of a treatment requires reliable outcome measures that can be tracked over time. In general, clinical evaluation of patients’ functional abilities is determined through functional tests. Performance in clinical tests of function, such as the timed up-and-go (TUG), 6–minute walk (6MW), 27 and stair-climbing test (SCT), 1,12 provides insight into physical ability and is the standard measure of functional performance in an elderly population. Though these clinical performance tests provide a measure of global lower extremity function, 2,30,32,46,47 they do not provide clinicians with insight into the ability of each limb independently or a means to differentiate between limbs.

Recent work has demonstrated that the integrity of the contralateral limb is central to predicting long-term bilateral functional ability after TKA. 29 Additionally, the high likelihood of developing OA in the contralateral limb 20 suggests that there may be a need for a test of unilateral limb ability that can provide clinicians with a metric for independently assessing recovery and response to treatment of both the operated and nonoperated limbs of patients following unilateral TKA. An assessment of unilateral activity limitations would provide clinicians with a deeper insight into a patient’s functional capacity, while also allowing the clinician to monitor changes in the nonsurgical limb, which is at high risk for developing knee OA. 18,30 Current functional tests for evaluating each limb independently, such as single-leg hopping tests 26 or unilateral squat jumping, 6 are appropriate for healthy young adults and athletes but may not be appropriate or safe for older populations, particularly of patients recovering from TKA. Furthermore, other unilateral tests, such as the step-down test, are commonly used to evaluate quality of movement 15,26 or to assess pain during stepping in patients with patellofemoral pain syndrome 20,25 but do not provide a metric of activity limitations.
and are not commonly used in patients after TKA.

Impairments of the quadriceps are associated with poorer performance in functional activities such as walking and climbing stairs. The single-step test (SST) was developed as a test of unilateral limb ability and involves the use of a single limb to raise and lower the body from the ground to a step and back down, combining concentric and eccentric actions of the quadriceps. The aim of this investigation was to assess the intertester reliability, validity, and responsiveness of the SST in patients after TKA. The intertester reliability and measurement accuracy of the SST were assessed by comparing measurements between testers and against a gold standard for recording timing data. Validity was determined by comparing SST performance between the surgical and nonsurgical limbs of patients after TKA, and between the limbs of patients after TKA and the limbs of individuals without knee OA. Additionally, validity was assessed by comparing the performance of the SST with that of clinic-based, functional performance measures in the same subjects. Responsiveness was determined by evaluating the change in SST performance from before to after outpatient physical therapy treatment of the surgical limb in patients who underwent TKA.

We hypothesized that the SST would be assessed as reliable between testers and against a gold standard for measuring timing variables. Furthermore, the SST would be a valid measure of activity limitations that would (a) distinguish between the limbs of patients after unilateral TKA, (b) distinguish between the limbs of patients with TKA and those of healthy controls, and (c) exhibit moderate correlations with clinic-based, functional performance measures. Lastly, we hypothesized that SST performance would be responsive to change during the course of postoperative outpatient physical therapy treatment.

**METHODS**

**Subjects**

Three different subject samples were assessed with the SST to meet the aims of the study: a bilateral TKA group, a unilateral TKA group, and a healthy control group. Exclusion criteria for all 3 samples were body mass index greater than 40 kg/m² (very severe obesity) or a history of cardiovascular disease, diabetes, or uncontrolled high blood pressure. The bilateral TKA group was used to determine the interrater reliability and accuracy of recording the timing of the SST.

The SST was implemented in a randomized clinical trial that compared the effects of progressive strength training with progressive strength training combined with neuromuscular electrical stimulation on recovery after TKA. The data presented for validity, responsiveness, and comparison across limbs were obtained from individuals who underwent unilateral TKA, where subjects were also excluded if they had pain in the contralateral knee (defined as knee pain of 4 or greater on a 10-point verbal analog scale) or any other lower extremity pathologies that interfered with their functional abilities. The healthy control group was composed of 61 individuals without knee OA, who were recruited through advertisements in local papers and by word of mouth. Informed consent was given by each subject prior to participation, and the rights of the subjects were protected. The study and inclusion of the SST were approved by the University of Delaware Human Subjects Review Board, and all procedures were in accordance with the Declaration of Helsinki.

Subjects were assessed with a battery of tests during the initial postoperative outpatient physical therapy evaluation (IE), which took place approximately 4 weeks after the operation, at 3 months after TKA, and at 1 year after TKA.

**Rehabilitation Protocol**

The rehabilitation protocol was completed at the University of Delaware Physical Therapy Clinic. Subjects were treated in the physical therapy clinic 2 to 3 times per week for 6 weeks, for an average of 17 sessions. All subjects received rehabilitation focused on progressive quadriceps strengthening, including strategies to reduce pain and swelling, improve knee extension and flexion range of motion, improve patellar mobility, and maximize function. Some subjects also received neuromuscular electrical stimulation to augment the quadriceps strengthening program.

**Single-Step Test**

For the SST, subjects were asked to stand on a block (15 cm), weight bearing on the test limb only. With the non–weight-bearing limb held straight by a knee immobilizer brace, subjects were asked to squat, using the test limb to touch the heel of the non–weight-bearing limb to the floor, and return to touch the step (FIGURE 1). The total time needed to complete 20 repetitions of the movement was recorded and used in the analyses. As a safety precaution, the subjects’ hands rested on top of the investigator’s hands, with instructions that the investigator was only to be used in the event of a loss...
of balance. The trial was not counted if the patient used the investigator for sustained support. A coin toss was used to randomly determine the order of testing for the 2 limbs, and time was recorded manually using a handheld stopwatch.

**Performance Measures**

The functional measures used for comparison were the SCT, the 6MW test, and the TUG test. The SCT required the patient to ascend and descend a standard flight of stairs (12 steps at 7.9 cm per step) as quickly and safely as possible. Patients were permitted the use of a single handrail, if necessary. The 6MW test required patients to walk as safely and as fast as they could around a designated pathway (157.3 m) for 6 minutes. The total distance traveled was then recorded and used in the analyses. The TUG test required patients to rise from a seated position in a chair (46 cm in height, with armrests and back support), to walk to a line on the ground 3 m away, and to return and sit in the chair, as fast as possible. For the SCT and the TUG test, subjects completed 2 trials. The average time from the 2 trials was used in the analyses. These tests were chosen because they are well-established functional performance measures for patients after TKA.

**Data Analyses**

Interrater reliability and the accuracy of using a stopwatch to record the time needed to complete the SST were assessed with an initial sample of 6 subjects who underwent bilateral TKA. Their data were examined prior to implementation of the measure in the clinical trial and separately from the secondary analysis of the data from the 146 participants who comprised the main group of this report.

Interrater reliability of the SST was examined by calculating the intraclass correlation coefficient (ICC) for data from 2 clinicians who simultaneously timed the 6 patients who performed the test. The accuracy of the raters’ use of the stopwatches was evaluated by comparing a clinician’s manually recorded times to those recorded by a 47 × 60-cm switch mat (model 14H; Recora Inc, Batavia, IL), a pressure-sensitive device connected to an analog-to-digital board, with custom-written software to record performance time based on contact with the ground of the non-weight-bearing limb. These data were also assessed using ICC.

Pearson correlation coefficients were calculated to determine the relationship between performance on the SST and performance on standard functional measures (TUG, SCT, and 6MW). Correlations were defined as being moderate if between 0.3 and 0.5 and large if greater than 0.5. Because the patients studied had unilateral OA and the chosen tests of function were standard for evaluating this population, correlations between the SST and these clinic-based performance measures were appropriate for validating this unilateral test. A large correlation with these measures was therefore used to represent convergent validity (r > 0.5).

Responsiveness of the SST to identify change in the patients’ unilateral limb ability was assessed by evaluating the change in SST from IE through 3 months, as this was the period in which the greatest change in function was expected and between IE and 1 year. Due to missing data for some subjects at different time points, separate linear mixed models were performed for each variable (SCT, TUG, 6MW, and SST) to precisely estimate the means and standard deviations for the given sample, had it been a complete data set. Mixed-model regression analyses were performed, with time as a fixed effect. A type 3 sum-of-squares assumption was used to account for missing data, and the maximal likelihood estimations were calculated through 1000 iterations. The issue of baseline variability of the IE measures was accounted for in the regression model by the inclusion of an intercept term. The effect-size indexes (ESIs) were calculated by dividing the estimated marginal means obtained from a linear mixed model by the standard deviations from the IE assessment.

To maintain sample-size equivalence across observations, data from 102 patients (of the 146 enrolled in the study) who completed testing at all 3 time points were used for the final analysis. A 3-by-2 repeated-measures analysis of variance (3 levels for the factor time, 2 levels for the factor limb) was performed for the SST measures to investigate changes over time and between limbs from the initial physical therapy assessment 1 month after surgery through 3 months after and 1 year after TKA. In the presence of a main effect, paired t tests were performed to identify differences between limbs and changes over time. The significance levels were initially set at .05. Bonferroni corrections were applied for the 7 within-limb and between-limb comparisons over time (2 for each limb over time and 3 between limbs), changing significance to α = .007.

Finally, independent t tests were used to compare the SST performance times at each of the 3 time points (IE, 3 months, and 1 year) for the surgical limbs of patients to the limbs of control subjects. The Levene test for equality of variances was conducted and, when significant, P values for equal variances not assumed were reported. The Bonferroni-adjusted significance level was adjusted for 6 comparisons (each limb at each time point), changing the significance level to α = .008.

**RESULTS**

**Subjects**

The reliability group contained 6 subjects (mean ± SD age, 68.8 ± 5.9 years; 1 woman). The data for the unilateral TKA group were from participants in a randomized clinical trial of 189 subjects with TKA; however, only 146 of these were assessed with the SST, as this test was added after the start of the trial (mean ± SD age, 64.9 ± 8.6 years; 77 women; time from surgery to IE, 27.7 ± 3.8 days). There were no differences between the 2 groups examined in the clinical trial (those who received neuromuscular electrical stimulation and those...
who did not) for any of the primary or secondary outcomes, including SST performance (independent-samples t tests comparing limbs of training groups at each time point) \( (P = .281) \); therefore, for this analysis, the groups were combined. One subject’s performance at IE (182.2 seconds) was more than 13 standard deviations from the mean \( \text{mean} \pm \text{SD} = 33.5 \pm 11.5 \) seconds and was, therefore, deemed an outlier and removed from further analysis.

The control group contained 61 individuals without knee OA \( \text{mean} \pm \text{SD} = 63.0 \pm 8.5 \) years; 35 women, in whom the same proportion of right and left limbs \( (56\% \text{ right}, n = 34) \) as that in the TKA group were examined.

Reliability and Validity of the SST
The intertester reliability \( \text{ICC}_{2,1} \) for our clinic, when 2 examiners assessed performance in the SST, was 0.999. The \( \text{ICC}_{2,1} \) for the accuracy of measurement of the SST between the manually recorded times and those from the switch mat was 0.999 and 0.996 for the 2 testers, respectively.

Convergent validity between the SST and the clinic-based performance tests in patients after unilateral TKA was demonstrated by the magnitude of the correlations between SST performance and performance on the SCT, TUG test, and 6MW test at each time point \( (\text{IE}, 3 \text{ months, and 1 year}) \) for the surgical limb, and by correlations between change scores for these measures (TABLE 1).

Responsiveness
The ability of the SST to measure change over time in patients after unilateral TKA was demonstrated by the effect sizes of 0.90 for the interval of IE to 3 months and 1.10 for the interval of IE to 1 year. When comparing the confidence intervals of the ESIs for the SCT \( (1.07) \), TUG test \( (-1.08) \), and 6MW test \( (-1.27) \), none of the confidence intervals included zero, and all ESIs indicated improvements in performance over time for both the intervals of IE to 3 months and IE to 1 year, suggesting that the responsiveness between the SST, SCT, TUG test, and 6MW test (absolute values were used due to the direction of change) was not different (FIGURE 2).^2

Performance of SST After TKA
The repeated-measures analysis of variance for the SST revealed a significant

### TABLE 1

<table>
<thead>
<tr>
<th>Test</th>
<th>IE</th>
<th>3 mo</th>
<th>1 y</th>
<th>Change From IE to 3 mo</th>
<th>Change From IE to 1 y</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCT</td>
<td>0.63 (0.52, 0.72); 135</td>
<td>0.68 (0.59, 0.76); 143</td>
<td>0.71 (0.61, 0.79); 123</td>
<td>0.50 (0.36, 0.62); 125</td>
<td>0.45 (0.29, 0.59); 108</td>
</tr>
<tr>
<td>TUG</td>
<td>0.61 (0.50, 0.71); 135</td>
<td>0.58 (0.46, 0.68); 143</td>
<td>0.72 (0.62, 0.80); 123</td>
<td>0.45 (0.30, 0.58); 125</td>
<td>0.49 (0.33, 0.61); 108</td>
</tr>
<tr>
<td>6MW</td>
<td>-0.62 (-0.72, -0.51); 129</td>
<td>-0.58 (-0.68, -0.46); 139</td>
<td>-0.66 (-0.75, -0.54); 117</td>
<td>-0.46 (-0.31, -0.59); 120</td>
<td>-0.47 (-0.30, -0.61); 98</td>
</tr>
</tbody>
</table>

*Values are intraclass correlation coefficient (95% confidence interval); n. All correlation coefficients, including correlations between change scores, were significant \( (P < .001) \), except those of the 6MW (change from IE to 3 mo, \( P = .01 \); change from IE to 1 y, \( P > .05 \)).

FIGURE 2. Effect-size index for changes from IE to 3 months after surgery and to 1 year after surgery, with 95% confidence intervals, for the SST, SCT, TUG, and 6MW. The effect size for the 6MW was negative; for comparison among measures, the absolute effect size is presented. Abbreviations: 6MW, 6-minute walk; IE, initial postoperative physical therapy evaluation; SCT, stair-climbing test; SST, single-step test; TUG, timed up-and-go.

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JOURNAL OF ORTHOPAEDIC & SPORTS PHYSICAL THERAPY | VOLUME 43 | NUMBER 2 | FEBRUARY 2013 | 69
interaction effect \( F = 49.8, df = 1.25, P < .001 \). SST times were significantly longer for the surgical limb compared to the nonsurgical limb at IE (mean difference, 5.2 seconds; \( t = 7.2, df = 101, P < .001 \)), as well as at 3 months (mean difference, 1.1 seconds; \( t = 3.0, df = 101, P < .004 \)). There were no differences between limbs at 1 year (mean difference, –0.1 seconds; \( t = –0.6, df = 101, P = .575 \)).

**Surgical Limb Over Time**

Pairwise comparisons of the surgical limb over time confirmed that SST performance times at IE were statistically longer (mean ± SD, 33.5 ± 11.5 seconds) than those at 3 months (21.8 ± 6.1 seconds; mean change, 11.7 seconds; \( t = 13.5, df = 101, P < .001 \)). Performance times of the SST with the surgical limb at 3 months were also significantly longer than performance times at 1 year (20.0 ± 4.9 seconds; mean change, 1.8 seconds; \( t = 6.2, df = 101, P < .001 \)) (FIGURE 3).

**Nonsurgical Limb Over Time**

SST performance times for the nonsurgical limb at IE (mean ± SD, 28.3 ± 9.6 seconds) were longer compared to 3 months (20.7 ± 6.0 seconds; mean change, 7.7 seconds; \( t = 11.2, df = 101, P < .001 \)). The performance times at 3 months were not significantly different from those at 1 year (mean ± SD, 20.1 ± 5.7 seconds; mean change, 0.6 seconds; \( t = 1.6, df = 101, P = .123 \)) (FIGURE 3).

**Comparisons to Controls**

SST performance times of the surgical limbs of patients who underwent unilateral TKA were significantly prolonged compared to those of the matched limbs of healthy control subjects (mean ± SD, 19.7 ± 5.4 seconds) at IE (mean difference, 13.6 seconds; \( t = 10.1, df = 182.3, P < .001 \)) and at 3 months (mean difference, 3.0 seconds; \( t = 2.8, df = 124.1, P = .007 \)), when equal variances were not assumed (TABLE 2). However, there was no significant difference between groups at 1 year (mean difference, 0.6 seconds; \( t = 0.6, df = 102.0, P = .513 \)). Similarly, SST performance times of the nonsurgical limb were significantly different from those of the matched limb of the control group at IE (mean difference, 9.8 seconds; \( t = 8.6, df = 197.5, P < .001 \)) and at 3 months (mean difference, 2.3 seconds; \( t = 2.6, df = 146.7, P = .012 \)) but not significantly different at 1 year (mean difference, 1.4 seconds; \( t = 1.5, df = 182, P = .140 \)).

**DISCUSSION**

The SST allows for assessment of unilateral limb ability without the potential for contralateral knee OA to influence performance. Similar to other validated measures of unilateral lower extremity performance in younger individuals (eg, hop test), this test is a reliable and valid measure when compared with standard clinic-based performance measures used to assess patients with unilateral OA, and is responsive to change in patients who receive postoperative outpatient physical therapy after unilateral TKA. Furthermore, it is relatively easy for clinicians to implement. Finally, performance of the SST successfully distinguished the surgical from the nonsurgical limbs of patients at an initial physical therapy evaluation and at 3 months after unilateral TKA. Similarly, performance of the SST distinguished the surgical and nonsurgical limbs of patients from the limbs of healthy controls at the initial physical therapy evaluation. These findings support our hypothesis that the SST can be used to differentiate between the limbs of patients after unilateral TKA, and between the surgically operated and nonsurgical limbs of patients who underwent unilateral total knee arthroplasty.
The SST as an Impairment-Based Test

Our hypothesis that the SST is a valid impairment-based measure of lower extremity ability was supported, as patient performance of the SST correlated with that of standard clinic-based performance measures (SCT, 6MW test, TUG test) at each time point. Findings from previous work suggest that the SCT, TUG test, and 6MW test be good measures for evaluating and detecting changes in functional ability over time. Furthermore, the changes in SST performance were similar to the changes in other performance measures over the first year after TKA, which also supports our hypothesis. The SST was responsive to change in patients after TKA who participated in postsurgical, outpatient physical therapy. There was large overlap in the ESI 95% confidence intervals for the SST and both the SCT and TUG test. However, there was small overlap between ESI for the SST and the 6MW test, suggesting that the 6MW test may be a more responsive measure in our patients. The responsiveness estimates for the SST and the clinic-based performance measures (SCT, TUG test, and 6MW test) were large (greater than 0.8), suggesting that all of these tests provide clinicians with a good metric for quantifying lower extremity activity limitations.

Consider the potential risks associated with negotiating stairs, as well as the difficulty of standardizing stair tests (eg, due to the varying number of steps and step heights among stairways), the SST may be an appropriate alternative to the SCT for assessing activity-limited patients. The SST may also be used for testing patients who are not comfortable or capable of ascending and descending stairs at a rapid pace or by clinics that do not have a flight of stairs for testing stair-climbing ability. The utility of stepping tests has been demonstrated when evaluating the quality of movement and for assessing the influence of pain in other populations, suggesting that a stepping task could also serve as a good tool to evaluate activity limitations in patients with knee OA and after TKA. More importantly, the SST should be considered as a good complement to the standard clinic-based performance tests, as it provides unique insight into the ability of each limb independently, especially in patients with contralateral, symptomatic knee OA.

Changes in the SST Over Time

The substantial improvements in SST performance from IE to 3 months were not surprising, as this was the period in which the rehabilitation protocol was completed and performance plateaus have previously been observed. However, at 3 months and at 1 year, the SST performance times for either limb of the TKA group were not significantly different from those of healthy controls. The finding of similar levels between patients after TKA and controls is surprising, as this was the period in which the rehabilitation protocol was completed and performance plateaus have previously been observed. However, at 3 months and at 1 year, the SST performance times for either limb of the TKA group were not significantly different from those of healthy controls.

Regarding the potential risks associated with negotiating stairs, as well as the difficulty of standardizing stair tests (eg, due to the varying number of steps and step heights among stairways), the SST may be an appropriate alternative to the SCT for assessing activity-limited patients. The SST may also be used for testing patients who are not comfortable or capable of ascending and descending stairs at a rapid pace or by clinics that do not have a flight of stairs for testing stair-climbing ability. The utility of stepping tests has been demonstrated when evaluating the quality of movement and for assessing the influence of pain in other populations, suggesting that a stepping task could also serve as a good tool to evaluate activity limitations in patients with knee OA and after TKA. More importantly, the SST should be considered as a good complement to the standard clinic-based performance tests, as it provides unique insight into the ability of each limb independently, especially in patients with contralateral, symptomatic knee OA.

### TABLE 2

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<td>33.9 ± 11.8 (P&lt;0.001; 135</td>
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<td>20.9 ± 5.7 (P = .540; 123</td>
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<tr>
<td>SST nonsurgical limb</td>
<td>29.5 ± 10.9 (P&lt;0.001; 142</td>
<td>22.0 ± 7.0 (P = .012; 144</td>
<td>21.1 ± 6.3 (P = 120; 123</td>
<td>197 ± 5.4; 61</td>
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</tbody>
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Abbreviations: IE, initial outpatient physical therapy evaluation; SST, single-step test.

*Values are mean ± SD seconds (P); n. P values are reported for equal variances not assumed, and indicate difference from the respective control group.
†Values are mean ± SD seconds; n.

The SST as a tool to evaluate activity limitations in patients after TKA, we

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**TABLE 2**

**SST Performance Times in Patients Who Underwent Unilateral Total Knee Arthroplasty and Those in the Matching Limbs of Control Subjects**

<table>
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*Values are mean ± SD seconds (P); n. P values are reported for equal variances not assumed, and indicate difference from the respective control group.
†Values are mean ± SD seconds; n.
applied a rule of thumb to estimate the minimal clinically important difference, based on half the standard deviation of the measure at IE (5.7 seconds), which is a distribution-based approach recommended by Norman et al. Based on this estimate, 70.7% of our patients would have been deemed as having shown improvement in their performance of the SST using the surgical limb from IE to 1 year. This finding is similar to the 72.7% of patients who reported being moderately or very satisfied after TKA. These patients would also have been deemed to show improvements in their performance of the SST (6.4 seconds, 82.0%), the TUG test (1.84 seconds, 81.0%), and the 6MW test (79.6 m, 82.0%).

**Study Limitations**

The strength of this study is the introduction of the SST as a reliably acquired and valid test of unilateral lower extremity ability in patients after TKA. However, the SST is not being recommended as a replacement for standard clinic-based performance measures, but as a complementary measure that will provide insights into how each limb may contribute to changes in ability over time.

Additionally, SST performance in the nonsurgical limb was slower than that of the controls, which may be interpreted as a limitation of the value of the measure. However, as with many individuals with knee OA and those who undergo TKA, there is a nonrandom progression of disease in the contralateral leg, such that disease may be present and not symptomatic in the contralateral knee and/or hip. Additionally, physical activity levels decline in patients with knee OA in response to a passive coping strategy, which, in turn, may lead to functional impairments. Therefore, it should not be surprising that SST performance of the nonsurgical limb in patients with knee OA after TKA is slower than that of the limbs of healthy controls. In fact, the added utility of the SST is that the impact of TKA and rehabilitation on each limb can be assessed independently.

**CONCLUSION**

**TKA procedures are being performed more regularly, and the prevalence of such procedures is expected to increase substantially over the next few decades.** With an increasing focus on maximizing functional abilities following TKA, clinicians need to have tests that can objectively assess and quantify activity limitations and abilities, and that can track progress through the course of the rehabilitation process. A challenge that clinicians face is to find measures that are adequate for use in the clinic and sensitive enough to detect changes in lower extremity abilities, and can assess each limb independently. The SST is a simple and inexpensive way for clinicians to evaluate activity limitation of each limb independently. The SST should, however, be utilized in combination with other bilateral tests of lower extremity function, clinical tests (eg, strength and range of motion), and instruments of self-perceived functional ability to provide clinicians with a truly comprehensive assessment of change over the course of disease or recovery from surgical interventions.

**KEY POINTS**

**FINDINGS:** This work demonstrated that the SST can be used to assess unilateral activity impairments in patients after TKA.

**IMPLICATIONS:** The SST is a low-cost, safe test that can be easily implemented in clinical practice to evaluate individuals after TKA.

**CAUTION:** The SST is not designed to replace, but to complement, the existing battery of clinic-based, lower extremity performance measures.

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