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Kinematic and Kinetic Indicators of Sit-to-Stand.

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Keywords
biomechanics, motion analysis, force plate

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Kinematic and Kinetic Indicators of Sit-to-Stand

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Introduction:

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

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

Previous research focused on assumptions of bilaterally equivalent anthropometrics, joint timing, and weight-bearing during STS. Most researchers evaluate STS with participants initiating movement from symmetric lower extremity postures involving more than 90° of knee joint flexion.[6,9,11,12,13] Kinetic evidence suggests individuals perform STS asymmetrically, despite 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 height[10] 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)

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

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

Methods:

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

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

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

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

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

Data Processing:

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

160 $Threshold_{start}$ = 0.05*(maximum value – minimum value)

161 $Threshold_{end}$ = 0.075*(maximum value – 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

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

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

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

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

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

Discussion:

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

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

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

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

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

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

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

There are limitations to this study. First, the only 'gold standard' STS timing measure is the vertical seated reaction force reaching zero at seat-off. Similar standards do not exist for initiation, vertical posture, or termination. Studying analog video synchronized with digital measurements and/or comparing hand analysis with automated detection may provide further evidence. Second, 5% start and 7.5% end thresholds of detection were utilized from previous studies[23] and incorporate movement ranges (based on maximum and minimum values) which may be affected by participant heights given the fixed seat height. Threshold points may also be impacted by combined lower extremity GRF data versus unilateral data. Further study of threshold optimization may produce more accurate STS indicators. For example, a lower start threshold for a dramatically changing measure like vertical GRF and a higher end threshold for an oscillating measure like AP COP may be appropriate. Third, the combination of data from 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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References:

1. Eriksrud O, Bohannon RW. Relationship of knee extension force to independence in sit-to-stand performance in patients receiving acute rehabilitation. *Phys Ther*. 2003; 83(6):544-551.
2. Janssen WGM, Bussmann HBJ, Stam HJ. Determinants of the sit-to-stand movement: A review. *Phys Ther.* 2002; 82(9):866-879.
3. Lusardi MM, Pellecchia GL, Schulman M. Functional performance in community living older adults. *J Geri Phys Ther*. 2003;26(3):14-22.
4. Etnyre B, Thomas DQ. Event standardization of sit-to-stand movements. *Phys Ther*. 2007;87(12):1651-1666.
5. Nuzik S, Lamb R, VanSant A, Hirt S. Sit-to-stand movement pattern. *Phys Ther.* 1986;66(11):1708-1713.
6. Kralj A, Jaeger RJ, Munih M. Analysis of standing up and sitting down in humans: Definitions and normative data presentation. *J Biomech.* 1990;23(11):1123-1138.
7. Schenkman M, Berger RA, Riley PO, Mann RW, Hodge WA. Whole-body movements during rising to standing from sitting. *Phys Ther.* 1990;70(10):638-651.
8. Gross MM, Stevenson PJ, Charette SL, Pyka G, Marcus R. Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women. *Gait Posture.* 1998;8(3):175-185.
9. Mourey F, Grishin A, d'Athis P, Pozzo T, Stapley P. Standing up from a chair as a dynamic equilibrium task: A comparison between young and elderly subjects. *J Gerontol A Biol Sci Med Sci. 2000;*55(9):B425-B431.
10. Schenkman M, Riley PO, Pieper C. Sit to stand from progressively lower seat heights - alterations in angular velocity. *Clin Biomech.* 1996;11(3):153-158.
11. Doorenbosch CAM, Harlaar J, Roebroeck ME, Lankhorst GJ. Two strategies of transferring from sit-to-stand: The activation of monoarticular and biarticular muscles. *J Biomech.* 1994;27(11):1299-1307.
12. Kerr KM, White JA, Barr DA, Mollan RAB. Analysis of the sit-to-stand movement cycle in normal subjects. *Clin Biomech.* 1997;12(4):236-245.
13. Lundin TM, Grabiner MD, Jahnigen DW. On the assumption of bilateral lower extremity joint moment symmetry during the sit-to-stand task (technical note). *J Biomech.* 1995;28(1): 109-112.
14. Schofield JS, Parent EC, Lewicke J, Carey JP, El-Rich M, Adeeb S. Characterizing asymmetry across the whole sit-to-stand movement in healthy participants. *J Biomech*. 2013;46(15):2730-2735.
15. Brunt D, Greenberg B, Wankadia S, Trimble MA, Shechtman O. The effect of foot placement on sit to stand in healthy young subjects and patients with hemiplegia. *Arch Phys Med Rehabil.* 2002;83(7):924-929.
16. Su FC, Lai KA, Hong WH. Rising from chair after total knee arthroplasty. *Clin Biomech*. 1998;13(3):176-181.
17. Kawagoe S, Tajima N, Chosa E. Biomechanical analysis of effects of foot placement with varying chair height on the motion of standing up. *J Orthop Sci*. 2000;5(2):124-133.
18. Cameron DM, Bohannon RW, Garrett GE, Owen SV, Cameron DA. Physical impairments related to kinetic energy during sit-to-stand and curb-climbing following stroke. *Clin Biomech*. 2003;18(4):332-340.

19. Kerr A, Rafferty D, Kerr KM, Durward B. Timing phases of the sit-to-walk movement: Validity of a clinical test. *Gait Posture*. 2007;26(1):11-16.
20. Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res.* 2005;23(5):1083-1090.
21. Shepherd RB, Gentile AM. Sit-to-stand: Functional relationship between upper body and lower limb segments. *Hum Mov Sci.* 1994;13(6):817-840.
22. Schenkman M, Hughes M, Samsa G, Studenski S. The relative importance of strength and balance in chair rise by functionally impaired older individuals. *J Am Geriatr Soc.* 1996;44(12):1441-1446.
23. Pai Y-C, Rogers MW. Control of body mass transfer as a function of speed of ascent in sit-to-stand. *Med Sci Sports Exerc.* 1990;22(3):378-384.
24. van der Linden ML, Rowe PJ, Myles CM, Burnett R, Nutton RW. Knee kinematics in functional activities seven years after total knee arthroplasty. *Clin Biomech.* 2007;22(5):537-542.
25. Lundin TM, Jahnigen DW, Grabiner MD. Maximum trunk flexion angle during the sit to stand is not determined by knee or trunk-hip extension strength in healthy older adults. *J Appl Biomech*. 1999;15(3): 233-241.
26. Alexander NB, Schultz AB, Warwick DN. Rising from a chair: Effects of age and functional ability on performance biomechanics. *J of Gerontol: Med Sci.* 1991;46(3):M91-98.
27. Burnett DR, Campbell-Kyureghyan NH, Cerrito PB, Quesada PM. Symmetry of ground reaction forces and muscle activity in asymptomatic subjects during walking, sit-to-stand, and stand-to-sit tasks. *J Electromyogr Kinesiol*. 2011;21(4):610-615.
28. Moxley Scarborough D, Krebs DE, Harris BA. Quadriceps muscle strength and dynamic stability in elderly persons. *Gait Posture.* 1999;10(1):10-20.
29. Papa E, Cappozzo A. Sit-to-stand motor strategies investigated in able-bodied young and elderly subjects. *J Biomech*. 2000;33(9):1113-1122.
30. Millington PJ, Myklebust BM, Shambes GM. Biomechanical analysis of the sit-to-stand motion in elderly persons. *Arch Phys Med Rehabil*. 1992;73(3):609-617.
31. Alexander NB, Schultz AB, Ashton-Miller JA, Gross MM, Giordani B. Muscle strength and rising from a chair in older adults. *Muscle Nerve.* 1997;20(S5):56-59.
32. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.
33. McGibbon CA, Goldvasser D, Krebs DE, Moxley Scarborough D. Instant of chair-rise lift-off can be predicted by foot-floor reaction forces. *Hum Mov Sci.* 2004;23(2):121-132.

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

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]

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

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)

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

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

	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

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

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

	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

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 kinematic STS indicator

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

	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		

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

	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
STS Vertical Indicators	**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

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

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

	Foot-Back Placement			Foot-Neutral Placement			Staggered Foot Placements		
STS Termination Indicators	**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

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