What Are the Validity of the Single-Leg-Squat Test and Its Relationship to Hip-Abduction Strength?

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**Context:** The Trendelenburg and single-leg-squat (SLS) tests are purported measures of hip-abduction strength that have not been previously validated. **Objective:** To correlate isometric hip-abduction strength to frontal-plane hip motion during an SLS and determine the criterion validity of a clinical-observation-analysis method to grade an SLS against 2-dimensional kinematic analysis. **Design:** Single-measure, concurrent validity. **Setting:** Biodynamics research laboratory. **Participants:** 50 uninjured participants. **Main Outcome Measures:** Hip-abduction strength and hip and knee kinematic data during a Trendelenburg test and an SLS. **Results:** A weak, positive correlation between hip-abduction strength and hip-adduction angle was found during both the Trendelenburg ($r = .22$, $P = .13$) and the SLS ($r = .21$, $P = .14$) tests. The observation-analysis method revealed a low sensitivity, .23, and a higher specificity, .86, when compared with the kinematic data. **Conclusion:** The usefulness of the Trendelenburg and SLS test in screening hip-abductor strength in a healthy physically active population is limited. The origin of observable deficits during SLS requires further objective assessment. **Key Words:** Trendelenburg test, kinematic analysis, functional testing, subjective analysis

Functional tests are indirect measurements of muscle strength and power.\(^1\)\(^2\) They have gained popularity and are often used in order to assess components of tasks, such as squatting and hopping. Although these functional tests are used regularly, their reliability and validity have not been well defined. The single-leg squat (SLS) is one such test used by investigators that has been suggested to assess general leg strength and muscle endur-
This test can be used when deciding whether to allow an athlete to return to play or advance further in a rehabilitation progression. No standardized method of performing the SLS has been described, and no relationship has been documented to determine what the SLS test is assessing. Liebenson suggested that the SLS test can be used to assess various dysfunctions affecting the kinetic chain but did not support these claims with any kinematic data.

The Trendelenburg test is a clinical test that is purported to evaluate hip-abduction strength, but its validity and reliability have not been reported. The test is considered positive when the pelvis on the non-weight-bearing side lowers. This lowering occurs because the hip abductors on the stance side are not strong enough to support the entire weight of the body. An SLS test incorporates components of a Trendelenburg test but is performed dynamically, potentially increasing the demand on the gluteus medius and challenging the motor control of trunk, hip, knee, and ankle muscles to a greater extent. No information exists describing the relationship between hip-adduction movement and gluteus medius strength. Zeller et al. used a 3-dimensional motion-analysis system to report kinematic differences between men and women performing an SLS. Women had approximately 4° more hip adduction than men when performing the SLS. Zeller et al. suggest that the increased hip adduction might result from difficulty controlling the hip muscles because of a weak gluteus medius muscle.

As a patient performs an SLS test, the investigator visually observes the task and assesses the patient’s strength and muscle function on these subjective observations. Assessment of the SLS has not been standardized. Observational practices are commonly used but have rarely been scrutinized scientifically. Previous research of an investigator’s ability to identify deviations from normal movement patterns such as walking and arm elevation have yielded only low to moderate reliability.

Many functional tests are available to evaluate various components of patients’ abilities, but many of them have not been critically evaluated with objective measurements. The validity of these tests needs to be evaluated. The SLS has good potential as a functional test because many daily and athletic activities involve components of this movement. Research on gluteus medius weakness in a weight-bearing position and the resulting amount of hip adduction is limited, and more research is needed to support the clinical efficacy of the Trendelenburg test and the SLS test. Therefore, the first purpose of this study was to determine the relationship between isometric hip-abduction strength and maximal hip-adduction angle during the performance of a Trendelenburg test and a standardized SLS test. The second purpose was to evaluate the validity of a clinical-observation method to assess SLS performance as compared with a criterion-referenced 2-dimensional kinematic analysis.
Methods

Participants
Fifty participants (age 24.32 ± 4.78 years; height 171.64 ± 11.16 cm; mass 74.84 ± 21.82 kg; 26 men, 24 women) volunteered for this study. Participants were excluded from the study if they had experienced any lower extremity injury or neurological disorder, including a concussion, during the month preceding the study or had undergone any lower extremity surgical procedures in the preceding 6 months. All participants had to be able to achieve 60° of knee flexion during an SLS. Before participation, we gave all participants a verbal explanation of the study, and they signed an institutional-review-board-approved informed-consent form.

Instrumentation

Kinematic Data Collection. Six high-speed Falcon high-resolution video cameras (Motion Analysis Corp, Santa Rosa, Calif) were used to collect kinematic data. Data were collected at 60 Hz. All video data were collected using the Eva HiRes 7.0 hardware–software system (Motion Analysis Corp) and stored on a PC in the biodynamics laboratory. We exported these data to an Excel® spreadsheet in which maximum and minimum values of hip adduction, hip abduction, knee valgus, and knee varus were calculated. Although the data were collected as 3-dimensional data, a 2-dimensional analysis provided the criterion reference information to compare with the visual-observation assessment made by 2 investigators.

Dynamometer Data Collection. We used a JTECH Commander Power Track II® (JTECH Medical, Salt Lake City, Utah) handheld dynamometer to test hip-abduction strength of the stance leg. We used a nylon strap, approximately 2 in wide by 10 ft long, to stabilize the dynamometer against the test leg while the investigator stabilized the dynamometer without applying any downward force (Figure 1). The reliability of measuring hip-abduction strength during the study using the nylon strap was high (ICC = .928, SEM = 12.49).

SLS Grading Criteria. We determined standardized grading criteria of active ranges of motion for the SLS using pilot testing and previous research.10 There were 3 criteria graded during the squat: Hip flexion should not exceed 65°, hip adduction should not exceed 10°, and knee valgus should not exceed 10°. These criteria were used to give a final SLS score for each trial as observed by the 2 investigators. Each of the testers was a certified athletic trainer. The investigators gave a score of 3 (excellent) if all 3 of the criteria were met, a score of 2 (good) if 2 of the 3 criteria were met, a score of 1 (fair) if 1 of the criteria was met, and a score of 0 (poor) if none of the criteria were met. A score of 0 was also given if the participant lost his or her balance and touched the opposite foot to the floor or was not able complete the squat in 6 seconds.
Procedures

Participants completed a health-history questionnaire and rated their activity level using the Tegner activity scale,\textsuperscript{19} with the average score being $4.9 \pm 1.2$ out of 10 in this cohort. We collected all data on the leg that each participant would use for support while kicking a ball.\textsuperscript{20} We tested hip-abduction strength of the stance leg using a handheld dynamometer. Participants were placed in a side-lying position with the nonstance leg against the table and bent to approximately $90^\circ$ of hip and knee flexion.\textsuperscript{21} We put the stance hip into a neutral position in the frontal plane and with the knee fully extended.\textsuperscript{21} We placed the handheld dynamometer over the lateral femoral condyle,\textsuperscript{21} and the participant was asked to abduct the hip against the dynamometer and the strap with a gradual buildup of force for 2 seconds and a maximal effort for 4 seconds (Figure 1). We averaged 3 hip-abduction strength measurements and normalized this to body weight for each participant. This value represented the normalized hip-abduction strength value.

We placed 6 kinematic reflective markers on the participant’s stance side using a method described by Winter.\textsuperscript{22} The marker locations were the lateral acromion process, the greater trochanter, the lateral femoral condyle, the lateral malleolus, the lateral heel, and the base of the fifth metatarsal (Figure 2). Two additional reflective markers were placed on the participant’s anterior superior iliac spines for the investigators to use as reference points. All loose clothing was secured and taped down to minimize movement artifact

Figure 1  Hip-abduction strength test position.
caused by clothing shifting. Participants stood in a double-leg stance and squatted down to 60° of knee flexion, which was confirmed with a universal goniometer. A physical block was used so that the subject would reach 60° of knee flexion during each squat attempt.

We then instructed the participants on how to perform an SLS, and they were allowed to practice until they felt comfortable; no more than 5 practice repetitions were required. Participants were instructed to stand on their stance leg while their nonstance leg was lifted off the ground so that their hip was flexed to approximately 45° and the knee was flexed to approximately 90°. The participants’ shoulders were flexed to 90° with their elbows in full extension and hands clasped together in front of them (Figure 3). The participants were instructed to squat down until their buttocks touched the physical block (Figure 4) and return to the start position in less than 6 seconds. A 1-second static file of the participant in double-leg stance was collected to determine starting joint positions. The amount of hip adduction for the Trendelenburg test was determined from a 1-second

Figure 2  Reflective-marker placement.
The 3 squat tests were recorded by the motion-analysis system and graded by the 2 investigators simultaneously.

**Data Reduction**

We saved the data collected from the motion-analysis system on a computer and digitized them using Eva 7.0 software. The x-, y-, and z-coordinates for the 6 reflective kinematic markers throughout the entire SLS were exported to an Excel spreadsheet. The coordinate system is displayed in Figure 2. We calculated segment lengths from these coordinates using the Pythagorean theorem. The frontal plane used the x- and z-coordinates, whereas the sagittal plane used the y- and z-coordinates.

We needed 3 segment lengths, A, B, and C, to calculate 1 joint angle, so the segments on either side of the joint whose angle was to be calculated were used in addition to an imaginary line dropped straight down from the most proximal marker of the proximal segment to the most distal marker of the distal segment. For example, to measure hip adduction, segment A
would be the trunk, segment B would be the femur, and segment C would be the imaginary line drawn from the marker on the acromion process of the shoulder to the marker on the lateral knee. We used segment lengths A, B, and C to calculate the joint angle using the law of cosine:

$$\theta_{rad} = \frac{C^2 - A^2 - B^2}{-2AB}$$

The angles in radians were converted to degrees using the following equation:

$$\theta_{deg} = \frac{180}{\pi} \theta_{rad}$$

In the double-leg static position, the average joint angles were recorded for hip abduction and adduction and knee valgus and varus. The maximum joint-angle displacements were defined for the Trendelenburg and SLS kinematic data as the change from the double-leg-stance static position.22
The maximum joint angles for hip abduction, hip adduction, knee valgus, and knee varus were determined by plotting the joint angles on a line graph. Knee flexion was included to ensure that maximal values occurred during the SLS test. These angles were the criterion reference values used to evaluate the clinical-observation-analysis methods. The maximum hip-adduction angles that were recorded during the 3 SLS trials were called the dynamic-hip-adduction angles. We subtracted the average joint angles in the single-leg-stance static file from those in the double-leg-stance static file and reported these values as static Trendelenburg values.

Statistical Analysis

We assessed the relationship between normalized hip-abduction strength and the amount of hip adduction during static single-leg stance or the Trendelenburg test using a Pearson bivariate correlation. A second Pearson bivariate correlation was determined between the normalized hip-abduction strength value and the maximal dynamic hip-adduction angle measured during the SLS performance. The second objective was to validate a clinical-observation method of grading SLS performance by 2 blinded investigators compared with an objective kinematic analysis. We evaluated the subjective scoring system to a priori criterion reference standard thresholds of 10° of hip adduction, 10° of knee valgus, and 65° of hip flexion. We calculated sensitivity, specificity, positive and negative likelihood ratios, and accuracy for the clinical-observation method. To determine interrater-reliability agreement between the clinicians a non-parametric kappa correlation was calculated. We used the Statistical Package for Social Sciences (SPSS®), version 10.0, statistical-analysis system for all statistical analyses.

Results

The average hip-adduction and knee-varus angles recorded during the static double-leg stance and static single-leg stance are presented in Table 1. The hip- and knee-joint angles that were recorded during the SLS represent a change from the double-leg stance. On average, participants reached a maximum of 4° ± 3° of hip abduction and 8° ± 4° of hip adduction during the SLS. Participants went into a maximum of 3° ± 3° of knee varus and 4° ± 4° of knee valgus. Table 2 shows the overall scores for the SLS as graded by the 2 investigators and the kinematic analysis.

There was a weak positive correlation between the normalized hip-abduction strength value and the static Trendelenburg \((r = .22, P = .13; \text{Figure } 5)\). There was also a weak positive correlation between the normalized hip-abduction strength value and the dynamic hip-adduction angle measured during the SLS \((r = .21, P = .14; \text{Figure } 6)\).
Table 1  Average Hip and Knee Angles for the Static Double- and Single-Leg Stances

<table>
<thead>
<tr>
<th>Stance</th>
<th>Hip-adduction angle (°)</th>
<th>Knee varus angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-leg</td>
<td>10 ± 4</td>
<td>1 ± 4</td>
</tr>
<tr>
<td>Single-leg</td>
<td>15 ± 4</td>
<td>2 ± 2</td>
</tr>
</tbody>
</table>

Table 2  The Frequency of Reported Scores by Investigators and Computer Using a Criterion-Referenced System of 150 Single-Leg Squats

<table>
<thead>
<tr>
<th>Final Single-Leg-Squat Score</th>
<th>0 (poor)</th>
<th>1 (fair)</th>
<th>2 (good)</th>
<th>3 (excellent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigator 1</td>
<td>0</td>
<td>7</td>
<td>51</td>
<td>92</td>
</tr>
<tr>
<td>Investigator 2</td>
<td>0</td>
<td>8</td>
<td>72</td>
<td>70</td>
</tr>
<tr>
<td>Kinematic analysis</td>
<td>0</td>
<td>6</td>
<td>60</td>
<td>84</td>
</tr>
</tbody>
</table>

Figure 5  Hip-abduction strength versus hip-adduction angle during a static Trendelenburg test.
The validity of the clinical-observation method in assessing SLS resulted in high specificity (.84 and .87) and low sensitivity (.25 and .22) when judging the hip-adduction criteria (Table 3). The 2 investigators had moderate to high specificity (.78 and .58) and low to moderate sensitivity (.46 and .54) when judging the knee-valgus criteria.

Table 3  Sensitivity, Specificity, Positive and Negative Likelihood Ratios (LRs), and Accuracy for the Investigators Using the 10° Knee-Valgus and Hip-Adduction Grading Criteria

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Position</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>+LR</th>
<th>–LR</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hip adduction</td>
<td>.25</td>
<td>.84</td>
<td>1.58</td>
<td>0.89</td>
<td>.64</td>
</tr>
<tr>
<td></td>
<td>Knee valgus</td>
<td>.46</td>
<td>.78</td>
<td>2.11</td>
<td>0.69</td>
<td>.75</td>
</tr>
<tr>
<td></td>
<td>Hip adduction</td>
<td>.22</td>
<td>.87</td>
<td>1.64</td>
<td>0.90</td>
<td>.65</td>
</tr>
<tr>
<td></td>
<td>Knee valgus</td>
<td>.54</td>
<td>.58</td>
<td>1.29</td>
<td>0.79</td>
<td>.58</td>
</tr>
</tbody>
</table>

Figure 6  Hip-abduction strength versus hip-adduction angle during a single-leg squat.
Agreement between the 2 investigators on rating knee valgus occurred 66.6% of the time ($\kappa = .28$, $P < .001$). Of that 66.6%, the investigators agreed that the participants did not have excessive knee valgus in 75% of the cases and that the participants did have excessive knee valgus in 25% of the cases. The investigators agreed on hip-adduction scores 71.3% of the time ($\kappa = .016$, $P = .84$). Of that 71.3%, the investigators agreed that the participant did not have excessive hip adduction in 95% of the cases and that the participant did have excessive hip adduction in only 5% of the cases.

**Comments**

**Validation of the Single-Leg Squat**

Clinical tests are regularly used to evaluate function. Some have undergone scientific scrutiny to document validity, such as the Lachman test, which is used to assess the integrity of the anterior cruciate ligament. Although many other clinical tests are described in the literature or taught in educational curricula, few have been validated. Tests such as the Trendelenburg and SLS tests are included in this group. This study evaluated the relationship of hip-abduction strength with the amount of hip adduction during a Trendelenburg test and during an SLS in order to evaluate the validity of using these tests as a screening mechanism for hip strength in a physically active population.

We hypothesized that participants with strong hip abductors would have less hip adduction during our testing. Our results did not support this hypothesis but, rather, indicated that the amount of hip adduction during both the Trendelenburg and SLS tests did not have a significant correlation ($r = .2$) to the amount of hip-abduction strength in a physically active, healthy population. We expected a negative correlation based on previous literature that suggested diminished hip-abduction strength would result in hip adduction. The fact that we did not support our hypothesis could be the result of several factors: the Trendelenburg and SLS tests are poor screening mechanisms for hip-abduction strength, the population studied was inappropriate for this analysis, or the ability to perform the Trendelenburg and SLS tests relies on other muscles that were not evaluated in our strength assessment.

The Trendelenburg test, as traditionally described in the literature, is a screen for hip-abductor weakness. In this study, using an isometric strength assessment and a 2-dimensional kinematic analysis, the Trendelenburg test and the SLS were objectively assessed to confirm these claims and clinical uses. The lack of correlation between hip strength and kinematic data in this physically active, healthy population suggests that neither the Trendelenburg test nor the SLS indicates hip-abductor weakness as previously suggested. Our correlation results are similar to other research that
has found a lack of correlation between lower limb muscle strength and sprinting times in both unhealthy\textsuperscript{25} and healthy\textsuperscript{26} subjects. This leads us to believe that just 1 muscle or muscle group cannot account for what is happening during a complex, functional activity that employs the whole lower extremity.

We did demonstrate with our data that the SLS has high to moderate specificity, meaning that we were visually able to determine when changes in hip adduction did not exceed the $10^\circ$ criteria. A clinical test that is moderate to highly specific is useful to rule in a disorder when the results are positive. Therefore, a positive SLS (hip adduction $>10^\circ$) indicates that a greater frontal-plane displacement has occurred. Because of the lack of correlation, this displacement cannot be accounted for by hip-adductor strength or weakness. Therefore, further evaluation of the strength of the trunk, hip, and leg using specific manual muscle tests is warranted.

Another explanation for our lack of correlation could have been that our population sample was too homogeneous, as indicated by the scatter plots. We attempted to identify the activity level of our population to get a diverse sample by using the Tegner activity scale, which ranges from 0 to 10.\textsuperscript{19} Our population ranged from 3 to 7. By selecting a larger sample population that better represents the entire spectrum, a better correlation might result. The population tested in this study was also physically active and healthy, not presenting with any lower extremity injuries. When studying a diagnostic test, the participants used should be representative of the population for whom the test is intended, in this case an injured or unhealthy population.\textsuperscript{27} Although this is a limitation of our study, it is common for clinicians to use these tests as screening exams to evaluate hip-adduction strength in a healthy population. Our results indicated that the amount of hip adduction during these tests is not directly related to hip-adduction strength. Future studies that evaluate the relationships between hip-adduction strength and these clinical tests in an injured population are needed; however, pain could limit how the subjects might perform and therefore limit the results of those studies, as well.

Trunk, hip, and knee muscles can all play a role in controlling the hip during an SLS. These muscles might have assisted the gluteus medius in controlling the hip during the SLS but might not have factored into the method of measuring hip-adduction strength that was used in this study, therefore accounting for the lack of correlation in this study. The muscle activity of the quadriceps is very high during the performance of a similar single-leg exercise, the Star Excursion Balance Test (SEBT). The SEBT is a series of single-leg squats that requires the participant to reach as far out as possible in anterior, posterior, and lateral directions with the opposite leg.\textsuperscript{18,28} Intratester\textsuperscript{18,29} and intertester\textsuperscript{18} reliability of the SEBT have been reported, but a search of the literature revealed no studies reporting its validity. Earl and Hertel\textsuperscript{28} relate that during the anterior-exursion portion of the test, the individual is required to squat and keep the trunk in a relatively erect
position as gravity acts on the body, creating a large knee-flexion moment that must be countered by an extension moment created by the quadriceps muscles. This version of the SEBT is very similar to the SLS, which suggests that the SLS might depend more on the strength and control of the quadriceps muscle than on hip strength. This could explain why we found a lack of correlation between hip-abduction strength and the SLS. Thus, it is our intention to continue to study other variables such as quadriceps strength and balance in future studies to determine their contribution to the SLS.

Although the Trendelenburg test has been used in practice for quite some time,¹¹,¹² the SLS is a relatively new test, so there is little research reported on it. The SLS has potential to be a useful test because it involves a dynamic movement that requires motor control, strength, and balance. More research is needed on the SLS, however, if it is to be used for a specific impairment. Because the SLS has high specificity, it can be a useful test when the result is positive. If a positive result occurs, it might be a good idea to strength-test proximally and distally on the kinetic chain to identify the source of weakness causing the excessive hip adduction or knee valgus.

This study provided values for a healthy population performing the SLS test. From these values we propose a new set of criteria to grade the SLS. By using a 90% confidence interval, we determined new ranges for the hip-adduction and the knee-valgus criteria. These new criteria allow participants to fall in a “normal” range of motion while performing a SLS, only considered to be failing if they exceed the specified range of motion. This new method would make it easier for clinicians to evaluate the SLS, allowing them to look for a range of values as opposed to a single value on which to base their decisions. The new range for the hip-adduction criteria is between 9° of hip abduction and 15° of hip adduction. For the knee, the new range is between 8° of knee varus and 11° of knee valgus. The hip-flexion criteria are not changed because hip flexion did not have an effect on our grading when using an SLS that was limited to 60° of knee flexion. It might become more important when not controlling for the amount of knee flexion during the SLS.

**Reliability of the Single-Leg Squat**

A secondary purpose of this study was to determine whether 2 novice investigators would be able to reliably assess an SLS as compared with a criterion-referenced 2-dimensional kinematic analysis. Previous research on subjective visual observations of gait and scapular-movement patterns has yielded only low to moderate interrater agreement (κ = .11–.52 and κ = .31–.42).¹⁴,¹⁵ Results from our study (κ = .016–.28) concur with those of previous research reporting low to fair agreement as determined by the kappa values. Even though our kappa correlations were low, agreement between the raters occurred 57% to 71% of the time. Most of the agreement occurred when the raters did not see excessive hip adduction or knee valgus. Because
of the lack of equal distribution, with high agreement in only 1 direction, a very low kappa correlation was produced. Although clinical visual-observation tools have not had high reliability in previous studies, clinicians continue to base judgments on these less than highly reliable tests. As clinicians, it is important to base our decisions on objective and valid clinical tests. By using evidence-based tests, the best information currently available helps guide us in making the best decisions for patients in their recovery from injury.

**Limitations and Future Research**

A major limitation of this study is the sample population. As stated previously, validity testing on the population of interest is necessary to validate a clinical test. Typically, the Trendelenburg and SLS tests are performed as part of a physical examination of a patient presenting with lower extremity pathology of some kind. In this study, a sample of convenience of physically active participants was used. Further investigation of these 2 clinical tests in a pathological population would be appropriate.

Another limitation of our study is the use of a 2-dimensional kinematic analysis to assess joint motions that occur in 3 dimensions. Rotation of the pelvis, femur, and tibia were not assessed because we used a 2-dimensional analysis. We chose to use a 2-dimensional analysis because that is how clinicians see the movement if they are viewing the patient from an anterior view. Incorporating 3-dimensional kinematic analysis and additional strength evaluations, particularly of the quadriceps muscles, would enhance future research in this area. In addition, when collecting kinematic data it is best to place the kinematic markers directly on the skin. In this study we placed the markers on the subjects’ clothing, which might have skewed our results because of clothing movement rather than actual body movement. We tried to prevent this as much as possible by securing loose clothing and taping it down to minimize movement.

Even though both of our investigators were involved in extensive pilot testing to develop the grading criteria, we think that a final limitation of our study was their inability to discriminate small motions at the hip and knee. Incorporating an education session using video examples of each grade of the SLS test would enable the clinicians to learn the difference between a passing and failing SLS effort. They would be better able to distinguish the squats when grading a patient and, one would hope, achieve enhanced reliability.

**Conclusion**

The Trendelenburg and SLS tests have little relationship to isometric hip-abduction strength in a healthy, normal population. The observational
method described revealed poor sensitivity but good specificity, however, in grading SLS performance. An observation of excessive hip adduction or knee valgus might indicate that further objective strength assessment of the lower extremity is necessary. The normative kinematic data obtained provide a foundation for further study of the SLS test and potential modification on the observational grading system. Clinical-observation systems are commonly used in clinical decision making. The low interobserver reliability demonstrates the importance of clearly describing thresholds of abnormal motion and the necessity of mastering clinical observational skills before using them for clinical assessment. This study illustrates the fact that scientific scrutiny of clinical tests can contest the expected findings and indicates that continued research is necessary to validate their usefulness before basing clinical decisions on the multitude of clinical tests described in the literature.

References

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