied movement velocities.

Therefore, evaluating the relationship between hop tests and strength will help to increase the validity of their use in both men and women within large-scale, preparticipation examinations and return-to-play evaluations. Our results indicated that hop measures incorporating body weight were a better indicator of PF and RFD than hop measures alone. They further suggest that that pooling data for men and women may overestimate the size of the correlations between hop tests and PF. Additionally, based on the isometric findings of our study and those of earlier isokinetic studies, the strength of the relationship between hop tests and PF may also be, in part, a function of the type of muscular contraction, with greater associations noted with concentric isokinetic muscular contraction than with isometric contraction. Under isometric PF testing conditions, other physiologic factors, such as muscle fiber characteristics and stiffness of the muscle-tendon complex, may play a greater role. Although hop tests may be time efficient and cost effective for determining lower extremity strength deficits during preparticipation examinations and sideline evaluations for assessing return-to-play status, it may be best to couple them with another type of performance test (eg, 1-leg–rising test) to emphasize maximal strength.[16]

In conjunction with other assessments, hop tests (especially those quantified by work performed) may be a viable time-efficient and cost-effective option for helping to determine the PF and RFD of these muscle groups within the context of preparticipation examinations and sideline evaluations for evaluating return-to-play status. Much like other functional performance tests, hop tests require minimal materials,[14] space, time,[14] and personnel for test administration,[44] making them ideal for inclusion in preparticipation examinations and return-to-play evaluations.[44] Although incorporating body weight into jump and hop measures of distance increases the magnitude of the relationship to strength, during preparticipation screening examinations and return-to-play evaluations, clinicians need to be able to quickly convert the distance hopped to work performed. To avoid their having to calculate this measure by hand, a printed paper chart would allow for quick conversion (see English et al[19] for a single-hop–work conversion chart).

Finally, the 30-second lateral-hop test for endurance was not associated with isometric strength endurance. Further work is needed to explore this relationship using functional performance tests conducted over longer durations (eg, 45–50 seconds). This increased time duration may be necessary to induce fatigue in the lower limb when performing functional performance tests designed to emphasize endurance.

Our study also provided insight into the differences in the size of coefficient of determination values by sex. When we stratified the analyses based on sex, we observed a decrease in the correlation value. Future authors should continue to use a stratified approach, which will allow for the development of sex-specific approaches to assess lower extremity strength.

Limitations

We acknowledge the following limitations. First, because we studied a sample of convenience and not a random sample, our findings may not be generalizable beyond this sample. Second, although all participants were recreational athletes, varied types and amounts of athletic involvement and years of experience may have influenced their performance on both the isometric strength and functional performance tests. Third, the PF and RFD were not normalized by height and weight. Height and weight could have acted as confounders between strength and the measures of functional performance. We did not normalize these data because this was a within-subject correlational design.[14] However, we acknowledge that corrections for height and weight may decrease the strength of the observed relationships. Future investigators should use statistical models that account for body size to avoid the assumption that the strength of the association was merely a reflection of participant body size.[5,16]

Lastly, although our findings provide insight into these relationships, they do not reflect causality. Future researchers should evaluate these same relationships using a predictive model. A predictive model would also help to determine if a combination of functional performance tests would be clinically useful in predicting a greater percentage of variance in strength than previously reported by a single functional performance test.

CONCLUSIONS

Hop tests are popular because they require minimal materials,[14] space, time,[14] and personnel for test administration,[44] which makes them ideal for use during preparticipation examinations and return-to-play assessments.[44] However, our results suggest that hop tests alone do not provide clinicians with enough information to make evidence-based decisions about lower extremity muscular strength in isolated muscle groups. Further investigation is needed into these relationships to validate their use as potential predictors of strength of the individual muscles of the hip and thigh. Future authors should investigate these relationships in combination with other cost-effective and time-efficient assessments (eg, 1-leg–rising test) reported to be related to lower extremity strength at the hip and thigh.

REFERENCES

1. Hislop HJ, Perrine JJ. The isokinetic concept of exercise. *Phys Ther*. 1967;47(2):114–117.
2. Mebes C, Amstutz A, Luder G, et al. Isometric rate of force development, maximum voluntary contraction, and balance in women with and without joint hypermobility. *Arthritis Rheum*. 2008;59(11):1665–1669.
3. Castro-Piñero J, Ortega FB, Artero EG, et al. Assessing muscular strength in youth: usefulness of standing long jump as a general index of muscular fitness. *J Strength Cond Res*. 2010;24(7):1810–1817.
4. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol*. 2002;93(4):1318–1326.
5. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol*. 2006;96(1):46–52.
6. Surakka J, Romberg A, Ruutiainen J, Virtanen A, Aunola S, Mäentaka K. Assessment of muscle strength and motor fatigue with a knee dynamometer in subjects with multiple sclerosis: a new fatigue index. *Clin Rehabil*. 2004;18(6):652–659.
7. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech*. 2006;22(1):41–50.
8. Kollock RO, Onate JA, Van Lunen B. Assessing muscular strength at the hip joint. *Athl Ther Today*. 2008;13(2):18–24.
9. Niemuth PE, Johnson RJ, Myers MJ, Thieman TJ. Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med*. 2005;15(1):14–21.
10. Souza RB, Powers CM. Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med*. 2009;37(3):579–587.
11. Tyler TF, Nicholas SJ, Mullaney MJ, McHugh MP. The role of hip muscle function in the treatment of patellofemoral pain syndrome. *Am J Sports Med*. 2006;34(4):630–636.
12. Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med*. 2008;36(8):1469–1475.
13. Tyler TF, Nicholas SJ, Campbell RJ, McHugh MP. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *Am J Sports Med*. 2001;29(2):124–128.
14. Hamilton RT, Shultz SJ, Schmitz RJ, Perrin DH. Triple-hop distance as a valid predictor of lower limb strength and power. *J Athl Train*. 2008;43(2):144–151.
15. Keays SL, Bullock-Saxton JE, Newcombe P, Keays AC. The relationship between knee strength and functional stability before and after anterior cruciate ligament reconstruction. *J Orthop Res*. 2003;21(2):231–237.
16. Ostenberg A, Roos E, Ekdahl C, Roos H. Isokinetic knee extensor strength and functional performance in healthy female soccer players. *Scand J Med Sci Sports*. 1998;8(5 pt 1):257–264.
17. Tsiokanos A, Kellis E, Jamurtas A, Kellis S. The relationship between jumping performance and isokinetic strength of hip and knee extensors and ankle plantar flexors. *Isokinet Exerc Sci*. 2002;10(2):107–115.
18. Baker D, Wilson G, Carlyon B. Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength. *Eur J Appl Physiol Occup Physiol*. 1994;68(4):350–355.
19. English R, Brannock M, Wan TC, Eastwood LS, Uhl T. The relationship between lower extremity isokinetic work and single-leg functional hop-work test. *J Sport Rehabil*. 2006;15(2):95–104.
20. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train*. 2007;42(1):76–83.
21. Carcia C, Eggen J, Schultz S. Hip-abductor fatigue, frontal-plane landing angle, and excursion during a drop jump. *J Sport Rehabil*. 2005;14(4):321–331.
22. Baldon RM, Lobato DFM, Carvalho LP, Wun PYL, Presotti CV, Serrão FV. Relationships between eccentric hip isokinetic torque and functional performance. *J Sport Rehabil*. 2012;21(1):26–33.
23. Meldrum D, Cahalane E, Conroy R, Guthrie R, Hardiman O. Quantitative assessment of motor fatigue: normative values and comparison with prior-polio patients. *Amyotroph Lateral Scler*. 2007;8(3):170–176.
24. Schwid SR, Thornton CA, Pandya S, et al. Quantitative assessment of motor fatigue and strength in MS. *Neurology*. 1999;53(4):743–750.
25. Sanjak M, Brinkmann J, Belden DS, et al. Quantitative assessment of motor fatigue in amyotrophic lateral sclerosis. *J Neurol Sci*. 2001;191(1–2):55–59.
26. Kollock RO, Onate JA, Van Lunen B. The reliability of portable fixed dynamometry during hip and knee strength assessments. *J Athl Train*. 2010;45(4):349–356.
27. Booher LD, Hench KM, Worrell TW, Stikeleather J. Reliability of three single-leg hop tests. *J Sport Rehabil*. 1993;2(3):165–170.
28. Gustavsson A, Neeter C, Thomee P, et al. A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(8):778–788.
29. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during

rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther*. 2007;87(3):337–349.
30. Ross MD, Langford B, Whelan PJ. Test-retest reliability of 4 single-leg horizontal hop tests. *J Strength Cond Res*. 2002;16(4):617–622.
31. Tegner Y, Lysholm J, Lysholm M, Gillquist J. A performance test to monitor rehabilitation and evaluate anterior cruciate ligament injuries. *Am J Sports Med*. 1986;14(2):156–159.
32. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res*. 2005;19(1):51–60.
33. Christensen PA, Jacobsen O, Thorlund JB, et al. Changes in maximum muscle strength and rapid muscle force characteristics after long-term special support and reconnaissance missions: a preliminary report. *Mil Med*. 2008;173(9):889–894.
34. Hopkins WG. A new view of statistics. Sportscience Web site. http://sportsci.org/resource/stats/. Accessed January 31, 2014.
35. Clarke DH, Clarke HH. *Research Processes in Physical Education, Recreation, and Health*. Englewood Cliffs, NJ: Prentice-Hall; 1970.
36. Andersen LL, Andersen JL, Zebis MK, Aagaard P. Early and late rate of force development: differential adaptive responses to resistance training? *Scand J Med Sci Sports*. 2010;20(1):e162–e169.
37. Bojsen-Moller J, Magnusson SP, Rasmussen LR, Kjaer M, Aagaard P. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *J Appl Physiol*. 2005;99(3):986–994.
38. Bottinelli R, Canepari M, Pellegrino MA, Reggiani C. Force-velocity properties of human skeletal muscle fibres: myosin heavy chain isoform and temperature dependence. *J Physiol*. 1996;495(pt 2):573–586.
39. Stone MH, Sands WA, Carlock J, et al. The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*. 2004;18(4):878–884.
40. Suetta C, Aagaard P, Rosted A, et al. Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. *J Appl Physiol*. 2004;97(5):1954–1961.
41. Negrete R, Brophy J. The relationship between isokinetic open and closed chain lower extremity strength and functional performance. *J Sport Rehabil*. 2000;9(1):46–61.
42. Murphy AJ, Wilson GJ. Poor correlations between isometric tests and dynamic performance: relationship to muscle activation. *Eur J Appl Physiol Occup Physiol*. 1996;73(3–4):353–357.
43. Howard JS, Fazio MA, Mattacola CG, Uhl TL, Jacobs CA. Structure, sex, and strength and knee and hip kinematics during landing. *J Athl Train*. 2011;46(4):376–385.
44. Clark NC. Functional performance testing following knee ligament injury. *Phys Ther Sport*. 2001;2(2):91–105.
45. Docherty CL, Arnold BL, Gansneder BM, Hurwitz S, Gieck J. Functional-performance deficits in volunteers with functional ankle instability. *J Athl Train*. 2005;40(1):30–34.

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