



# Validation of Devices for the Five Times Sit To Stand Test: Comparing Plantar Pressure and Head Motion Analysis with Manual Measurement

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**Purpose:** This study aims to evaluate a new method for the five times sit to stand test (FTSST), crucial for addressing frailty in an aging population. It utilizes a smart insole for plantar pressure analysis and a marker-less motion capture device for head height analysis.

**Materials and Methods:** Thirty-five participants aged 50 years or older underwent FTSST assessment using three methods: manual measurement with a stopwatch (FTSST-M), plantar pressure analysis with smart insoles (FTSST-P), and head height analysis with a marker-less motion capture device (FTSST-H). Simultaneous measurements using three methods were done. Correlation between results of these methods were analyzed using intraclass correlation coefficient (ICC) and  $\kappa$  coefficient. Comprehensive clinical examinations were conducted with ethical approval.

**Results:** Participants' mean scores for FTSST-M, FTSST-P, and FTSST-H were  $2.43 \pm 1.20$ ,  $2.43 \pm 1.29$ , and  $2.37 \pm 1.31$ , respectively. Correlations of the times and corresponding scores between FTSST-P and FTSST-M, as well as FTSST-H and FTSST-M, exceeded 0.9 (ICC and  $\kappa$  coefficients,  $p < 0.001$ ). Using an FTSST score of 3 or less to indicate vulnerability, the  $\kappa$  value for vulnerability classification between two measurements was 0.886 ( $p < 0.001$ ).

**Conclusion:** This study showed strong correlation between FTSST results using smart insoles and marker-less motion capture, compared to conventional methods. These findings highlight the potential of these technologies for precise FTSST measurements, offering convenience and cost-effectiveness. Simultaneous use of these devices enables diverse analyses, enhancing our understanding of frailty.

**Key Words:** Aged, foot orthoses, frailty, motion capture, physical functional performance

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## INTRODUCTION

With the global population aging, there is a growing emphasis on comprehending and addressing frailty, a subject that has garnered significant scientific attention in recent decades. Frailty is characterized by increased vulnerability, reduced physiological reserve, and a diminished capacity to withstand stressors resulting from accumulated age-related deficits.<sup>1</sup> This condition is associated with various adverse health outcomes, including disability, falls, hospitalization, and mortality.<sup>2,3</sup> An estimated 25%–50% of individuals over 85 years of age are frail, with the prevalence increasing with age.<sup>4</sup> Therefore, early identification

and management of frailty in community-dwelling older adults are crucial.

A prominent indicator used to assess frailty is the five times sit to stand test (FTSST), a simple test involving transitioning from a seated to a standing position.<sup>5,6</sup> The FTSST offers a practical method for measuring frailty in diverse settings, including hospitals, clinics, and homes. Recent researches highlight the FTSST as an independent predictor of muscle strength in the lower extremities,<sup>7</sup> muscle performance,<sup>8</sup> functional fitness,<sup>9</sup> and aerobic endurance.<sup>10</sup> The conventional method of measuring FTSST using a stopwatch is widely utilized, well-validated, and reliable, offering advantages such as simplicity, speed, cost-effectiveness, and reproducibility. However, it requires an additional rater and may introduce interpersonal errors based on the rater's experience.<sup>11</sup>

Recently, new devices for measuring the FTSST, with several advantages, have been developed.<sup>12-14</sup> Furthermore, a novel method has been developed to measure the short physical performance battery, including the FTSST.<sup>11</sup> This device utilizes a load cell array, which is composed of 16 load cells and measures the weights applied on them, to detect the two-dimensional location of each foot and incorporates a LiDAR, which is a one-dimensional light detection and ranging sensor, to determine the distance between the sensor and participants. However, despite this, current FTSST devices face several drawbacks that complicate their use, such as inconsistent sensor positioning, high sensor costs, spatial issues, etc., limiting their scalability. Therefore, there is a pressing need for more comfortable, convenient, and user-friendly techniques for measuring long-term frailty in everyday life.

Smart insoles, capable of real-time plantar pressure detection during daily activities, have shown promise for medical applications.<sup>15</sup> Studies report high accuracies in gait and postural analysis, expanding the use of a smart insole.<sup>15</sup> Given their ease of use and portability, they could serve as viable alternatives to conventional and recently introduced FTSST measurement methods. Meanwhile, a marker-less motion capture device also has been widely used in clinical measurement using motion detection technology and has previously been validated for its accuracy.<sup>16,17</sup> Considering that no special preparation for testing is required, this could be anticipated as another method of measurement for the FTSST.

Therefore, our study aimed to assess a new measurement approach for the FTSST by employing smart insoles for plantar pressure analysis and comparing it with manual measurements obtained using a stopwatch. Additionally, we aimed to evaluate the accuracy of a marker-less motion capture device, previously validated, as an assessment tool for the FTSST. Through this investigation, we sought to confirm the viability of utilizing both of these novel FTSST measurement methods for assessing frailty.

## MATERIALS AND METHODS

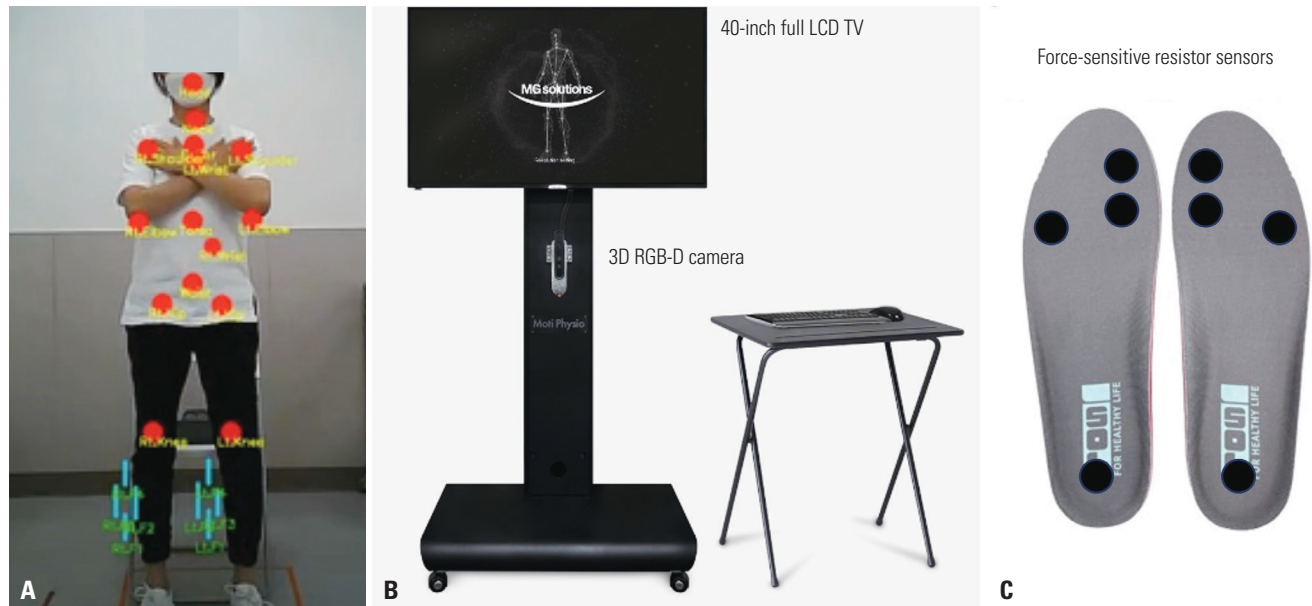
### Study participants

This study prospectively included 35 participants who underwent a comprehensive clinical examination before enrollment to ensure compliance with specific inclusion criteria, which were as follows: 1) age of 50 years or older; 2) capability of walking independently, with or without a gait aid; 3) ability to sit down and stand up; and 4) sufficient cognitive function to perform the required tests as per medical instructions. The exclusion criteria were as follows: 1) inability to walk, sit, or stand up; 2) acute medical or surgical conditions; 3) terminal illness with a life expectancy of less than 6 months; and 4) cognitive impairments preventing the completion of consent forms or adherence to medical staff instructions.

Before beginning the test, we conducted three assessments to gauge participants' basic functional abilities. We used the functional ambulatory category (FAC) to assess walking ability, ranging from 0 (non-functional ambulator) to 5 (independent ambulator).<sup>18</sup> To evaluate the fall risk, we employed the Berg Balance Scale (BBS), a 14-item scale observing balance in older adults.<sup>19</sup> Frailty status was determined using the Korean version of the Frailty, Resistance, Ambulation, Illness, and Loss of weight scale (K-FRAIL), a validated tool requiring only 2-3 minutes to administer with no specialized equipment.<sup>20</sup> Participants indicating 1-2 positive items were classified as prefrail, while 3-5 positive items categorized them as frail.

### Study protocol

In this prospective study, three devices were simultaneously applied for the FTSST (Fig. 1A). Initially, manual FTSST measurements were conducted using a stopwatch (FTSST-M). Secondly, a marker-less motion capture device (Moti Physio, MG Solutions, Seoul, Republic of Korea) embedding three-dimensional red-green-blue-depth camera (Astra Pro, Orbbec 3D Technology International, Inc., Troy, MI, USA) was employed for head height detection (FTSST-H) (Fig. 1B). The marker-less motion capture device operates on the principle of continuously projecting a pattern video and capturing the image of the scene using structured light, enabling the estimation of 3D positions of each joint point based on the input from the camera.<sup>21</sup> This equipment provides the x, y, and z coordinates for a total of 19 joint points, and we specifically used the phase change of the head point to identify variations in head height. Thirdly, for plantar pressure analysis, we utilized a commercially available smart insole (I-SOL, Gilon, Seongnam, Republic of Korea), as illustrated in Fig. 1C (FTSST-P). This smart insole featured varying thicknesses of 6 mm at the front, 10.5 mm in the middle, and 10 mm at the back, with a total weight of 60 g. Each insole was equipped with four circular force-sensitive resistor (FSR) sensors, each 14 mm in diameter, precisely detecting the changes in force at four key points: the hallux, medial forefoot, lateral forefoot, and heel. Data were recorded at a frequency



**Fig. 1.** Example of the test procedure and devices used in this study. (A) A photo capturing the patient during assessment of the five times sit to stand test. Red dots indicate joint points recognized in real time by the marker-less motion-detecting device, whereas blue graph depicts plantar pressure measured by the smart insole. (B) The marker-less motion-detecting device embedding a three-dimensional red-green-blue-depth (3D RGB-D) camera. (C) A commercially available smart insole featuring four force-sensitive resistor sensors placed on the hallux, medial forefoot, lateral forefoot, and heel.

of 40 Hz using a Raspberry Pi 3 system. The insole was available in a range of sizes, with 5-mm increments, from 230 mm to 280 mm, enabling participants to choose the size that best suited their feet.

We synchronized the smart insole and the marker-less motion capture device to enable simultaneous measurements. Prior to initiating the study, the examiner, who had 5 years of experience in conducting standardized FTSST assessments, underwent specific training to administer simultaneous FTSST. Participants performed the FTSST according to the standardized protocol in front of a marker-less motion capture device while wearing smart insoles.<sup>6</sup> To conduct the test, a straight-backed armless chair measuring 43 cm in height and 47.5 cm in depth with a firm seat was employed. Participants were instructed to stand up and sit down five times, as quickly as possible, with their arms crossed over their chests. The examiner guided participants to stand fully between repetitions and refrained from touching the back of the chair during each cycle. The test began with the verbal cue, “Three, two, one, go,” and concluded upon the successful completion of the fifth stand. The time taken to complete the task was recorded and subsequently converted into the participant’s score on established cutoff points, as described in a previous study:  $\leq 11.1$  seconds for a score of 4, 11.2–13.6 seconds for a score of 3, 13.7–16.6 seconds for a score of 2, and  $\geq 16.7$  seconds for a score of 1.6

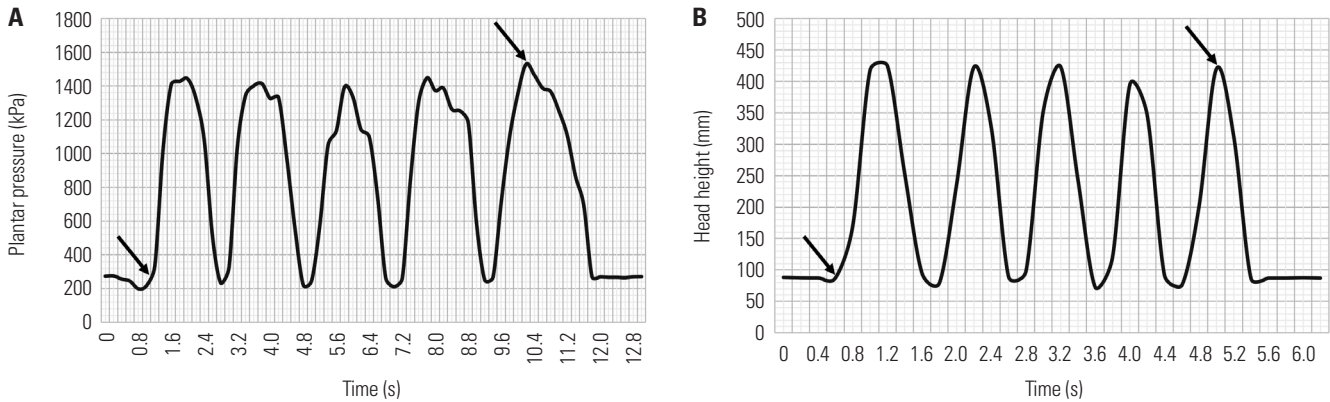
### Interpretation of time-based graphs of plantar pressure and head height

The plantar pressure data obtained from the four FSR sensors were converted into kilopascal units using the equations speci-

fied in a previous study.<sup>22</sup> We calculated the total plantar pressure for both feet by summing all pressure values. Subsequently, the changes in pressure over time for both feet were transformed into a time-pressure graph. Additionally, the phase changes in head height were depicted in a time-height graph. Two independent interpreters, blinded to the demographic and clinical parameters of the participants, scrutinized the graphs of each participant. They determined the start and end points of the test based on shifts in the graph patterns. The start and end of the graph changes were identified as the first vertical increase and last decrease above an empirically established threshold, referencing changes observed in the test videos and the graphs from five previous trials (Fig. 2).<sup>23</sup> In instances where identifying these points posed challenges, the interpreters engaged in discussions and arrived at a mutual agreement. To facilitate interpretation, 200-ms vertical grids were introduced in the graphs to pinpoint specific time intervals.

### Statistical analysis

Descriptive data were expressed as frequencies or percentages and mean  $\pm$  standard deviation. Inter-interpreter and intra-interpreter reliability between the interpreted times and corresponding scores for FTSST-P and FTSST-H were established using the Pearson correlation coefficient and  $\kappa$  coefficient, respectively. This evaluation was based on time-pressure and time-height graphs. The correlation of the times and scores between two measurement methods (FTSST-M and FTSST-P, FTSST-M and FTSST-H) were established using the intraclass correlation coefficient and  $\kappa$  coefficient, respectively. In the case of the kappa coefficient being 0.81 or higher, it was judged as



**Fig. 2.** Examples of (A) time-pressure and (B) time-height graphs for the five times sit to stand test. Arrow indicates the start and end points of the test.

very good agreement. Bland–Altman plots were used to visually represent the observed differences between the FTSST-P and FTSST-H times recorded by the two interpreters and the times of the FTSST-M. We hypothesized good validity if the difference was within 2.5 s, a value previously reported as the minimal detectable change for the FTSST.<sup>24</sup> The Shapiro-Wilk test was employed to assess the normal distribution of the results obtained from the FTSST. The analysis was conducted using the R statistical package version 4.1.2 (R Foundation for Statistical Computing, Vienna, Austria). All tests were two-sided, and statistical significance was set at a *p*-value<0.05.

**Ethical considerations**

This study was approved by the Institutional Review Board of Gangnam Severance Hospital (IRB no. 3-2022-0440) and performed in accordance with the pertinent guidelines of the Declaration of Helsinki. All participants provided written informed consent for all examinations.

**RESULTS**

This study comprised 35 participants (22 women and 13 men), with a mean age of 72.89±9.52 years, mean height of 159.46±9.09 cm, and mean weight of 60.00±9.70 kg (Table 1). All participants were generally healthy adults without any restrictions on their ability to undergo assessments. The participants exhibited a mean FAC score of 4.17±1.04, mean BBS score of 45.51±9.07, and mean K-FRAIL score of 1.63±1.11, which indicated that participants are averagely non-frail and independent ambulators. No adverse events related to the tests, such as falls or pain, were reported. The mean scores for FTSST-M, FTSST-P, and FTSST-H were 2.43±1.20, 2.43±1.29, and 2.37±1.31, respectively (Table 2).

Fig. 2 provides examples of time-based graphs illustrating plantar pressure and head height in the FTSST. Both intra-interpreter and inter-interpreter reliability regarding the times after interpreting time-pressure and time-height graphs were confirmed to be above Pearson correlation coefficients of 0.9, with

**Table 1.** Characteristics of Study Participants (n=35)

Characteristics	Value
Sex, men	13 (37.14)
Age (yr)	72.89±9.52
55–64	8 (22.86)
65–74	9 (25.71)
75–84	18 (51.43)
Height (cm)	159.46±9.09
Weight (kg)	60.00±9.70
BMI (kg/m <sup>2</sup> )	23.49±2.46
FAC score	4.17±1.04
BBS score	45.51±9.07
K-FRAIL score	1.63±1.11

BBS, Berg Balance Scale; BMI, body mass index; FAC, functional ambulatory category; K-FRAIL, Korean version of the Fatigue, Resistance, Ambulation, Illness, and Loss of Weight scale.

Data are presented as mean±standard deviation or n (%).

**Table 2.** Results of the FTSST Using Three Measurement Methods

FTSST	Value
Time, s	
FTSST-M	16.87±8.94
FTSST-P	16.78±9.57
FTSST-H	17.08±9.27
Score, points	
FTSST-M	2.43±1.20
FTSST-P	2.43±1.29
FTSST-H	2.37±1.31
Score >3	
FTSST-M	17 (48.57)
FTSST-P	17 (48.57)
FTSST-H	16 (45.71)

FTSST-M, five times sit to stand test using a manual method; FTSST-P, five times sit to stand test using plantar pressure detection; FTSST-H, five times sit to stand test using head height detection.

Data are presented as mean±standard deviation or n (%).

all *p*-values less than 0.001, indicating significant findings (Table 3). Also, intra-interpreter and inter-interpreter reliability regarding the scores, derived from the time recordings, exhibit

ed outstanding reliability, with  $\kappa$  coefficients of 0.9 or higher. Bland-Altman concordance analysis revealed a relatively minimal spread in the FTSST-P and H times, as inferred from the graphical interpretation, compared to the FTSST-M times (Fig. 3). All mean differences between the two measurements demonstrated strong agreement, with the mean difference staying within 2.5.

Table 4 provides the results of the analysis on the correlation between the times and scores obtained through FTSST-P, FTSST-H, and FTSST-M. The correlation between the times and scores of FTSST-P and FTSST-M, as confirmed by ICCs and  $\kappa$  coefficients, exceeded 0.9 each, with a  $p$ -value of less than 0.001. Similarly, the correlation between the times and scores of FTSST-H and FTSST-M also exceeded 0.9, with a  $p$ -value of less than 0.001.

Considering an FTSST score of 3 or less as a vulnerable state, 17 (48.57%), 17 (48.57%), and 16 (45.71%) individuals were classified as vulnerable by FTSST-M, FTSST-P, and FTSST-H, respectively (Table 2). The  $\kappa$  value for classifying vulnerability between two measurements was 0.886 ( $p < 0.001$ ).

**Table 3.** Intra- and Inter-Interpreter Reliability of the FTSST Measured through Time-Pressure and Time-Height Graph Interpretation

	Intra-interpreter reliability	Inter-interpreter reliability
FTSST times		
Plantar pressure detection	0.99 (<0.001)	0.98 (<0.001)
Head height detection	0.99 (<0.001)	0.98 (<0.001)
FTSST scores		
Plantar pressure detection	0.97 (<0.001)	0.95 (<0.001)
Head height detection	0.98 (<0.001)	0.98 (<0.001)

FTSST, five times sit to stand test.

Time values were tested using the Pearson's correlation coefficient, and score values were tested using the  $\kappa$  correlation coefficient.

## DISCUSSION

In this study, we assessed and compared the precision of a commercially available smart insole with plantar pressure measurement capabilities and a marker-less motion capture device in performing the FTSST, against the conventional manual method using a stopwatch. Our findings revealed a high correlation between the FTSST results obtained through the smart insole (FTSST-P) and the motion capture device (FTSST-H) and those from the manual approach (FTSST-M), both in terms of time and score measurements. Furthermore, strong correlations were observed between the interpretations made by two independent interpreters, as well as within each evaluator, when analyzing both the time-pressure and time-height graphs. These results underscore the efficacy of both the smart insole and the motion capture device in accurately measuring the FTSST, thereby emphasizing their utility as reliable tools for FTSST assessment, and highlighting their potential for scalability.

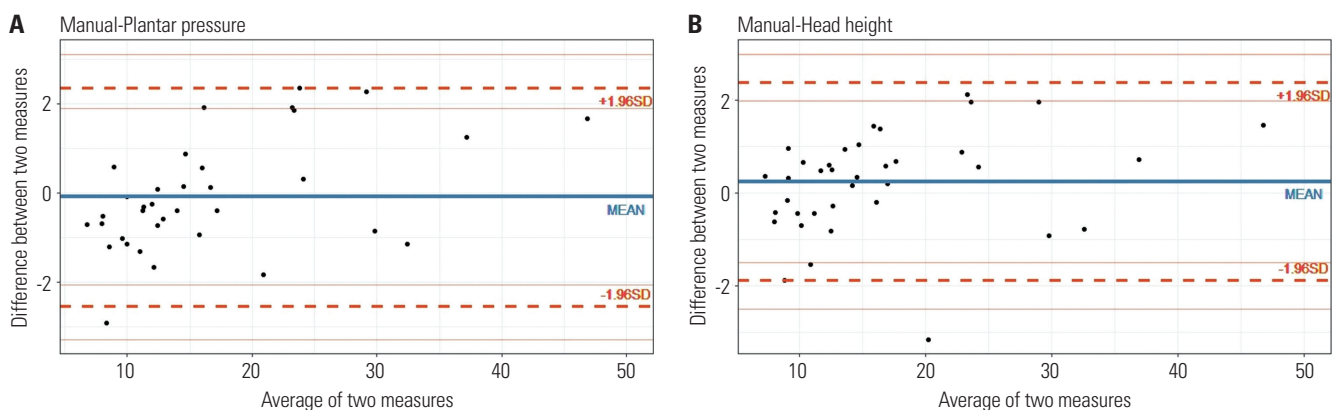
Previous studies have proposed various measurement methods for FTSST, utilizing digital equipment, such as inertial sensors integrated into belts, glasses, and pendants,<sup>13,14,25</sup> and approaches combining pressure sensors with LiDAR sensors.<sup>11</sup> The primary objective of these methods is to minimize human error. However, these devices often overlook specific characteristics of FTSST, such as quick testing time, lack of spatial constraints, and the importance of cost-effectiveness.<sup>26</sup> Devices

**Table 4.** Correlation Assessments among the Results of the FTSST Using a Manual Method, Plantar Pressure Detection, and Head Height Detection

	Manual-Plantar pressure	Manual-Head height
FTSST times	0.99 (<0.001)	0.99 (<0.001)
FTSST scores	0.93 (<0.001)	0.94 (<0.001)

FTSST, five times sit to stand test.

Time values were tested using the intraclass correlation coefficient, and score values were tested using the  $\kappa$  correlation coefficient. Both values compared the results of a manual method with the average of the results through two tests: plantar pressure and head height detection.



**Fig. 3.** Bland-Altman plots. (A) Time difference between the manual method and plantar pressure detection and (B) difference between the manual method and head height detection. Solid horizontal line represents the mean difference, and dotted lines represent the 95% limits of agreement between the two measurements.

embedding inertial sensors in belts, glasses, and pendant necessitate repetitive re-wearing for FTSST assessment, introducing the inconvenience of precise sensor positioning and calibration with each wear, resulting in additional time consumption. Belts positioned at the L3 and L5 lumbar vertebral bodies may pose a risk of displacement during sit-to-stand movements, and glasses and pendants have similar limitations.<sup>13,14,25</sup> This may cause discomfort, particularly for individuals who are unaccustomed to wearing such items, thereby incurring additional costs. Combining pressure sensors with LiDAR sensors requires installation in a predetermined location, demanding a secured space in hospitals or research facilities, along with additional personnel and equipment costs for FTSST measurements. Compared with the conventional stopwatch method, these factors present limitations in terms of convenience, cost, and feasibility for continuous examinations in community-dwelling older adults.

Our study introduces a smart insole as a potential solution to these limitations, offering tailored sizing and seamless insertion into the shoe after removal of the existing insoles.<sup>27</sup> This obviates the need for frequent repositioning during each use, occupies no additional space beyond the confines of the shoe, and facilitates continuous data collection in everyday life. Furthermore, these insoles are readily available, economically viable, and have proven accuracy and user-friendly features, contributing to their growing utilization in various medical fields for both treatment and diagnosis.<sup>15,28,29</sup> Meanwhile, marker-less motion capture devices require no equipment for the subject to wear, and there is no special preparation required other than the subject standing in front of the camera, overcoming the limitations of existing methods. Thus, our study serves as foundational research to broaden the application scope of smart insoles and marker-less motion capture devices.

Especially, the simultaneous measurement of the FTSST using a smart insole and a marker-less motion capture device is noteworthy. Compared with the conventional method, measurement of the FTSST using these devices demonstrate high agreement in both timing and scores. In addition to the discovery that the FTSST can be effectively performed by analyzing head height, the results suggest the potential scalability of a smart insole. Marker-less motion capture devices measure movement outcomes across multiple joint points in the x-, y-, and z-axes, whereas a smart insole with accelerometer sensors provides detailed information on plantar pressure, stride length, walking metrics, and foot angles.<sup>27</sup> Thus, simultaneously acquiring these datasets could enable diverse analyses, including assessing falls in older adults. Future research should explore a broader range of data for objective assessment of movements during FTSST.

Meanwhile, the agreement of scores obtained from the marker-less motion capture device was lower than that achieved using the smart insole measurement method. This variance is likely due to a slight time difference in score evaluation at the

FTSST cutoff point, leading to a relatively diminished concordance. A prior study indicated that the minimal detectable change for the FTSST, signifying the smallest detectable performance change, exceeds 2.5 s.<sup>24</sup> Consequently, differences within the limits of agreement are deemed clinically insignificant, and the high concordance in scores further emphasizes the potential of both devices to substitute for the conventional stopwatch method.

This study had some limitations. First, a single examiner with over 5 years of experience adhering to standardized protocols performed the simultaneous assessment of FTSST except for the introduction of smart insoles and the marker-less motion-detecting device. Precision was maintained through training sessions with five participants to ensure strict adherence to the standardized protocols. Second, potential errors may exist in the evaluation method. Two independent interpreters defined the start and end points based on graphs of plantar pressure and head height measured by smart insoles and the marker-less motion capture device. The average duration of each analyzed movement was calculated, with efforts to minimize methodological errors by analyzing the high reliability of both inter- and intra-interpreter assessments. Third, this study included eight participants under the age of 65. This study aimed to validate FTSST accuracy using a smart insole and marker-less motion capture device across different age groups. A normality distribution test, specifically the Shapiro-Wilk test, confirmed that both scales followed a normal distribution pattern.

This study evaluated a novel measurement approach for the FTSST utilizing plantar pressure analysis with a smart insole and head height analysis through a marker-less motion capture device. By comparing the concordance of the two measurement methods, it was demonstrated that both devices, excluding human errors associated with manual stopwatch measurements, could scientifically measure the FTSST. Despite the relatively long overall evaluation time for the FTSST and certain limitations, this study holds significance for developing a new measurement technique and obtaining meaningful results. Subsequent research, including the development of automated algorithms based on the data from this study, has the potential to enhance the comfort, convenience, and user-friendliness of the FTSST in clinical settings. Additionally, integrating positional data from various joint points and feet obtained from these devices could offer novel insights into frailty assessment.

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## AUTHOR CONTRIBUTIONS

**Conceptualization:** Jung Hyun Park. **Data curation:** Chan Woong Jang and Kyoungmin Park. **Formal analysis:** Sanghyun Jee, Chan Woong

Jang, and Kyoungmin Park. **Investigation:** Sanghyun Jee and Sanghoon Shin. **Methodology:** Chan Woong Jang, Kyoungmin Park, and Jung Hyun Park. **Resources:** Jung Hyun Park. **Supervision:** Sanghoon Shin and Min-Chul Paek. **Validation:** Kyoungmin Park and Jung Hyun Park. **Visualization:** Chan Woong Jang. **Writing—original draft:** Sanghyun Jee and Chan Woong Jang. **Writing—review & editing:** Sanghoon Shin, Min-Chul Paek, and Jung Hyun Park. **Approval of final manuscript:** all authors.

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