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Kinematic and Kinetic Indicators of Sit-to-Stand


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Kinematic and Kinetic Indicators of Sit-to-Stand

Abstract

Variation in the timing indicators separating sit-to-stand (STS) into movement phases complicates both research comparisons and clinical applications. The purpose of this study was to use kinetic reference standards to identify accurate kinematic and kinetic indicators for STS movement analysis such that consistent indicators might be used for STS from varied initial postures. Healthy adults performed STS using 4 foot placements: foot-neutral, foot-back, right-staggered, and left-staggered. Kinetic and kinematic data were collected from force platforms and an 8-camera video system. Initiation, seat-off, vertical posture, and termination were detected with 5% start and 7.5% end thresholds for changes in kinetic and kinematic STS indicators. Timing differences between kinetic and kinematic indicator time points and the reference vertical seated reaction force end point (seatoff) were determined. Kinematic indicators were compared with selected kinetic indicators using timing differences, statistical similarity, and internal consistency measures. Our results suggest that a single force platform system measuring vertical GRF or a simple camera system to evaluate the shoulder marker position and velocity can accurately and consistently detect STS initiation, seat-off, and vertical posture. In addition, these suggested STS indicators for initiation, seat-off, and vertical posture were not dependent upon foot placement.

Keywords

biomechanics, motion analysis, force plate

Disciplines

Biomechanics | Exercise Science | Expeditionary Education | Kinesiology

Comments

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2 **Kinematic and Kinetic Indicators of Sit-to-Stand**

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23 **Running Title:** Indicators of Sit-to-Stand
24

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29 postures. Healthy adults performed STS using four foot placements: foot-neutral, foot-back,
30 right-staggered and left-staggered. Kinetic and kinematic data were collected from force
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39 posture. In addition, these suggested STS indicators for initiation, seat-off, and vertical posture
40 were not dependent upon foot placement.

41
42 **Keywords:** biomechanics, motion analysis, force plate

43

44 **Introduction:**

45 The sit-to-stand (STS) movement is a fundamental activity of daily living required for
46 upright posture, gait initiation, and personal-care tasks.^{1,2} Hence, it is frequently utilized in a
47 rehabilitation environment for screening or assessment purposes.³ Researchers have investigated
48 links between physical capability and performance environment to evaluate movement
49 compensations in STS.² However, there is a range of descriptions for STS performance and
50 assessment methods.⁴

51 The STS task is a transitional movement, requiring an individual to move the center of mass
52 (COM) from a stable position in sitting to more unstable base of support in stance.² Although
53 some authors simplify STS into two parts (a flexion phase and an extension phase),⁵ others report
54 four components (initiation, seat-off, ascension and stabilization)⁶ or four phases (flexion-
55 momentum, momentum transfer, extension and stabilization).⁷ The flexion-momentum phase
56 occurs from movement initiation to seat-off, followed by momentum transfer phase from seat-off
57 to maximal ankle dorsiflexion. The third phase is extension, progressing from maximal
58 dorsiflexion until hip extension is completed. Finally, stabilization proceeds from full hip
59 extension until postural stability is achieved and movement termination is denoted. Besides
60 varying the STS phase descriptions, authors vary the indicators for the beginning and ending
61 points of each phase of STS movement. Inconsistent definitions for indicators and phases
62 complicates the comparisons between published reports.^{8,9,10}

63 Previous research focused on assumptions of bilaterally equivalent anthropometrics, joint
64 timing, and weight-bearing during STS. Most researchers evaluate STS with participants
65 initiating movement from symmetric lower extremity postures involving more than 90° of knee
66 joint flexion.^{6,9,11,12,13} Kinetic evidence suggests individuals perform STS asymmetrically, despite
67 symmetric foot positioning.^{13,14} Clinical experience suggests individuals with pathology may

68 utilize an asymmetric foot placement as a compensatory mechanism during STS.^{15,16} Healthy
69 individuals may use an asymmetric placement preceding sit-to-walk transitions or for anticipated
70 directional changes upon standing. Although investigators altered chair height¹⁰ and symmetrical
71 foot placement,¹⁷ limited evidence exists on STS phase and event sequencing with systematically
72 manipulated lower extremity positions including asymmetric foot placements.^{2,4,18} Therefore,
73 determining consistent mechanisms for STS evaluation across various lower extremity postures
74 may have substantial utility with clinical populations who cannot attain symmetric positioning,
75 for expanding sit-to-walk as a fall screening tool,¹⁹ or for identifying muscle or joint impairments
76 in individuals with asymmetric STS movement patterns.^{14,20}

77 Depending on instrumentation and setting (laboratory versus clinic), variation exists in the
78 availability of kinematic and kinetic measurements during STS performance (Table 1). This
79 difference in equipment availability may affect the assessment of STS duration and phases due to
80 variation in movement indicators. Some authors evaluate STS only from seat-off as it is
81 identifiable from seat switches or force platforms under the feet.^{10,25} Others collect data through
82 the end of ascension as it is detected with kinematic measures, rather than assessing STS through
83 the stabilization phase.^{5,22,26,27,30} All STS phases can be accomplished in various ways as
84 individuals demonstrate multiple strategies for successful STS.^{10,11} The selected STS strategy
85 may provide key information to a clinician about physical limitations which guide rehabilitation
86 and impact functional capability.²⁸

87 The variation in STS movement indicators may affect descriptions of strategies, performance
88 duration, and time normalization for biomechanical analysis. Kinetic indicators based solely on
89 measurements from a single in-ground or portable force platform would allow for a simple
90 equipment setup. Etnyre & Thomas (2007) identified consistent ground reaction force (GRF)

91 events with different STS techniques (arms free, arms crossed, using armrests, and hands on
92 knees).⁴ Kinematic indicators are used with motion analysis systems, standard video or
93 potentially visual assessment. Knowledge of kinematic and kinetic indicators would allow
94 clinicians and researchers to consistently evaluate STS for collaborative rehabilitation projects
95 such as using STS movement strategies to evaluate rehabilitation efficacy,^{28,29} or for prognostic
96 research on disease progression or treatment response. The purpose of this investigation was to
97 select accurate kinetic and kinematic indicators for STS movement analysis in healthy adults
98 using kinetic measures as reference standards such that consistent indicators might be used for
99 varied initial postures.

100 Kinetic and kinematic indicators were evaluated for accuracy and consistency in detecting
101 STS movement time points. Our first hypothesis was vertical GRF would provide the most
102 accurate and consistent kinetic indicator of initiation and seat-off due to its ability to detect
103 different STS techniques.⁴ Our second hypothesis was shoulder horizontal position would be the
104 most accurate and consistent kinematic indicator of initiation as it is sensitive to anterior or
105 posterior postural changes. Based on previous work,^{9,10,20} our third hypothesis was hip marker
106 vertical position would be the most accurate and consistent kinematic indicator of seat-off as it
107 relates to leaving seated support. Our fourth hypothesis was trunk angular velocity would be the
108 most accurate and consistent kinematic indicator for vertical posture and termination in
109 conjunction with previous authors.^{8,9} Lastly, as STS movement sequencing does not appear to be
110 altered in healthy populations of various ages,^{12,28} we expected that selected movement
111 indicators for each time point would exhibit similar levels of accuracy and consistency across
112 symmetric and asymmetric placements.

113

114 **Methods:**

115 Eighteen healthy older adults (67.8 ± 7.5 years) and seventeen healthy younger adults ($32.7 \pm$
116 4.2 years) participated. A verbal review of medical history and physical activity was completed
117 with each participant. Exclusion criteria included physical impairments which limited STS
118 movement performance without upper extremity assistance. The Human Subjects Research
119 Compliance Office at Iowa State University approved the experimental protocol, and research
120 participants provided informed consent before study participation.

121 During the experimental session, participants' height and weight were assessed. Retro-
122 reflective markers were applied to participants for tracking by an eight-camera video system
123 (Peak Performance, Centennial, CO). Spherical markers were attached to skin or snug-fitting
124 clothing. A static standing trial was collected with markers placed bilaterally on the participants'
125 toes, midfeet, heels, lateral malleoli, medial malleoli, shins, lateral and medial femoral condyles,
126 thighs, greater trochanters, posterior superior iliac spines, acromion processes, upper arms,
127 lateral elbow joints, forearms, and ulnar styloids. Additional markers were placed at the
128 suprasternale and sacrum. This marker set divided the body into eleven segments: right/left feet,
129 right/left calves, right/left thighs, right/left upper arms, right/left forearms, and a head/trunk
130 segment. Video data were collected at a sampling rate of 120 Hz and low pass filtered at a
131 frequency of 6 Hz with a symmetric, fourth-order Butterworth filter.

132 Participants began each STS trial in a seated posture at a height of 48.5 cm on a bench-
133 mounted force platform (AMTI, Watertown, MA) to measure vertical seated reaction forces as a
134 seat-off reference standard for comparison with proposed kinetic and kinematic indicators.²³
135 With their feet at a comfortable width on separate force platforms (ATMI, Watertown, MA) to
136 record GRF, participants performed STS with four initial foot placements. The initial foot

137 placements included: foot-neutral (90° bilateral knee flexion), foot-back (100° bilateral knee
138 flexion), right-staggered and left-staggered. The staggered foot placements entailed a
139 combination of the foot-back and foot-neutral placements. For example, in the right-staggered
140 placement, the right knee was flexed to 100° while the left knee was flexed to 90°. The force
141 platform data were collected at 120 Hz and synchronized with video data through Peak Motus
142 software.

143 Participants performed three repetitions of each foot placement for a total of twelve trials.
144 The order of trials was alternated across participants to reduce the influence of learning and a
145 minimum interval of one minute was allocated between trials to minimize fatigue and allow
146 repositioning. Multi-colored athletic tape marked the three foot placements and the depth of the
147 participant's buttocks on the bench during initial positioning to ensure consistency between trials.
148 Participants were verbally instructed to position their feet according to tape color for each trial. A
149 two-stage verbal command ("Ready, Go") cued participants to initiate STS. For all trials,
150 participants' arms remained crossed over their torso throughout the duration of the STS
151 movement, to minimize variation in momentum contributions and movement asymmetry due to
152 arm swing,^{2,4} and to avoid marker occlusion. Participants remained standing in their final
153 position for five seconds at the conclusion of the STS movement.

154 Data Processing:

155 Kinetic and kinematic indicators for STS time points of initiation, seat-off, vertical posture,
156 and termination were based on previous studies (Table 1). To detect changes in potential STS
157 indicators, start and end point thresholds were calculated using minimum and maximum values
158 from the range of data for the specific kinematic or kinetic indicator during each trial:

159

160 $\text{Threshold}_{\text{start}} = 0.05 * (\text{maximum value} - \text{minimum value})$

161 $\text{Threshold}_{\text{end}} = 0.075 * (\text{maximum value} - \text{minimum value})$

162 The start point of a potential STS indicator was detected when a 5% threshold change (increasing
163 or decreasing) from the baseline seated value occurred. The end point of an indicator was
164 detected when a 7.5% threshold change from the final standing value occurred starting at the end
165 of the trial and moving backward in time.²³ Baseline seated and final standing values were
166 determined from the initial or final 10 time points of data from each trial respectively. Depending
167 on the temporal pattern of the potential STS indicator, a maximum and/or a minimum value was
168 also detected. To form a common time comparison of all indicators, a known reference time
169 point was determined. The end point of the vertical seated reaction force was chosen since this
170 measure falls to zero at seat-off.

171 Kinetic STS indicators included anterior-posterior (AP) GRF, vertical GRF, and AP center of
172 pressure (COP). AP COP velocity was calculated, but did not have a consistent pattern across
173 participants and was not further considered. All kinetic values were calculated by combining
174 values from force platforms under the right and left feet, to allow systematic evaluation while
175 accounting for symmetric and asymmetric initial positions. Besides start and end time points, AP
176 GRF and vertical GRF had maximum points, while AP COP had a minimum point. Kinematic
177 movement indicators included hip marker horizontal/vertical position and velocity, shoulder
178 marker horizontal/vertical position and velocity, hip flexion angle and angular velocity, and
179 trunk lean angle and angular velocity. The hip flexion angle was a relative angle between the
180 trunk segment (hip marker to shoulder marker) and the thigh segment (hip marker to knee
181 marker), while the trunk lean angle was between the trunk segment and the global horizontal axis.
182 All positions, velocities and angles were calculated using markers on the right side of the body.

183 In addition to start and end time points for each kinematic indicator, velocities and angles had
184 maximum points, while angular velocities had maximum and minimum points.

185 Data Analysis:

186 Kinetic and kinematic indicators were determined for the foot-back placement because it is a
187 preferred posture due to lower physical demands during STS^{2,10,12,17} and similar knee flexion
188 ranges (95-110°) have been used for healthy adults.^{5,6,11,25,31} Timing differences between the
189 proposed kinetic and kinematic indicator time points and the reference vertical seated reaction
190 force end point were calculated for the foot-back placement for all participants. The proposed
191 kinetic and kinematic indicators were ordered by timing difference from earliest to latest
192 occurrence (Table 2). A one-way factorial ANOVA compared timing differences with a
193 significance level set at $P > 0.05$ to denote statistical similarity amongst kinetic and kinematic
194 indicators for all time points. Previous investigators identified 6-10% timing differences in
195 movement phases as differentiating STS strategies,²⁸ so differences below 230 milliseconds
196 defined an acceptable accuracy level based on a STS time of 2.3 seconds.⁴ A reliability analysis
197 of foot-back placement trials was performed to evaluate the internal consistency of indicators at
198 each time point, using correlation coefficients above 0.3 as representative of moderate inter-item
199 consistency, and above 0.5 as representative of a strong correlation.³² SPSS software (SPSS, Inc.,
200 Chicago, Illinois) was used for statistical analysis.

201 Timing differences between the proposed kinematic indicators and vertical and AP ground
202 reaction force time points were calculated for initiation (Vertical and AP GRF Start), seat-off
203 (Vertical and AP GRF Maximum), vertical posture (Vertical GRF End), and termination (AP
204 GRF End) for the foot-back placement. The vertical and AP GRF kinetic reference points were
205 used for kinematic comparisons due to the clinical utility of one piece of equipment to assess all

206 STS phases and the ability to compare with previous literature referencing vertical GRF.^{4,6,8,10,11}
207 Kinematic indicators were compared to kinetic indicators using timing differences, statistical
208 similarity, and internal consistency measures. This analysis was repeated for the remaining foot
209 placement conditions to test if timing differences, similarity, and consistency were dependent
210 upon foot placement.

211 **Results:**

212 The AP and vertical GRF maximum points displayed the lowest timing differences ($t = -0.04$
213 to 0.03 s respectively) from the vertical seated reaction force end point as kinetic indicators of
214 seat-off across all foot placements (Table 2; Figure 1). The vertical GRF and AP GRF start
215 points exhibited the lowest timing differences ($t = 0.04$ to 0.09 s) and statistical similarity ($P = 1.0$)
216 compared to the vertical seated reaction force start point in detecting STS movement initiation
217 for all foot placements (Table 3). The vertical GRF starting point exhibited strong correlations
218 ($r = 0.745$ - 0.931) with the vertical seated reaction force start point for all foot placements. The AP
219 GRF start point demonstrated a moderate correlation ($r = 0.380$) with the vertical seated reaction
220 force start for the foot-back placement, but low correlations during other placements. The AP
221 COP start point did not correlate with the vertical seated reaction force start point nor other
222 kinematic STS indicators ($r < 0.3$) and was not further considered.

223 The shoulder horizontal position and hip flexion angle start points exhibited statistical
224 similarity ($P = 1.0$) and the lowest timing differences ($t = -0.05$ to 0.07 s) compared to the vertical
225 and AP GRF start points for detecting STS initiation across foot placements (Table 4; Figure 2).
226 The shoulder horizontal position start point demonstrated moderate correlations with vertical and
227 AP GRF in the foot-back and staggered placements ($r = 0.306$ - 0.496), however low correlations in
228 foot-neutral ($r = 0.230$ - 0.251). The hip flexion angle start point exhibited moderate correlations

229 with vertical and AP GRF in the foot-back placement for initiation ($r=0.463$), yet low
230 correlations in the other foot positions ($r=0.093-0.267$).

231 As a seat-off indicator, the hip flexion angle maximum point demonstrated the lowest timing
232 differences ($t= -0.13$ to -0.07 s), statistical similarity ($P=1.00$), and moderate correlations
233 ($r=0.337-0.400$) with the vertical GRF and AP GRF maximum points during the foot-back
234 placement (Table 5). Although equivalent timing differences and statistical similarity were
235 present in the other foot placements, the hip flexion angle maximum point exhibited low to
236 moderate correlations ($r=0.075-0.449$) with kinetic maximums. The shoulder vertical velocity
237 maximum point exhibited the next lowest timing differences ($t=0.20$ to 0.22), statistical
238 similarity ($P=1.00$), and strong correlations ($r=0.579-0.790$) compared to the vertical GRF
239 maximum point for all foot placements (Table 5; Figure 2). The shoulder horizontal velocity
240 maximum point had low timing differences ($t= -0.14$ to -0.16 s) and statistical similarity
241 ($P=1.00$), yet low to moderate correlations ($r=0.122-0.389$) compared to the AP GRF maximum
242 point across foot placements. Hip marker position-related indicators demonstrated larger timing
243 differences (Table 2) and small correlations (<0.3) with seat-off kinetic reference points.

244 The shoulder vertical position and velocity end points demonstrated the lowest timing
245 differences ($t= -0.15$ to 0.08 s), statistical similarity ($P=1.00$), and moderate correlations
246 ($r=0.292-0.721$) when compared to the vertical GRF end point as indicators of vertical posture
247 during all foot placements (Table 6). The AP COP minimum point did not have a correlation
248 above 0.3 with any kinematic STS indicator and was not considered further.

249 The trunk angular velocity and lean angle end points exhibited the lowest timing differences
250 ($t= -0.22$ to -0.20 s), statistical similarity ($P=1.00$), and moderate strength correlations ($r=0.300-$
251 0.307) compared to the AP GRF end point as an indicator of STS termination in the foot-back

252 placement (Table 7). However, the timing differences were larger ($t = -0.36$ to -0.44 s) and
253 approached statistical significance for other foot placements ($P < 0.08$). The AP COP end point
254 did not correlate ($r < 0.3$) with any kinematic STS indicator in the foot-back placement, and was
255 not further considered.

256 **Discussion:**

257 For this study, kinematic and kinetic STS indicators for the time points of initiation, seat-off,
258 vertical posture and termination were identified using an algorithmic approach. For a kinetic or
259 kinematic indicator to be used for clinical and laboratory assessments, we recommend it be
260 accurate and consistent for varied foot placements and different populations. A common kinetic
261 or kinematic indicator to detect initiation, seat-off, vertical posture, and termination is desired.
262 Therefore, a set of kinetic and kinematic STS indicators was assessed based on the following
263 factors: 1) accuracy as evaluated by low average timing differences between kinetic and
264 kinematic indicators, 2) statistical similarity with reference time points, and 3) internal
265 consistency with kinetic indicators.

266 Our first hypothesis was the vertical GRF would provide the most accurate and consistent
267 kinetic indicators of STS initiation and seat-off. This hypothesis was supported with the vertical
268 GRF start point for initiation and the maximum point for seat-off (Figure 1). For initiation, the
269 vertical GRF start point had low timing differences (40 ms) and was strongly correlated with the
270 vertical seated reaction force start point (Table 3). For seat-off, the vertical GRF maximum point
271 had low timing differences (20-30 ms) when compared to the vertical seated reaction force end
272 point (Table 2). This is consistent with literature indicating seat-off from vertical GRF within 80
273 ms.³³ For vertical posture, the vertical GRF end point had low timing differences (140-150 ms)
274 and was strongly correlated with the shoulder vertical position end point (Table 6). These results

275 suggest a portable single force platform system measuring vertical GRF could be used clinically
276 to assess STS initiation, seat-off, and vertical posture timing points.

277 AP GRF was considered as a kinetic indicator of STS timing points. The AP GRF maximum
278 point demonstrated a low timing difference (20-40 ms) compared to the vertical seated reaction
279 force for seat-off for all foot placements (Table 2). However, low correlations with vertical
280 seated reaction force during foot-neutral and staggered foot placements (Table 3) suggest the
281 vertical GRF is a superior choice as the kinetic indicator for STS initiation. No time point was
282 associated with AP GRF indicating vertical posture. The AP GRF end point appears to indicate
283 STS termination, but its effectiveness may be limited to foot-back placements (Table 7).
284 Alternate kinetic measures such as AP COP acceleration and different termination thresholds
285 merit further investigation.

286 Our second hypothesis of shoulder horizontal position being the most accurate and consistent
287 kinematic indicator of initiation was partially supported. For initiation, the shoulder horizontal
288 position start point had low timing differences (0-10 ms) compared to the vertical GRF start
289 point, but failed to exhibit consistent correlations across foot placements (Table 4). Regarding
290 seat-off, the third hypothesis of hip vertical position as an accurate indicator was not supported
291 as the shoulder vertical velocity maximum point was more accurate (200-220 ms) and exhibited
292 strong correlations with the vertical GRF maximum point across foot placements (Table 5). As
293 stated, a common kinematic indicator across multiple STS time points is desired. For detecting
294 vertical posture, the shoulder vertical position end point had low timing differences (140-150 ms)
295 and strong correlations with the vertical GRF end point across foot placements (Table 6). These
296 results are encouraging as shoulder-based kinematic measures (Figure 2) could indicate initiation

297 (shoulder horizontal position start point), seat-off (shoulder vertical velocity maximum point),
298 and vertical posture (shoulder vertical position end point).

299 As shoulder position is involved in hip flexion angle determinations, hip flexion angle may
300 be an alternative to joint marker position as an indicator because it incorporates lower and upper
301 body movements. Although the hip angle start point inconsistently detected STS initiation across
302 foot placements (Table 4), the hip flexion angle maximum point had the lowest timing
303 differences (120-130 ms) and moderate correlations with the vertical GRF maximum point at
304 seat-off for symmetrical foot placements (Table 5). Maximal hip flexion angle may provide
305 information about the STS movement strategy utilized, as suggested by previous
306 investigators.^{21,28} From a clinical perspective, observing seat-off relative to initiation and
307 termination time points may be important for assessing lower extremity strength, movement
308 strategy, or weight-shifting capability.^{28,31} Alternatively, specific determinations of seat-off may
309 be more relevant to laboratory-based activities.

310 Our fourth hypothesis that trunk angular velocity would be the kinematic indicator of choice
311 for STS vertical posture and termination was only partially supported. The trunk angular velocity
312 timing points had high timing differences and low correlations compared to the vertical GRF end
313 point. As mentioned, the shoulder vertical position end point is recommended for the kinematic
314 vertical posture indicator.

315 The trunk lean angle and angular velocity end point had the lowest timing differences (200-
316 220 ms) and moderate correlations compared with the AP GRF end point as an indicator of
317 termination in the foot-back placement (Table 7). However, higher timing differences (360-440
318 ms) were observed with other placements and statistical similarity was not maintained. Other
319 kinematic indicators such as AP COM position or velocity may detect the termination point

320 across all foot placements, but require a more complex video analysis. Other investigators
321 suggested poor reliability of an algorithmic approach to detect STS termination, and used visual
322 estimation of steady standing posture as an alternative.⁴ The stabilization phase of STS may be
323 analyzed using techniques associated with quiet standing, although such analysis may require a
324 force platform to measure COP, which may preclude its clinical utility.

325 As expected, STS timing differences of the indicators for initiation, seat-off, and vertical
326 posture did not vary upon foot placement. This suggests that kinetic and kinematic indicators
327 could be consistently utilized for STS assessment without specific requirements for initial seated
328 posture. This is consistent with previous work in younger individuals suggesting standardized
329 indicators for STS analysis with the caveat of armrest involvement.⁴ However, timing differences
330 for STS termination were dependent upon foot placement using the indicators in this study.

331 There are limitations to this study. First, the only ‘gold standard’ STS timing measure is the
332 vertical seated reaction force reaching zero at seat-off. Similar standards do not exist for
333 initiation, vertical posture, or termination. Studying analog video synchronized with digital
334 measurements and/or comparing hand analysis with automated detection may provide further
335 evidence. Second, 5% start and 7.5% end thresholds of detection were utilized from previous
336 studies²³ and incorporate movement ranges (based on maximum and minimum values) which
337 may be affected by participant heights given the fixed seat height. Threshold points may also be
338 impacted by combined lower extremity GRF data versus unilateral data. Further study of
339 threshold optimization may produce more accurate STS indicators. For example, a lower start
340 threshold for a dramatically changing measure like vertical GRF and a higher end threshold for
341 an oscillating measure like AP COP may be appropriate. Third, the combination of data from
342 younger and older healthy adults in this study may differ from indicators selected from a more

343 homogenous sample. However, we expect the results to be robust given similar movement
344 sequencing in healthy individuals^{12,30} and similar STS times for individuals utilizing a consistent
345 chair height.^{10,26} Individuals who struggle with STS movements may utilize alternate STS
346 strategies and exhibit movement patterns with slower, smoothed, or unpredictable changes in
347 indicators. A measurement used as an indicator or threshold levels may require adjustment if
348 STS time points are not consistently detected. Although the selected indicators were consistent
349 across foot placements, the timing differences (10-220 ms) may impact STS time normalization
350 which could alter phase designations and movement strategy determinations. Finally, requiring
351 participants to complete STS with arms crossed in this study may limit variation in movement
352 patterns analyzed. However, previous work demonstrated a common sequence of STS events
353 during upper extremity conditions in healthy individuals with the exception of armrest usage.⁴

354 Research laboratories analyzing STS movements commonly incorporate one or more force
355 platforms and automated motion capture cameras to provide a three-dimensional assessment.
356 However, elaborate set-ups and equipment are not available in many clinical settings to analyze
357 movement to an equivalent extent. This study offers recommendations for alternative assessment
358 methods in the event equipment available for STS analysis is limited. These results suggest a
359 single force platform system measuring vertical GRF can accurately and consistently detect STS
360 initiation, seat-off, and vertical posture. Additionally, results suggest a simple camera system to
361 evaluate shoulder marker position and velocity can detect STS timing points. A simplified
362 movement analysis system may allow increased collaboration between clinicians and researchers,
363 with the potential to impact individuals with pathology through improved assessment and
364 intervention.

365

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451 **Table 1: Variation in Published Movement Indicators for Sit-to-Stand**
 452

Initiation	Seat-Off	Termination or Vertical Posture
Vertical GRF ^{4,6,21}	Vertical GRF ¹⁰	COM Position ^{10,18,22}
COM Velocity ²³	Seated GRF ^{13,23}	COM Velocity ²³
Trunk Angle ¹⁸	Max Horizontal GRF ^{8,11}	Hip Angular Velocity ²⁰
Trunk Angular Velocity ^{8,9}	Seat Switch ^{4,6,21}	Trunk Angular Velocity ^{8,9}
Hip Flexion ^{14,17,20}	Hip Vertical Position ^{9,22,24}	Hip Vertical Position ²⁴
Head Movement ²⁴		Hip Horizontal Velocity ²¹
Forward Lean ^{11,12}		Backward Lean ¹²
Body Movement ⁵		Pelvic Position ⁵

453 GRF (Ground Reaction Force); COM (Center of Mass)

454 **Table 2: STS Timing Indicators.** Indicator time points are referenced to when vertical seated reaction force drops to zero (seat-off, shaded in grey). Time results are presented as mean (SD) for Foot-Back, Foot-Neutral, and Staggered (combined) placements.

STS Timing Indicators	Foot-Back	Neutral	Staggered	STS Timing Indicators	Foot-Back	Neutral	Staggered
Hip Angular Velocity Start	-0.68 (0.33)	-0.57 (0.15)	-0.64 (0.24)	Vertical GRF Maximum	0.02 (0.03)	0.03 (0.05)	0.02 (0.03)
Trunk Angular Velocity Start	-0.65 (0.22)	-0.63 (0.21)	-0.67 (0.23)	Hip Horizontal Velocity Maximum	0.20 (0.31)	0.14 (0.20)	0.15 (0.35)
Hip Horizontal Velocity Start	-0.61 (0.36)	-0.51 (0.33)	-0.66 (0.44)	Hip Vertical Velocity Maximum	0.22 (0.23)	0.20 (0.13)	0.25 (0.33)
Shoulder Horizontal Velocity Start	-0.58 (0.47)	-0.58 (0.09)	-0.60 (0.16)	Shoulder Vertical Velocity Maximum	0.22 (0.08)	0.25 (0.09)	0.23 (0.09)
Hip Vertical Velocity Start	-0.58 (0.47)	-0.54 (0.35)	-0.57 (0.46)	Hip Angular Velocity Minimum	0.35 (0.21)	0.34 (0.11)	0.36 (0.33)
AP COP Start	-0.52 (0.20)	-0.57 (0.16)	-0.52 (0.14)	Trunk Angular Velocity Maximum	0.37 (0.24)	0.36 (0.11)	0.40 (0.33)
Trunk Lean Angle Start	-0.52 (0.17)	-0.50 (0.13)	-0.51 (0.15)	Shoulder Vertical Position End	0.51 (0.13)	0.54 (0.13)	0.52 (0.14)
Vertical Seated Force Start	-0.49 (0.12)	-0.49 (0.10)	-0.47 (0.10)	Vertical GRF End	0.66 (0.12)	0.68 (0.12)	0.66 (0.12)
Shoulder Horizontal Position Start	-0.45 (0.11)	-0.44 (0.07)	-0.44 (0.09)	Shoulder Vertical Velocity End	0.68 (0.14)	0.73 (0.18)	0.74 (0.31)
Vertical GRF Start	-0.45 (0.11)	-0.45 (0.11)	-0.43 (0.10)	Hip Vertical Position End	0.73 (0.60)	0.67 (0.53)	0.66 (0.54)
AP GRF Start	-0.40 (0.18)	-0.42 (0.12)	-0.41 (0.14)	AP COP Minimum	0.81 (1.47)	0.34 (0.98)	0.64 (1.34)
Hip Flexion Angle Start	-0.38 (0.10)	-0.38 (0.08)	-0.38 (0.10)	Shoulder Horizontal Velocity End	0.94 (0.34)	0.92 (0.49)	0.99 (0.55)
Shoulder Vertical Velocity Start	-0.27 (0.09)	-0.29 (0.09)	-0.29 (0.10)	Hip Flexion Angle End	0.95 (0.51)	0.85 (0.32)	0.86 (0.37)
Trunk Angular Velocity Minimum	-0.19 (0.24)	-0.22 (0.03)	-0.18 (0.34)	Shoulder Horizontal Position End	1.08 (0.46)	1.05 (1.03)	1.20 (0.72)
Shoulder Horizontal Velocity Maximum	-0.18 (0.03)	-0.17 (0.03)	-0.17 (0.03)	Trunk Lean Angle End	1.15 (0.60)	1.19 (0.63)	1.11 (0.48)
Trunk Lean Angle Maximum	-0.17 (1.60)	-0.29 (1.63)	-0.00 (1.69)	Hip Vertical Velocity End	1.15 (1.23)	1.42 (1.55)	1.29 (1.30)
Hip Vertical Position Start	-0.17 (0.18)	-0.15 (0.18)	-0.13 (0.13)	Trunk Angular Velocity End	1.16 (0.62)	1.17 (0.79)	1.12 (0.73)
Hip Horizontal Position Start	-0.17 (0.15)	-0.13 (0.07)	-0.13 (0.11)	Hip Horizontal Position End	1.24 (0.66)	1.18 (0.55)	1.25 (0.59)
Hip Angular Velocity Maximum	-0.16 (0.44)	-0.19 (0.45)	-0.23 (0.34)	Shoulder Vertical Position Maximum	1.31 (0.75)	1.24 (0.83)	1.34 (1.03)
Hip Flexion Angle Maximum	-0.11 (0.05)	-0.09 (0.03)	-0.10 (0.05)	AP GRF End	1.36 (0.51)	1.55 (0.65)	1.55 (0.82)
Shoulder Vertical Position Start	-0.04 (0.08)	-0.08 (0.10)	-0.05 (0.10)	Shoulder Horizontal Position Maximum	1.39 (1.60)	1.17 (0.69)	1.15 (1.57)
AP GRF Maximum	-0.04 (0.05)	-0.02 (0.04)	-0.03 (0.04)	Hip Angular Velocity End	1.44 (1.07)	1.47 (1.11)	1.39 (1.09)
Vertical Seated Force Zero	0.00	0.00	0.00	Hip Horizontal Velocity End	2.56 (1.45)	2.53 (1.56)	2.42 (1.48)
				AP COP End	5.04 (1.10)	5.28 (1.32)	5.39 (1.30)

456 AP (Anterior-Posterior); COP (Center of Pressure); GRF (Ground Reaction Force)

457 **Table 3: Kinetic STS Initiation Indicators.** Indicator timing differences referenced to the vertical seated reaction force start point
 458 (shaded in grey). Statistical similarity was defined as $P > 0.05$. Positive correlations of moderate strength were defined as $r > 0.30$.
 459

	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
STS Initiation Indicators	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Vert Seated Force Start	0.00			0.00			0.00		
Vert GRF Start	0.04	1.000	0.931	0.04	1.000	0.814	0.04	1.000	0.745
AP GRF Start	0.09	1.000	0.380	0.07	1.000	0.085	0.06	1.000	0.075

460 AP COP did not have a correlation >0.3 with seated reaction forces.

461 **Table 4: Kinematic STS Initiation Indicators.** Indicator timing differences referenced to the vertical GRF and AP GRF start points
 462 (shaded in grey). Statistical similarity was defined as $P > 0.05$. Positive correlations of moderate strength were defined as $r > 0.30$.
 463

	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
STS Initiation Indicators	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Shoulder Horiz Velocity Start	-0.13	1.000	0.466	-0.13	1.000	0.235	-0.17	1.000	0.377
Trunk Lean Angle Start	-0.07	1.000	0.344	-0.05	1.000	0.021	-0.07	1.000	0.250
Shoulder Horiz Position Start	0.00	1.000	0.496	-0.00	1.000	0.251	-0.01	1.000	0.306
Vert GRF Start	0.00			0.00			0.00		
Hip Flexion Angle Start	0.07	1.000	0.463	0.06	1.000	0.093	0.05	1.000	0.256
Hip Horiz Position Start	0.28	0.999	0.322	0.31	1.000	0.123	0.30	1.000	0.074
STS Initiation Indicators	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Shoulder Horiz Velocity Start	-0.18	1.000	0.462	-0.16	1.000	0.240	-0.19	1.000	0.332
Shoulder Horiz Position Start	-0.05	1.000	0.485	-0.02	1.000	0.230	-0.04	1.000	0.316
AP GRF Start	0.00			0.00			0.00		
Hip Flexion Angle Start	0.02	1.000	0.357	0.04	1.000	0.153	0.03	1.000	0.267

464 Note: The AP COP start point did not have a correlation above 0.3 with the vertical seated reaction force start point or any other
 465 kinematic STS indicator

466 **Table 5: Kinematic STS Seat-Off Indicators.** Indicator timing differences referenced to the AP GRF and vertical GRF maximum
 467 value points (shaded in grey). Statistical similarity was defined as $P > 0.05$. Positive correlations of moderate strength were defined
 468 as $r > 0.30$.
 469

	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
STS Seat-Off Indicators	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Hip Flexion Angle Max	-0.13	1.000	0.337	-0.12	1.000	0.449	-0.13	1.000	0.259
Vert GRF Max	0.00			0.00			0.00		
Shoulder Vert Velocity Max	0.20	1.000	0.697	0.22	1.000	0.790	0.21	1.000	0.579
Shoulder Vert Position End	0.48	0.346	0.560	0.51	0.443	0.607	0.49	0.008	0.452
STS Seat-Off Indicators	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Shoulder Horiz Velocity Start	-0.55	0.108	0.305	-0.56	0.102	0.371	-0.57	0.001	0.291
Shoulder Horiz Velocity Max	-0.14	1.000	0.389	-0.16	1.000	0.122	-0.14	1.000	0.259
Hip Flexion Angle Max	-0.07	1.000	0.400	-0.07	1.000	0.075	-0.07	1.000	0.329
AP GRF Max	0.00			0.00			0.00		

470

471 **Table 6: Kinematic STS Vertical Posture Indicators.** Indicator timing differences referenced to the vertical GRF end point (shaded
 472 in grey). Statistical similarity was defined as $P > 0.05$. Positive correlations of moderate strength were defined as $r > 0.30$.
 473

STS Vertical Indicators	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Shoulder Vert Velocity Max	-0.43	0.643	0.670	-0.44	1.000	0.810	-0.43	0.105	0.746
Shoulder Vert Position End	-0.15	1.000	0.721	-0.14	1.000	0.720	-0.14	1.000	0.708
Vert GRF End	0.00			0.00			0.00		
Shoulder Vert Velocity End	0.03	1.000	0.559	0.05	1.000	0.463	0.08	1.000	0.292

474 Note: The AP COP minimum value point did not have a correlation above 0.3 with any kinematic STS indicator.
 475

476 **Table 7: Kinematic STS Termination Indicators.** Indicator timing differences referenced to the AP GRF end point (shaded in grey).
 477 Statistical similarity was defined as $P > 0.05$. Positive correlations of moderate strength were defined as $r > 0.30$.
 478

STS Termination Indicators	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation	Timing (s)	P-Value	Correlation
Shoulder Horiz Velocity End	-0.42	0.694	0.312	-0.62	0.018	0.026	-0.56	0.001	0.437
Hip Flexion Angle End	-0.41	0.746	0.385	-0.70	0.002	0.201	-0.70	0.001	0.121
Trunk Lean Angle End	-0.22	1.000	0.300	-0.36	1.000	0.070	-0.44	0.065	0.073
Trunk Angular Velocity End	-0.20	1.000	0.307	-0.38	1.000	0.141	-0.44	0.075	0.137
AP GRF End	0.00			0.00			0.00		

479 Note: The AP COP end point did not have a correlation above 0.3 with any kinematic STS indicator

