

# An accelerometer-based method for estimating fluidity in the sit-to-walk task

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**Abstract.** [Purpose] The purpose of this study was to clarify the validity of accelerometer data for quantifying fluidity during the sit-to-walk task. [Subjects] The participants were 16 healthy young males. [Methods] The timing of events (task onset, maximum trunk inclination, and first heel strike) was determined from the acceleration waveform and compared to the timing determined from a three-dimensional motion analysis (task onset, maximum trunk inclination) or foot pressure sensor data (first heel strike). Regression analysis was used to estimate the fluidity index (FI) from the duration between events and the magnitude of the acceleration peak. The task was performed at two speeds (comfortable and maximum). [Results] A comparison of the timings from two different systems indicated no systematic bias. Specific events could be identified from acceleration data using regression analysis under both speed conditions. In addition, significant regression equations predictive of FI were constructed using the duration between events under both speed conditions. The duration from the maximum trunk inclination to the first heel strike was the best predictor of FI. [Conclusion] Accelerometer data may be used to precisely and conveniently evaluate fluidity. The clinical utility of these data should be tested in elderly individuals or patient populations.

**Key words:** Sit-to-walk task, Fluidity, Accelerometer

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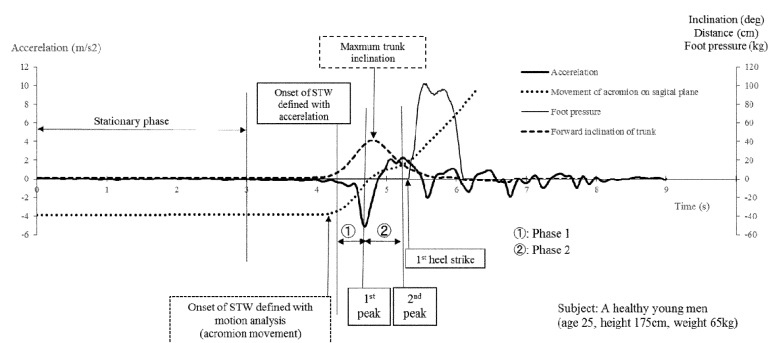
## INTRODUCTION

Standing from a seated position and walking are basic components of many daily activities and have been analyzed using various methods. The sit-to-walk (STW) task involves the sequential motions occurring from standing to initiating gait. The STW task has been used in both basic and clinical research. Magnan<sup>1)</sup> and Kerr<sup>2, 3)</sup> examined the STW task using a three-dimensional motion analysis system and ground reaction force plates. These authors analyzed the timing of defined events such as task onset, seat off, and toe off in movements and in phases divided by these events during the STW task while focusing on the velocity of the body's center of gravity and the ground reaction force, and revealed that seat-off and gait initiation were executed simultaneously in healthy participants. Kouta<sup>4)</sup> showed that the forward and vertical speeds of the center of gravity during the STW task were lower in elderly adults than in younger adults. Similarly, most other studies of the STW task have focused on the transition between standing and gait initiation. Dion<sup>5)</sup> defined this transitional ability or strategy as "fluidity" or a "fluid strategy", and developed a fluidity assessment

scale known as the fluidity index (FI). FI was shown to associate with general clinical measurements and decreasing fluidity among patients with hemiplegia<sup>5)</sup>. Asakura<sup>6)</sup> further demonstrated that the environment influenced the FI during the STW task. FI is calculated using the change in forward momentum of the center of gravity, and thus can objectively and sensitively evaluate fluidity. However, large equipment, such as a motion analysis system, is required to calculate FI; therefore, the fields in which FI can be used are limited. To address this problem, Malouin<sup>7)</sup> developed the fluidity scale (FS), in which fluidity is assessed on a four-point graded ordinal scale. This grade is determined using the timings of trunk extension completion and first toe off. FS is acceptably and easy to use. However, it is unsuitable for precise examinations.

Accelerometers have recently become easy to obtain. These devices are sufficiently small and lightweight to be carried by a subject without hindering motion. Therefore, accelerometers enable measurements not only in laboratory settings, but also in clinical settings, which are not equipped with motion analysis systems. These devices have been widely used in various contexts, including gait analysis<sup>8-13)</sup> and sit-to-stand tasks<sup>14, 15)</sup>. The Timed Up-and-Go test, which includes elements of the STW task, has been analyzed using accelerometers<sup>16-19)</sup>. Weiss<sup>16)</sup> examined healthy participants and patients with Parkinson's disease and showed that an accelerometer-based assessment was better than an assessment based only on a stopwatch. Although it is feasible to use an accelerometer to evaluate fluidity in the STW task, this application has not previously been reported.

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**Fig. 1.** A typical acceleration waveform and definitions of the events from acceleration and reference data. A negative change indicates anterior trunk inclination or backward acceleration. A positive change indicates posterior trunk inclination or forward acceleration. When the trunk inclines, the accelerometer detects gravitational acceleration.

The aim of this study was to evaluate the possibility of an accelerometer-based fluidity evaluation. We compared event timings in the STW task calculated with an accelerometer to those calculated using a three-dimensional motion analysis system and foot pressure sensing system. We have also discussed the possibility of estimating FI from the timing of these events and the magnitude of acceleration.

## SUBJECTS AND METHODS

The participants were 16 healthy young males (mean age:  $23.7 \pm 2.2$  years, mean height:  $174.2 \pm 3.7$  cm, mean weight:  $67.5 \pm 8.1$  kg) without any disabilities that would restrict performance of the STW task. The Epidemiologic Research Ethics Committee of Gunma University Faculty of Medicine approved this study (No. 26-2), and informed consent was obtained from each participant.

The STW task was performed under conditions based on those reported by Malouin et al<sup>7)</sup>. Participants sat on a chair without a back support or armrests and with a seat height standardized to 100% of the individual participant's leg length. Participants were instructed to look forward and, during the task, to fold their arms on their chest. After the start of the data collection, participants remained in a stationary position for 3 s, and upon hearing an auditory cue were required to stand up and walk toward a target placed 2 m in front of the chair. The task was performed at two speeds: comfortable and maximum. Participants practiced the task at each speed until they could reproduce the movements smoothly and naturally. Each trial was then recorded simultaneously using a three-axial piezoelectric acceleration sensor (TA-513G, Nihon Khoden, Tokyo, Japan), a motion capture system (MA3000, Anima, Tokyo, Japan) with six infrared cameras, and a foot pressure sensing system (Walk Way, Anima). The sampling frequency was 100 Hz. The acceleration sensor was directly attached to the skin between the L3 and L4 vertebrae<sup>13, 18, 19)</sup> and was orientated to measure the sagittal, frontal (medial-lateral), and vertical planes. In this study, only sagittal data were analyzed. Reflective markers were attached to the acromion, anterior superior iliac spine, greater trochanter, knee joint, lateral malleolus, and head of the fifth metatarsal on both sides of the body.

Acceleration and kinematic data were filtered using a zero-phase low-pass filter with a cut-off frequency of 8 Hz.

A typical acceleration waveform and definitions of the events are shown in Fig. 1. The onset of the STW task was defined as the point at which the acceleration exceeded two standard deviations (SD) of the mean of data from the 3-s stationary period. This was compared to the onset time of the STW task calculated as the initiation of forward acromion motion as recorded by the motion capture system. After initiation of the STW task, sagittal plane acceleration was negative and reached a local minimum. This was defined as the first peak, and the timing of the first peak was compared to the timing of maximum trunk inclination recorded by the motion capture system. Acceleration then became positive and yielded positive peaks. The last positive peak, which was followed by rapid negative acceleration, was defined as the second peak. The timing of the second peak was then compared to the timing of the first heel strike determined using the foot pressure sensing system. For each comparison, a Bland-Altman plot was generated by plotting the difference between the two measures against the mean of the two measures to provide a visual representation of heteroscedasticity. The existence of systematic bias was also examined. In addition, a simple linear regression analysis was performed using the accelerometer-measured event timing as the independent variable and the motion analysis system- or foot pressure sensor-measured event timing as the dependent variable. Discrete phases were identified from the acceleration data. Phase 1 was defined as the onset of the STW task to the first peak, phase 2 as the first peak to the second peak, and phase 1 + 2 as the onset of the STW task to the second peak.

The degree of fluidity was evaluated using the FI. This index corresponds to the percent change in the body forward momentum, which is calculated from motion capture system data. In a typical trial, the forward body momentum increases immediately after the peak initiation of motion and subsequently decreases to the lowest value. Subsequently, the momentum increases again. FI is calculated as the ratio of the lowest to the peak value. In a fluid motor strategy, the body forward momentum is maintained or slightly decreased after the first peak, and this is reflected by a higher FI. Simple and multiple linear regression analyses were

**Table 1.** Differences of event timings measured by two systems

Speed condition	Onset of STW								
	Accelerometer -Motion analysis system			1st peak -Maximum trunk inclination			2nd peak -Heel strike		
	mean	SD	95% CI	mean	SD	95% CI	mean	SD	95% CI
Comfortable	0.20	0.14	-0.07-0.47	-0.10	0.05	-0.20-0.00	-0.04	0.07	-0.18-0.09
Maximum	0.27	0.16	-0.05-0.59	-0.05	0.04	-0.14-0.04	-0.05	0.05	-0.14-0.04

STW: sit-to-walk, SD: standard deviation, CI: confidence interval

1st peak: The first negative peak in acceleration.

2nd peak: The last positive peak followed by rapid negative acceleration

**Table 2.** Results of a single regression analysis to predict event timing from acceleration data

Speed condition	Regression equation	R <sup>2</sup>	
Comfortable	Onset = 2.11 + 0.59 × (timing of onset defined by acceleration)	0.36	*
	Maximum trunk inclination = 1.29 + 0.81 × (timing of 1st peak)	0.61	***
	Heel strike = 0.73 + 0.90 × (timing of 2nd peak)	0.96	***
Maximum	Onset = 1.56 + 0.67 × (timing of onset defined by acceleration)	0.56	**
	Maximum trunk inclination = -0.05 + 1.02 × (timing of 1st peak)	0.88	***
	Heel strike = 0.22 + 0.97 × (timing of 2nd peak)	0.95	***

\* p < 0.05, \*\* p < 0.01, \*\*\* p < 0.001

performed to estimate the FI from acceleration data. In these analyses, the durations of phase 1, phase 2, and phase 1 + 2 and the magnitude of the second acceleration peak were used as independent variables. In all statistical analyses, one trial was used for each speed condition. All statistical analyses were performed using SPSS statistics 22.0 (IBM, Armonk, NY, USA). Statistical significance was set at p < 0.05.

## RESULTS

Differences in the timing of events calculated using either accelerometer or reference data (motion analysis system or foot pressure sensor) are shown in Table 1. Accelerometer-defined STW task initiation appeared sooner than did motion analysis data-defined task initiation under both speed conditions. The first acceleration peak and maximum trunk inclination were almost simultaneous. The second acceleration peak and first heel strike were also simultaneous. According to the Bland-Altman analysis, no fixed bias or proportional bias was observed across all three comparisons. The results of a simple linear regression analysis to estimate the timing of events from the acceleration data are shown in Table 2. For all events, significant regression equations were constructed under both speed conditions. The coefficient of determination ranged from 0.36 to 0.96. FI, the duration of each phase, the magnitude of the second acceleration peak, and the results of a simple linear regression analysis to estimate FI are shown in Table 3. Under the comfortable speed condition, the durations of phase 2 and phase 1 + 2 were included in the regression equation. Under the maximum speed condition, only the duration of phase 2 was included. Similarly, in the multiple regression analysis, only the duration of phase 2 was retained for both speed conditions.

## DISCUSSION

The acceleration waveform recorded during the STW task was similar to that reported by Mellone et al.<sup>19)</sup> for the Timed Up-and-Go test. To evaluate the events identified using the acceleration waveform, we compared the event timings with those of events identified using other data, namely motion analysis system and foot pressure sensor data. Some differences between the two measurements were apparent from the results; however, Bland-Altman plots indicated that these differences were random and small, yet sufficient to identify specific events. The timing of the first acceleration peak agreed with the timing of maximum trunk inclination. Therefore, the first acceleration peak can be used to identify the completion of trunk inclination and the switch to an extension movement. The second acceleration peak was similar to that observed by Zijlstra<sup>9)</sup> and Mellone<sup>19)</sup> in accelerator-based gait analyses. These authors defined the timing of the second peak using a peak detection method and equated this peak to the heel strike. In the present study, we used the same method to identify the second peak and found that the outcome compared well with the heel strike determined from foot pressure sensor data. Events such as the maximum trunk inclination and first heel strike have been used in kinematic analyses. The identification of these events from acceleration data is therefore important.

The duration of phase 2 was the best predictor of FI. FS, which evaluates whether the first toe off occurs before the completion of trunk extension, correlates with the FI. The first toe off cannot be identified on an acceleration waveform. Therefore, in this study we used the timing of the first heel strike, which appears clearly on the acceleration waveform and exhibits a similarly high correlation with the FI. Phase 2 is defined as the period from maximum trunk inclination to

**Table 3.** Results of a single regression analysis to predict FI from the duration of each phase and the degree of second peak acceleration

	mean	SD	Regression equation	R <sup>2</sup>
FI (%)				
Comfortable	70.7	17.5		
Maximum	95.7	5.4		
Phase 1 (s)				
Comfortable	0.55	0.15	FI=81.76 - 20.06 × (Phase 1)	0.03
Maximum	0.41	0.15	FI=96.96 - 2.95 × (Phase 1)	0.01
Phase 2 (s)				
Comfortable	0.85	0.17	FI = 142.10 - 83.63 × (Phase 2)	0.64 **
Maximum	0.56	0.08	FI = 118.85 - 2.95 × (Phase 2)	0.34 *
Phase 1 + 2 (s)				
Comfortable	1.4	0.24	FI=140.81 - 49.96 × (Phase 1 + 2)	0.46 **
Maximum	0.97	0.15	FI=108.84 - 13.56 × (Phase 1 + 2)	0.14
Magnitude of 2nd peak acceleration (m/s <sup>2</sup> )				
Comfortable	2.25	1.36	FI=77.13 - 0.28 × (2nd peak)	0.05
Maximum	2.51	1.79	FI=93.25 + 0.98 × (2nd peak)	0.11

\* p &lt; 0.05, \*\* p &lt; 0.01

FI: fluidity index, SD: standard deviation

Phase 1: Duration from the onset of the sit-to-walk task to the first peak

Phase 2: Duration from the first peak to the second peak

Phase 1 + 2: Duration from the onset of the sit-to-walk task to the second peak

the first heel strike and therefore includes the transition from sitting to standing to gait initiation. During this phase, motor control is important for maintaining a high momentum. In addition, in the maximum speed condition, phase 2 was the best predictor of FI, but the coefficient of determination was slightly lower than that observed in the comfortable speed condition. In the maximum speed condition, the FI converged to near 100% and the variability was narrow. This finding might explain why the determination was lower at the maximum speed than at a comfortable speed. In the present study, it was difficult to estimate the FI from the magnitude of the second acceleration peak. This difficulty is attributed to individual variations in the heel strike.

In this study, we clarified that accelerometer data could be used to conveniently and precisely estimate the FI. It must be considered, however, that all study participants were healthy young individuals. The acceleration waveforms in elderly individuals or patient populations are not necessarily identical to those in healthy young individuals. In addition, a piezoelectric acceleration sensor was used as the accelerometer in this study. A peculiarity of this sensor renders it difficult to distinguish between dynamic acceleration and gravitational acceleration (static acceleration). In other words, it is difficult to identify precisely whether the waveform indicates anteroposterior movement or accelerometer inclination. These are limitations of this study. In future studies, this method should be used for the clinical analysis of elderly individuals or patient populations. To improve the precision of this method, it might be useful to test other types of accelerometers such as capacitance-type or equipping gyroscope accelerometers.

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