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Identifying consistent biomechanical parameters across rising-to-walk subtasks to inform rehabilitation in practice: A systematic literature review

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PII:	S0966-6362(20)30578-6
DOI:	https://doi.org/10.1016/j.gaitpost.2020.10.001
Reference:	GAIPOS 7921
To appear in:	*Gait & Posture*
Received Date:	20 May 2020
Revised Date:	7 August 2020
Accepted Date:	2 October 2020

Please cite this article as: D Jones G, L Jones G, James DC, Thacker M, A Green D, Identifying consistent biomechanical parameters across rising-to-walk subtasks to inform rehabilitation in practice: A systematic literature review, *Gait and amp; Posture* (2020), doi: https://doi.org/10.1016/j.gaitpost.2020.10.001

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Highlights

- Normal rising-to-walk (RTW) performance is fluid, but is non-fluid with pathology
- Rehabilitation could be tested if RTW controlled performance variables were known
- Consistent variables regardless of healthy RTW performance represent candidates
- In this review of 9 studies, no compelling evidence of consistency was found
- Studies designed to confirm consistent biomechanical variables are needed

1 Abstract

Background: The best approach to rehabilitate the control of everyday whole-body movement (e.g. rise-to-walk) after pathology remains unclear in part because the associated controlled performance variables are not known. Rise-to-walk can be performed fluidly (sit-to-walk) or non-fluidly (sit-to-stand, proceeded by gait-initiation). Biomechanical variables that remain consistent in health regardless of how rise-to walk is performed represent controlled performance variable candidates which could monitor rehabilitative change.

Research Question: To determine if any biomechanical parameters remain consistent across rising-to-walk (RTW) subtasks (sit-to-stand, gait-initiation, and sit-to-walk) in healthy adults for purposes of movement control assessment in clinical practice.

Methods: Data sources included Medline, Cinahl, and Scopus databases, and the grey literature. Study Selection was based on eligibility criteria and must have reported spatiotemporal, kinematic and/or kinetic biomechanical parameters featuring >1 RTW subtask. Data Extraction and Synthesis; standardised-mean-differences (SMDs) were calculated (pooled if replicated in >1 study) for each parameter. Consistency was determined if SMD95%CIs included the zero-effect line.

Results: Nine studies (n=99) were included (40±7.5yrs). Seven parameters were replicated in >1 study and subjected to meta-analysis (fixed-effect model). Two were consistent between sit-to-stand and sit-to-walk: flexion-momentum time (M(95%CI)= 0.055(-0.423 to 0.533); p=0.823) and peak whole-body-centre-of-mass vertical velocity (M(95%CI)= -0.415(-0.898 to 0.069); p= 0.093); and centre-of-pressure to whole-body-centre-of-mass distance at toe-off (M(95%CI)= -0.137(-0.712 to 0.439); p= 0.642) between gait-initiation and sit-to-walk. Another 20 parameters were consistent based on single-study SMDs.

Significance: Consistent parameters might exist across RTW subtasks. However, the evidence is based on few studies with small samples and variable RTW protocols. Future studies designed to confirm consistency using a standardised RTW protocol are needed.

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Keywords: early ambulation; gait-initiation; rehabilitation research; systematic review; sit-to-stand; sit-to-walk

2 Introduction

Transitional movements are considered to occur whenever rhythmic (e.g. walking or running) or sedentary movements (e.g. lying, sitting, or standing) are combined [1], although there is no consensus upon a standard definition. They are complex because an individual is not only required to control the propulsive forces that move their body segments but must simultaneously maintain their balance during the transition too. Transitional movements are therefore challenging and potentially destabilising movement tasks, for which an individual's sensorimotor system requires sufficient resources in order to control [2].

Rising-to-walking (RTW) is an everyday transitional movement executed daily on average 49 times in healthy people [3] and incorporates two cardinal subtasks; firstly sit-to-stand (STS), and secondly the initiation of walking from standing (gait initiation; GI). A healthy person can execute a continuous version of RTW where the transition of rising (STS), through GI, and into walking forward occurs fluidly and is known as sit-to-walk (STW). Healthy people can also execute another version where the subtasks are performed consecutively but independently and may be partially (hesitant-STW) or entirely separated (separated-STW) as part of a normal dual or combination task [3]. These are collectively known as sit-to-stand-and-walk (STSW) [4], where a pause separates STS from GI. STW and STSW therefore represent the extremes of RTW behaviour.

The assessment of sensorimotor control parameters in ambulatory transitional tasks like RTW can be dichotomised into either the observation of activity with a standardised rating of performance, or the biomechanical measurement of the performance [5]. While performance ratings are ubiquitous in clinical environments due to their time and resource practicalities (e.g. the Berg Balance Scale [6]), biomechanical assessments (e.g. mean anteroposterior centre-of-pressure (COP) displacement velocity [7]) offer less subjectivity despite the disadvantage of often being dependent on lab-based equipment [5].

Rising from sitting commences with movement-onset. The initial priority is to generate anterior whole-body-centre-of-mass (BCOM) momentum which transitions to vertical momentum around the event of seat-off. The phase between movement-onset to seat-off, termed flexion-momentum [8] represents the transition from a dynamically stable three-point, to a two-point base-of-support [9]. Once upright is achieved in STS, forward propulsion is arrested, requiring generation of a substantial (compared to STW) BCOM braking force, manifest as greater peak posterior ground reaction forces (GRFs) [10, 11]. GI, when executed from standing, is characterised by an anticipation phase where the COP is translated posterolaterally towards the swing limb creating a moment arm to propel the BCOM forward [12]. Then, a dynamic execution phase of GI starts at heel-off (HO1) [13]. The first walking step delineated between toe-off (TO1) and initial contact (IC1) [14] with steady-state walking typically established by the end of the second step in healthy individuals, if the transition to walking is continued in a forward direction [15].

A similar COP momentum arm also exists during the anticipation phase of GI in STW, albeit of a lower magnitude due to the BCOM's latent forward momentum generated during initial rising [11, 16]. The challenge in STW is to continue to control rising, despite

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GI having already started (GI-onset) before upright is reached [16, 17]. This phase shift is indicative of the rapid and fluid merging of rising and GI around seat-off in STW, and presents a significant motor control challenge [18-20].

Healthy individuals can choose depending on context, attention, purpose or freewill to execute RTW within the range of permutations represented by STS, GI, STW and STSW. This is because healthy people have abundant sensorimotor resources available to them [21]. Put another way, this abundance means that task-specific performance variables can be stabilised by sets of elemental variables that are organised by the central nervous system [22]. For example, leg joint angles (elemental variables) can be organised to stabilise, and therefore control, the BCOM during the stance phase of gait (performance variable) [23]. A biomechanical parameter that remains *consistent* independent of how a complex transitional task like RTW is executed in healthy individuals might therefore represent a controlled performance variable and thus be a candidate proxy for in-tact sensorimotor-system control. This in turn means that discrimination between healthy and pathological sensorimotor-system control is possible by assessment of the consistent parameters(s) during RTW performance.

Consistency in this context is defined as a biomechanical parameter that does not vary (significantly) across RTW performance. Thus, parameters are considered to demonstrate absolute consistency across RTW tasks if the posed null hypothesis (no difference in biomechanical parameter between RTW tasks) is retained following appropriate statistical significance testing. Accordingly, consistent parameters may be used to monitor change in dysfunctional RTW performance, which can enable the development of alternative rehabilitation techniques designed to improve movement control to be tested in clinical practice.

Transitional sensorimotor control is often impaired in older or pathological populations in RTW and its subtasks leading to slower temporal durations of movement phases. For example, lower limb muscular weakness has been shown to prolong STS movement duration in normal aging [24], and stroke impairments have been observed to prolong the relative duration of the transition-phase (seat-off to GI-onset) and overall movement-time in STW [19, 25]. Thus, individuals with pathology execute RTW within a more limited set of permutations more biased towards STSW compared to healthy individuals.

Observations of other *differences* in temporo-spatial, kinematic, or kinetic biomechanical parameters are therefore unsurprising within RTW subtasks (i.e. STS, GI from quiet-standing, or STW) between health and pathology. For instance, longer phase durations have been observed during STW in stroke [19], and during GI in Parkinson's disease (PD) [26] compared to healthy individuals. Furthermore, smaller separation distances between the BCOM and the COP have been observed at movement events during STW in healthy older, compared to healthy younger adults [16] during STW in adults with PD compared to healthy older adults [27], and during GI in adults with PD compared to older or younger healthy individuals [28]. In addition, greater momentum and peak mediolateral ground-reaction-forces (GRFs) during STW compared to STS, are examples of differences between RTW subtasks in healthy adults [11, 18]. However, whether any biomechanical parameters exhibit *consistency* throughout the RTW continuum in healthy adults is unclear. This is because explicit evaluations are not-commonly referred to in the literature which means consistency is either not reported at all, or is only implicitly reported in the literature and does not therefore frequently feature in studies' titles, abstracts and discussions.

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Aims

The aim of this systematic review is to determine if any reported spatiotemporal, kinematic and/or kinetic biomechanical parameters remain consistent across rising-to-walk (RTW) subtasks in healthy adults and thereby act as candidate markers to discriminate pathology and evaluate recovery in the rehabilitation of transitions to walking. The objectives are to:

1. Systematically identify biomechanical parameters within individual RTW studies that were assessed in at least two RTW subtasks within healthy participants;
2. For each biomechanical parameter identified, determine whether any have been reported by more than one study;
3. Determine if the biomechanical parameters are consistent between RTW subtasks within or across studies using meta-analysis.

3 Methods

A systematic review was performed and its findings are reported in accordance with the Preferred Reporting Items for Systematic Reviews and meta-analyses (PRISMA) statement guidelines [29] (see Supplementary Table 1: PRISMA Checklist).

Protocol Registration

The protocol for the systematic review was registered with the International Prospective register for Systematic Reviews (PROSPERO; registration no CRD 42019124750).

Search strategy

The Population/Participants, Intervention, Comparison, and Outcome (PICO) framework was used to define the search strategy concepts [30-32]. Participants must have been healthy human volunteers. Interventions were defined as any instruction to execute any of the following conventional RTW subtasks: sit-to-stand (STS), gait-initiation (GI) and/or sit-to-walk (STW), or other accepted movement instructions (timed-up-and-go test (TUAG) [33], or STSW). The comparison in this case was consistency (as defined) between another RTW sub-task. Studies were included whether healthy participants executing RTW subtasks were part of a control group or not. Single case studies, study protocols, and systematic or narrative reviews were excluded. There was no other restriction on study designs. The outcomes were any spatiotemporal, kinematic and/or kinetic parameter measured in at least 2 RTW subtasks to facilitate determination of consistency.

Electronic databases were searched from database inception to the 15th October 2018. Studies were identified by searching electronic databases; MEDLINE (OVID), SCOPUS and CINAHL. Keywords related to the key concepts (healthy adults, RTW subtasks, and kinematic or kinetic biomechanical parameters) were matched to a controlled vocabulary (exploded MeSH terms or subject headings) which was combined with free text terms (see Supplementary Table 2: Example Search Strategy). In addition, grey literature was assessed including postgraduate theses (masters or doctoral using EthOS and WorlCat Dissertation and Thesis (OCLC) databases) in addition to conference abstracts and proceedings [34]. A secondary search, or pearling, of bibliography lists was manually undertaken in publications that fulfilled eligibility criteria.

Two reviewers (GDJ, GLJ) independently performed the electronic database search, subsequent screening, quality assessment, and data extraction. Candidate citations were transferred to a proprietary systematic review platform (Covidence Systematic Review Software. Veritas Health Innovation Ltd. Melbourne, Australia) along with the full text.

Eligibility criteria

Reviewers screened titles and abstracts using customised criteria including keyword searching in Covidence (see Supplementary Table 3: Title and abstract screening tool). In cases where eligibility was inconclusive, the full text was independently screened.

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Disagreements were resolved by discussion, or if consensus not reached by a third experienced reviewer (MT) independently assessing.

Type of studies

Only studies published in English were included. Single case studies, study protocols, and other systematic or narrative reviews were excluded. There was no other restriction on study design. The search therefore included cross-sectional, cohort studies, prospective cohort or any other experimental study types.

Type of participants

Human healthy adults aged ≥18 years were included. No upper age limit was applied to avoid exclusion of patients based on an arbitrary age limit [35], and because consistent biomechanical data *between* RTW tasks *within* healthy participants was the focus of the review.

Type of biomechanical parameters

Studies that included spatiotemporal, kinematic and/or kinetic parameters measured between reported movement events during any two RTW subtasks were eligible. The parameters encompassed time and spatial measures of the whole-body centre-of-mass (BCOM), centre-of-pressure (COP) or other individual or combined (e.g. head-arm-trunk (HAT)) specific body segments; velocities or momenta, directional components of the ground-reaction-force (GRF), or measures of fluency for example hesitation, coordination, or smoothness [20].

Study exclusion

Studies investigating participants with reported pathologies affecting normal walking function were excluded unless the study included analysis and separate reporting of a healthy control group. Studies were excluded if only one RTW task was analysed (e.g. STW only [25]) or if a RTW subtask included initial positions other than sitting or standing (e.g. lying-to-walk [3]). If studies assessed walking directions that deviated from forward (e.g. backwards walking [36]) or if studies included walking that included transitions from one surface to another (e.g. stepping up onto a 16cm high box [37]), then they were also excluded.

Studies were also excluded if the main focus was the impact on either a medical, surgical or public health concern using RTW tasks as an assessment (e.g. using timed-STS to assess vitamin D deficiency interventions [38]); or ambulation function using physical performance tests but with no RTW task as a comparison (e.g. using TUAG to assess high-intensity-training effect [39]). Lastly, studies were excluded if reported parameters were dependent on EMG, sensors, or assistive device technology [40].

Risk of bias within individual studies

It was predicted that most literature found in this review would be cross-sectional. Consequently, standardised experimental-design specific quality assessment tools such as PEDro [41, 42] were inappropriate. As a result, study quality was assessed using the Joanna Briggs Institute (JBI) Checklist for Analytical Cross Sectional Studies [43], which is an accepted and valid approach for reporting observational study designs [44, 45]. It uses a 3-point nominal rating system of bias where a score of 0 (zero) is assigned for *low*, 1 for *unclear*, and 2 for a *high risk of bias* for each of the eight quality criteria leading to a total score between zero and 16 (see Supplementary Table 4: Methodological quality assessment tool). To comply with each critical appraisal criterion and be rated low-risk, the study had to meet elements detailed in the criterion description. To be rated a high-risk, the study had to explicitly detail some, but not all, of the criterion description or provide no information. To be rated unclear-risk, the study had to provide some information but without complete clarity as per the criterion description. Cohen's kappa (κ) [46] was used to determine inter-rater agreement of study quality between the two

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reviewers according to accepted rating criteria [47] in each of the 8 quality domains and between the reviewer's total risk of bias score. Disagreements were resolved by discussion, or if consensus not reached via assessment by a third experienced reviewer (MT) independently, yielding final total rating scores. A high risk of bias was concluded if a study returned a final rating of >50% of the total possible score (i.e. >8) [48] and was subsequently excluded from further analysis [43].

Data extraction

Mean (±SD) study characteristics and biomechanical parameters (see below) were extracted and populated in Covidence by the reviewers independently using customised tables. Disagreements between reviewers were resolved by discussion, or if consensus not reached by assessment by a third experienced reviewer (MT) independently. In cases where the standard error of the mean (SE) but not SD was reported, the SD was calculated as the product of the square-root of the sample size and the SE. If no variance statistic was provided, the range was extracted.

Study characteristics

Characteristics were collected in order to describe studies' participants and protocols. They comprised: year of publication, aims, number of healthy participants, their gender and handedness, participant height (m), body-mass (kg) or body-mass-index (BMI) and seat height from which participants rose (expressed as either the proportion of knee height (%KH), as an absolute height (m) or as a pre-determined sitting knee angle (°)).

In addition, protocol descriptors were extracted to characterise and compare starting position, task execution and contexts. Pre-determined nominal classifications were used: feet position (standardised/self-selected), arm use (constrained/semi-constrained/self-selected), tempo (controlled/self-selected) and ecological task purpose (upper limb task/walk to target). Other protocol task characteristics extracted were limb-lead, walk distance (m) or alternatively the number of prescribed steps, what RTW subtasks were included and the number of trials undertaken.

Biomechanical parameters

The number of different biomechanical parameters reported in eligible studies was expected to be high. All parameters measured were initially recorded using the terminology used in the original study. Then, parameters where labelled and classified using a consistent terminology agreed by the reviewers to enable pooled results to be generated across studies.

Method of analysis

For each extracted biomechanical parameter, the main outcome of interest was the effect size (ES) calculated between two RTW subtasks. The ES was expressed as the standardised mean difference (SMD) and associated 95% confidence intervals (CI).

SMDs were calculated either from data extracted within a single-study if the parameter was only present in one study, or combined across studies if data were extracted in more than one study. SMDs were calculated based on the effect-size (Cohen's d) [49]; the proportion of the difference between the mean values and the pooled SD [50]. A minor bias exists in d where it tends to overestimate the absolute value of the SMD particularly when sample sizes are small ($n \leq 10$ in each group) [51] which was anticipated. An approximated correction factor (J) was therefore calculated [52] and when combined as a product of d yielded a corrected SMD ES (Hedge's g)[53]. Parameters were considered consistent as defined if the SMD 95% CI included the null value (the line of zero-effect) [52].

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Where parameters were shared in 2 or more studies, combined mean effects were calculated to meta-analyse between-task consistency. Fixed-effect analyses were performed because sample sizes and numbers of studies were small. Descriptive analyses of included studies representing the healthy adult population were therefore reported, despite the fact that the studies were likely to have been drawn from researchers working independently where random-effect analyses would be more appropriate [52]. First, the weighted effect size (W) for each study's g was calculated as the reciprocal of g^2, then the weighted mean effect size (M) was calculated as the sum of the product of g and W divided by the sum of W [52]. If combined effect size 95% CIs included the null value (line of zero-effect), then the null hypothesis was not rejected, and the parameter was considered consistent as defined.

4 Results

Study Selection

A total of 2862 studies were identified through the defined strategies (Figure 1). After 963 duplicates were removed, 1899 titles and then abstracts were screened with 43 studies selected based on eligibility criteria for full-text screening. Thirty studies included upon inspection only one RTW subtask, or steady-state gait or TUAG as the task of interest, and thus were excluded. Two other studies were excluded because they proved unobtainable in full-text despite numerous inter-library requests (2 PhD theses). Two other duplicates were removed. Thus, nine studies were selected for inclusion in the final review.

[Figure 1 here]

Included study characteristics

Design and Participants

All nine included studies employed a cross-sectional cohort design of which one was a short communication paper [54] and two were published abstracts with data not wholly published subsequently in full text papers [55, 56]. A modest number of participants were tested in each study: mean (range) 10.8 (8-13) yielding a total of 99 participants. Two studies failed to report participants' height or mass [55, 57]. Four studies did not report gender distribution [18, 27, 55, 56], whereas in the remainder only 21% were female. In general, studies adopted 5 repeated RTW trials with at least 3m walk distances (Table 1).

[Table 1 here]

Starting position

One study specified a definitive seat height in its experimental protocol [55] while all others standardised it to knee-height, leg-length, or knee-joint angle. Feet positioning was standardised across studies by fixed orientation or positioning and maintained through trials, but two studies allowed a self-selected start position [11, 58]. In five studies, upper limbs were constrained across the trunk or on the waist [11, 18, 27, 56, 57], and the remainder did not include any detail (Table 2).

[Table 2 here]

Walking and RTW subtasks

Tempo was self-selected throughout, whereas lead-limb was controlled in some studies. Participants self-selected their preferred lead-limb and then maintained it in four studies [11, 18, 27, 55], one specified the left lead-limb [57], one specified both the dominant and non-dominant limb [54], and the remainder provided no details. Only two studies provided any detail of the walking task including an ecologically valid purpose, for example: walking to a target [27] or an upper limb task (switching off a light [54]). All studies included STW as one RTW subtask, five compared it with STS [11, 18, 55, 56, 58], one with GI [57], one with STSW [54], and two compared STW with both STS and GI [10, 27] (Table 2).

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Risk of Bias Within Studies

Across the 9 included studies, the assessors agreed on 45 instances of low bias, 12 unclear, and 7 high bias. However, there were 8 instances where the assessors disagreed on quality. The inter-rater agreement for risk of bias scoring was high, κ = 0.772 (95% CI 0.623 to 0.921) (Table 3).

Once the disagreements were resolved (Table 3), the mean (±SD) risk of bias score (from a maximum of 16) was low per study but variable (3.33 ±3.81 (range 0-12)). One study was rated with unacceptable bias (risk of bias score 12) and was not included in analyses [56]. Inadequate reporting of healthy group inclusion criteria (criterion 1), participant characteristics (criterion 2) and the omission of confounding variable management (criterion 5) were the most common domains where bias was found across studies.

[Table 3 here]

Final biomechanical parameters used for analysis

In total, there were 104 biomechanical parameters reported across all studies. However, 52 parameters were either not compared between RTW tasks in healthy participants or data were not possible to extract. For instance, variance statistics were not reported in two studies [57, 58], only partially reported in two others [10, 11] and some parameters were not analysed between-tasks [27, 54, 56]. Thus, 52 biomechanical parameters with between-RTW task data were available for analysis across individual studies (Figure 2).

When the 52 parameters were considered across-studies for replication, three studies (total participants: n=31) analysed flexion-momentum time [11, 27, 54]; three studies (n=27) analysed rise time [11, 54, 55]; three studies analysed peak BCOM vertical velocity (n=31) [10, 27, 54]; two studies (n=22) analysed peak BCOM horizontal velocity and COP-BCOM distance at seat-off and toe-off [27, 54]; and two studies (n=19) analysed swing-limb peak GRF [11, 54]. One biomechanical parameter (flexion-momentum phase duration), unique to the study with high risk of bias [56], was excluded. Thus, it was possible to extract effect-size data for 44 independent biomechanical parameters; 37 unique to individual studies, four replicated across 2 studies, and three parameters replicated across 3 studies (Figure 2).

[Figure 2 here]

Results of Individual Studies

Of the 37 parameters unique to only one RTW comparison study, 20 were consistent (Table 4). These were: 1st step width and velocity in GI compared to STW [27]; peak vertical GRF during rising, peak positional stability during steps 1, 2, and 3, and the duration of steps 1, 2, and 3 in STSW compared to STW [54]; peak posterior (braking) GRF and the time from movement-onset to both peak anterior and posterior GRFs in STS compared to STW [55]; time between movement-onset to peak BCOM vertical velocity and the total vertical BCOM displacement in STS compared to STW [10]; and finally, the time between movement-onset and both peak BCOM horizontal and vertical momentum, anteroposterior BCOM and COP position at seat-off, peak BCOM vertical momentum during rising and the peak stance limb vertical GRF during rising in STS compared to STW [11]. Kerr and colleagues [18] reported no consistent parameters between STS and STW.

[Table 4 here]

Synthesis of Combined Studies

Of the seven biomechanical parameters replicated in more than one study three were common to three studies and four were common to two studies. Of those common to three studies, combined results showed consistency (combined ES 95% CIs included the line of zero effect) between STS and STW in flexion-momentum time (M (95% CI) = 0.053 (-0.423 to 0.533); p=0.823) and in peak BCOM vertical velocity during rising (M (95%

CI) = -0.415 (-0.898 to 0.069); $p = 0.093$). In contrast, a longer rise-time was found during STS compared to STW((M (95% CI) = 0.950 (0.410 to 1.490); $p<0.001$) (Figure 3).
[Figure 3 here]

In biomechanical parameters common to two studies, the COP-BCOM horizontal distance was consistent between STW and GI at initial toe-off (M (95% CI) = -0.137 (-0.712 to 0.439); $p = 0.642$) whereas at seat-off it was greater during STS compared to STW (M (95% CI) = 0.610 (0.028 to 1.193); $p = 0.040$), (Figure 4).
[Figure 4 here]

There was no consistency between STS and STW in peak BCOM horizontal velocity during rising where it was faster during STW (M (95% CI) = -1.707 (-2.452 to -0.963); $p<0.001$) nor in peak swing-limb ground reaction force before the first toe-off event where it was greater during STW (M (95% CI) = -1.350 (-2.033 to -0.667); $p<0.001$) (Figure 5).
[Figure 5 here]

Summary of consistent parameters

37 parameters were unique to individual studies and not replicated elsewhere, twenty of which (54%) can be considered consistent by virtue of their 95% CI effect size crossing the line of no effect (zero) (see Table 4 above). Combined with the 3 consistent parameters common to more than one study (see Figure 3 and Figure 4 above), the overall review yielded 23 parameters that were consistent as defined (Table 5). Twenty of the 23 (87%) were consistent between STW and STS (or STSW in one study [54]), with the remaining three parameters (13%) consistent between STW and GI.
[Table 5 here]

Risk of Publication Bias Across Studies

A risk of publication bias assessment was planned *a priori* using a funnel plot approach where the relationship between study-size and effect-size is plotted and bias then interpreted by visualisation of any asymmetry in the plot [59]. But, in parameters sharing extracted data, the maximum number of synthesised studies was three. Thus, there was not enough data to undertake an assessment of publication bias in this review.

5 Discussion

Summary of Evidence

The aim of this systematic review was to identify whether any spatiotemporal, kinematic and/or kinetic biomechanical parameters remain consistent independent of how RTW is executed in healthy individuals. If any consistent parameters were identified, they would thereby represent candidate proxies for intact sensorimotor-system control and could potentially discriminate between healthy and pathological sensorimotor-system control and be used to monitor change in dysfunctional RTW performance. This in turn could enable the development of alternative rehabilitation techniques designed to improve impaired movement control to be tested in clinical practice

Consistency was assumed if the 95% confidence intervals around the effect size (MSD from single or combined studies) included the null value (line of zero-effect). Studies analysing only one RTW task, or those only reporting parameters dependent on EMG, sensors, or assistive device technology were excluded.

Abstracts and titles from 43 out of 1899 were full-text screened. Of these, nine studies were found to be eligible and included in the final review. None of the studies stated an aim to assess biomechanical parameter consistency between RTW subtasks in healthy participants. Consequently, spatiotemporal, kinematic and/or kinetic biomechanical parameter data between RTW tasks were extracted to assess for consistency within

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reviewed studies. One-hundred and four candidate biomechanical parameters were identified between-RTW subtasks. Once parameters with a high risk of bias were removed and replication ensured, the final analysis consisted of 44 parameters: 37 unique to single studies, 4 each replicated across 2 studies, and 3 each replicated across 3 studies.

Combined-study effect sizes for parameters which shared RTW subtask comparisons across more than one study showed that two parameters were consistent between STW and STS; these were: flexion-momentum time, and peak BCOM vertical velocity during rising. These parameters are both associated with the critical RTW event of seat-off. Flexion-momentum time reflects the transition from a stable base-of-support (BOS) in sitting to an unstable bipedal BOS at seat-off, whereas peak vertical BCOM velocity reflects the transfer of kinetic energy from a predominantly horizontal direction to a vertical one at seat-off [9].

Seat-off represents an event where risks to postural stability are high. For example, STS studies have confirmed that the vertical projection of the BCOM must be stabilised over a small BOS during the rising phase to mitigate the risk of falling due to a failure to stand up [60, 61]. It has also been established that the control of the BCOM horizontally before seat-off, and then vertically after seat-off, is relatively invariant at different STS speeds suggesting it is a tightly controlled and prioritised strategy [60]. During STW, prioritising stability around seat-off is equally crucial as it coincides with the cardinal tasks of STS and GI merging [11]. Therefore, the consistency in flexion-momentum time and peak vertical BCOM velocity between RTW tasks suggests that stability around seat-off is prioritised independently of how RTW is achieved.

The COP-BCOM horizontal distance, which is positively correlated with postural stability [27, 62], was also a consistent biomechanical parameter based on a combined-study effect size across two studies between STW and GI at toe-off. Toe-off proceeds seat-off in RTW and reflects a postural to dynamic phase transition in GI [63] where the base-of-support (BOS) changes from being bipedal to unipedal. It is possible therefore that postural stability is prioritised across RTW subtasks at events proceeding seat-off into GI.

In fact, biomechanical parameter consistency was observed into the first steps of walking after GI, at least in the single studies analysed. Specifically, step 1 stance width and velocity were consistent between STW and GI [27]. Furthermore, peak COP-BCOM distance during steps 1, 2, and 3 and the respective phase durations were consistent between STW and STSW [54]. It is possible these parameters are consistent (as defined) simply because events associated with steady-state walking are sufficiently dissociated from the initial transitional movement. If so, this would mean that these parameters are simply not influenced by any factors attributable to how RTW is performed. It would be interesting to determine whether parameters proceeding steady-state gait during deceleration phases and the transition to gait termination (GT) are influenced by RTW subtasks preceding them.

In other single-studies, consistency at seat-off in the anteroposterior position of both the BCOM and COP between STS and STW [11] was observed as was the peak vertical stance limb GRF [11], and the net GRF from both limbs [54], during rising which are practically coincident with seat-off [64]. Consistency was also observed in the time between movement-onset and peak GRFs in the anterior and posterior directions [55], in addition to the durations between movement-onset and the peak horizontal and vertical BCOM momenta (two events adjacent with seat-off) [11] and in the proportional time to peak BCOM velocity [10]. However, as these data are based on single studies, caution in their interpretation should be exercised. That said, these parameters' apparent consistency between STS and STW around seat-off event supports the notion that control of stability might be prioritised around this unstable event.

It was surprising that the remaining single-study consistent parameter between STW and STS was in peak posterior (braking) GRF magnitude [55]. Braking GRFs are deployed to arrest the forward momentum generated during STS around seat-off and thereby achieve an upright position which is stable. They are typically higher in STS [10, 11] compared to STW because GI-onset occurs before upright is reached in STW and the maintenance of forward momentum after seat-off is desirable [16, 17]. The sample size these data were drawn from was small (*n*=8). So, it is possible that consistency (as defined) in peak posterior GRF between STW and STS was surprisingly found simply because the sample size was not large enough for true differences to be statistically significant.

Limitations

Sample sizes

All the included studies across RTW tasks possessed relatively low sample sizes. The maximum sample size in individual studies whose data were extracted was *n*=14 [56] and in pooled studies was *n*=31. Small sample sizes often lead to effect-size calculations being insufficiently precise [65] leading to poor confidence in the validity of the data rendering findings inconclusive. This is particularly pertinent in this review because it was forecasted that studies would not have a common effect size and not be functionally equivalent, so an *a priori* decision to apply random-effects modelling when calculating pooled effect sizes was made. However, pooled effect sizes were drawn from only a maximum of only 3 papers and a fixed-effect model was therefore employed due to the small number of studies because the estimate of the between-studies variance in a random-effects model would have poor precision in combined ES calculations [52].

Number of combined studies

The small number of studies reviewed meant that synthesis of data was limited. Typically, if it is possible to extract and synthesise data to answer the literature review question, it must be conceded that interpretation of the synthesis will reflect bias if these data are drawn from a biased sample of published data [66]. The current literature review approached publication bias like many others by attempting to conduct as comprehensive a search as possible inclusive of the grey literature. Despite this, the risk remained that synthesised results would over-estimate true effect sizes [52] and an assessment of publication bias was planned. However, the numbers of included studies with common parameters was too small to perform this and subsequently, it was not practicable to use funnel plots because there was insufficient data available for them to be meaningful.

Protocol characteristics

Instructing participants to move at self-selected tempo was the only selected protocol characteristic that was commonly adopted across all reviewed studies. During gait executed at self-selected velocity, step width and length parameters have been shown to be least variable, compared to slow and maximal velocities [67]. Adopting self-selected tempo in RTW is therefore advantageous because it allows participants to perform naturally and presumably safely, even if instructions to pause before walking is included in order to allow different variants of RTW to be investigated.

All other recorded protocol characteristics in reviewed studies were either unspecified or specified differently across studies. These characteristics included seat-height which was either explicitly stated or was 100% of knee-height (KH). Thus, the literature does not conclusively define a seat-height that both healthy and pathological participants can

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execute RTW tasks safely and successfully from. Typical seat-heights of 100%KH present little difficulty for healthy participants. However, if a standardised protocol is to include participants with pathology e.g. stroke; a specified higher seat-height will be required between 115%KH [68] and 130%KH [69] as they are likely to find rising from 100%KH challenging [70]. One of the reviewed studies concluded that while a higher than normal seat-height (120%KH) required less effort compared to 100%KH, seat-height did not fundamentally alter the either STW or STSW task dynamics [54] and a higher seat-height is therefore desirable if a standardised protocol is to include participants with pathology.

Gender representation

Gender was nor reported in 4 or the 9 studies reviewed, and in the 5 who did, only 2 studies included females. Gender and sex-specific differences in pathological processes exist including cardiovascular and neurological diseases [71], and in gait kinematics and muscle activity [72]. So, it is vital that interpretations of RTW data are not based on male data alone. As such, if clinical practice is to be informed, those data must be drawn equally from males and females, irrespective of whether sex and gender biases are intentional or not [73].

Conclusions

This first of its kind systematic review confirmed our hypothesis that no published studies to date include an explicit aim to determine consistency in biomechanical parameters between RTW sub-tasks in healthy participants. The evidence synthesised from across the 9 eligible studies indicates that flexion-momentum time and peak BCOM vertical velocity during rising between STW and STS, and BCOM horizontal distance at initial toe-off between STW and GI are potentially consistent biomechanical parameters that do not vary significantly across RTW performance. Evidence from single studies revealed potentially 20 other consistent biomechanical parameters between RTW sub-tasks, particularly around the event of seat-off.

Seat-off represents a movement event associated with a high risk to postural stability in RTW. So, it is possible that parameter consistency was found here because postural stability is prioritised to mitigate risks of falling. Consistent parameters were also found after seat-off in GI and in the transition to walking, but it is unknown whether consistency observed here is simply a function of walking normalising downstream of RTW events. Nonetheless, this systematic review of the literature provides evidence supporting the notion that candidate consistent parameters might exist that could in theory discriminate and evaluate clinical change in the sensorimotor control of movement. Some of the parameters are based on temporal measures (e.g. flexion-momentum time) which means that clinical applications with patients performing RTW tasks using relatively low-tech equipment is certainly an aspiration if future work confirms parameters' consistency, validity, and reliability.

Any optimism associated with the evidence this systematic review provides needs to be cautious, however. Small sample sizes, inconsistent RTW protocols, and an under-representation of female gender limit the inferential nature of this evidence to a wider population. Therefore, while this systematic review suggests consistent biomechanical parameters across RTW subtasks exists, a specific evaluation of biomechanical parameters that remain consistent in a sample of both healthy male and female individuals between STW and STSW as the extremes of RTW is required.

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CRediT Author Statement

Gareth D Jones: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization, Project Administration. **Gareth L Jones:** Formal Analysis, Investigation, Writing – Review and Editing **Darren C James:** Conceptualization, Methodology, Writing – Review and Editing, Visualization, Supervision. **Michael Thacker:** Conceptualization, Methodology, Writing – Review and Editing, Supervision. **David A Green:** Conceptualization, Methodology, Validation, Resources, Writing – Review and Editing, Project Administration, Supervision.

Funding

The authors received no specific funding for this work.

Conflict of Interest Statement

There are no conflicts of interest among any of the authors.

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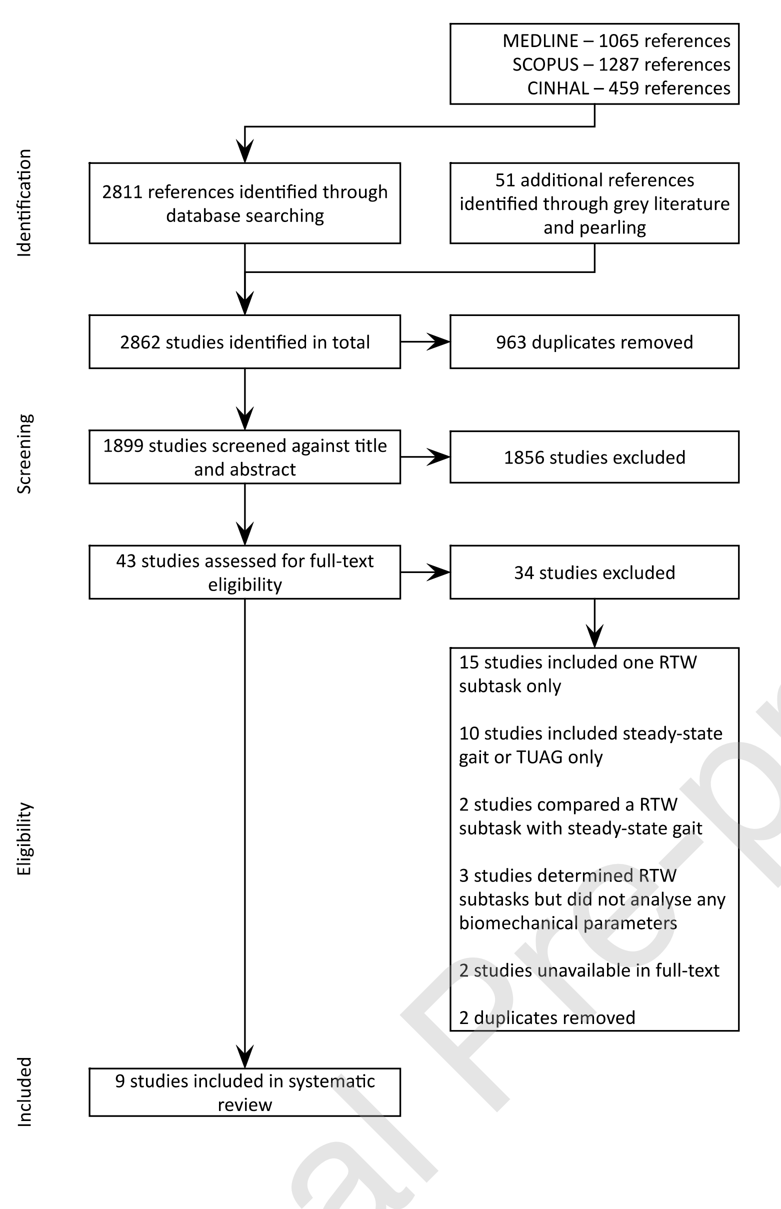

Figure 1: Search strategy flowchart

The strategy follows PRISMA guidelines for preferred reporting of systematic reviews [20]

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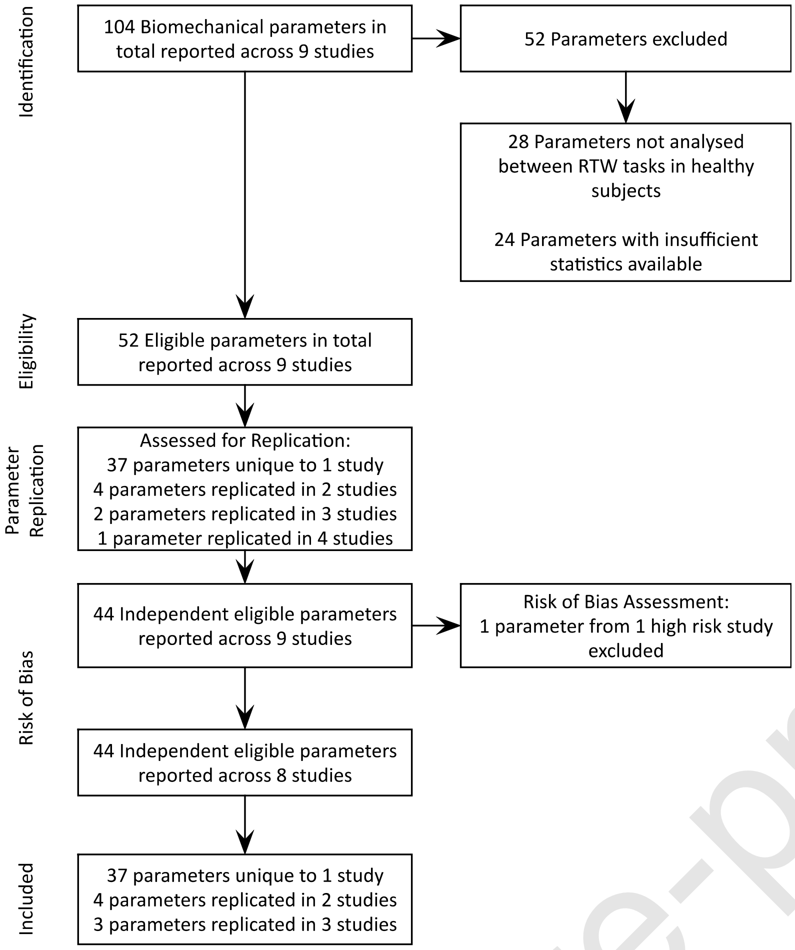

Figure 2: Final Biomechanical Parameter Inclusion Flowchart

Flow from total number of biomechanical parameters measured in the 7 reviewed studies, to parameter data eventually extracted after assessing for eligibility, replication, and risk of bias

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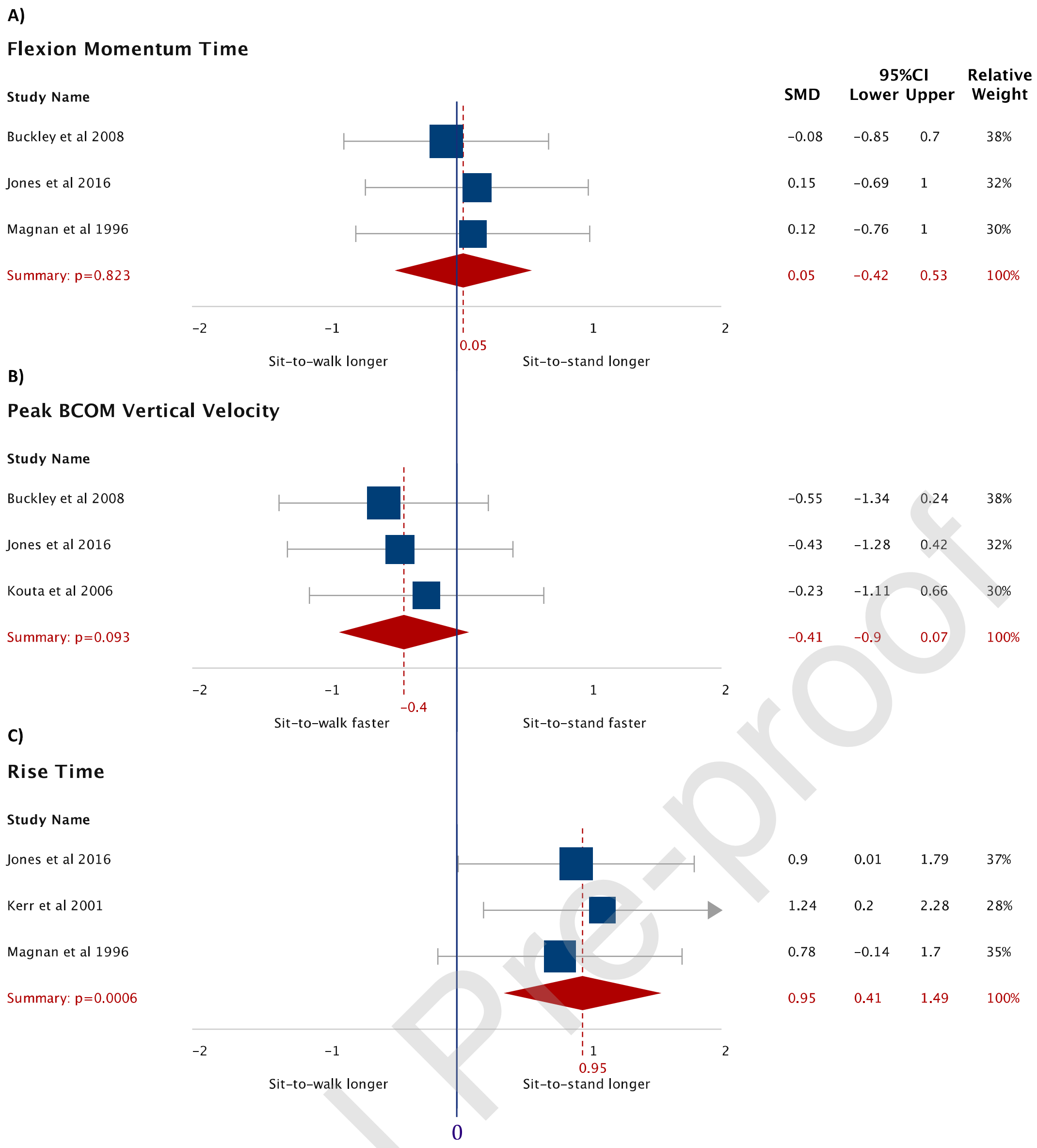

Figure 3: Combined-study effect sizes for parameters shared in 3 studies

Forest plots of the individual and combined-study weighted standardised-mean difference (SMD; Hedge's g) and 95%CIs calculated using fixed-effect models for 3 studies (n=31) measuring flexion-momentum time (movement-onset to seat-off) between STW and STS (panelA), 3 studies (n=31) measuring peak BCOM vertical velocity during rising between STW and STS (panel B) and 3 studies (n=27) measuring rise-time (movement-onset to upright) between STW and STS (panel C). No difference (consistency) is demarcated as a vertical line at zero (0).

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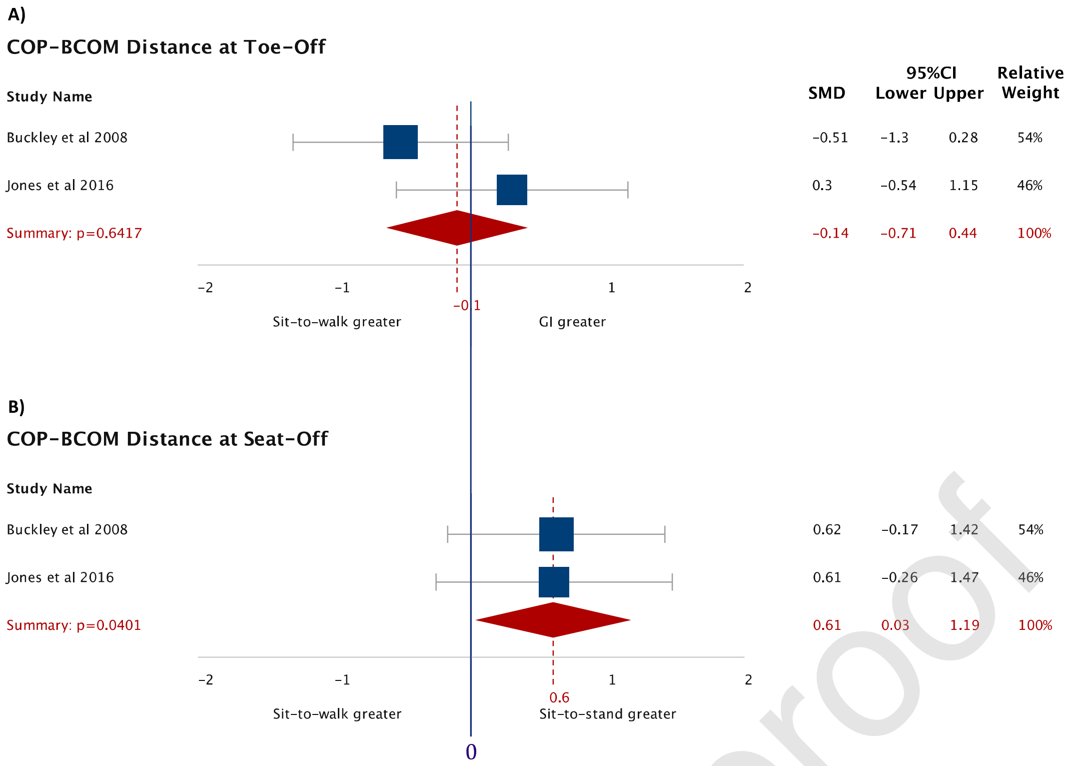

Figure 4: Combined-study effect sizes for COP-BCOM horizontal distance at seat-off and toe-off
Forest plots of the individual and combined-study weighted standardised-mean difference (SMD; Hedge's g) and 95%CI calculated using fixed-effect models for 2 studies (n=22) measuring centre-of-pressure (COP) to BCOM horizontal distance between STW and GI at the first toe-off event (panel A), and between STW and STS at the seat-off event (panel B). No difference (consistency) is demarcated as a vertical line at zero (0).

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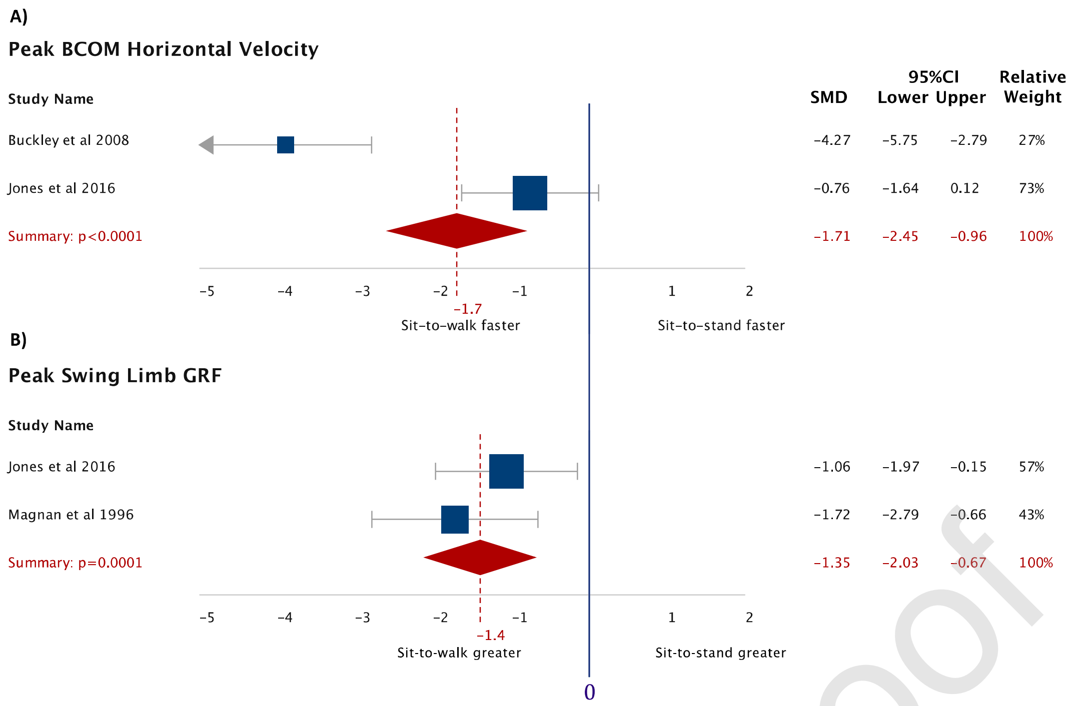

Figure 5: Combined-study effect sizes; peak horizontal velocity and peak swing-limb GRF

Forest plots of the individual and combined-study weighted standardised-mean difference (SMD; Hedge's g) and 95%CIs calculated using fixed-effect models for studies 2 (n=22) measuring peak BCOM horizontal velocity during rising between STW and STS (panel A), and 2 (n=19) studies measuring peak swing-limb ground-reaction-force (GRF) before 1st toe-off between STW and STS (panel B). No difference is demarcated as a vertical line at zero (0).

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Table 1: Included Studies' Participant and Protocol Characteristics

Included studies are listed with their aims by first author alphabetically showing; number of participants, gender, and mean (±SD) participant age, dominant limb, mass, plus walking distance and number of trials per RTW task.

			Gender (n)		Age (yrs)		Dom Leg (*n*)		Height (m)		Mass (kg)		Walk Distance (m)	Task Trials (*n*)
Study	Aim(s)	*n*	M	F	Mean	(SD)	Right	Left	Mean	(SD)	Mean	(SD)		
Buckley *et al* 2008	To determine if performance of the component STW tasks (STS and GI) are modified during STW in people with PD compared to age-matched healthy participants	12	NR	NR	63.0	(6.93)	NR	NR	1.698	(0.100)	79.20	(15.59)	4	5
Jones *et al* 2016	To determine if seat-height or limb-lead influence temporal and kinetic task dynamics either during STW or STSW in young healthy participants	10	5	5	29.1	(7.70)	9	1	1.710	(0.077)	73.50	(10.90)	5	5
Kerr & Kerr 2001	To determine if there are larger initial propulsive forces during STS compared to STW in young healthy participants	8	NR	NR	43.4	32-56†	NR	NR	NR	NR	NR	NR	NR	3
Kerr & Kerr 2002	To determine if there is a difference in the initial flexion momentum phase duration during STS compared to STW in healthy participants	14	NR	NR	39.8	(11.80)	NR	NR	1.760	(0.110)	80.90	(15.80)	NR	5
Kerr *et al* 2004	To determine discrete phases of STW movement (based on phases previously described during STS, and on events described during STW) and then assess the repeatability of the determined STW phases in healthy participants.	13	NR	NR	39.8	(12.30)	NR	NR	1.760	(0.100)	80.90	(15.80)	7	5
Kouta *et al* 2006	To determine if there are differences in temporal parameters during GI compared to STW and in peak horizontal and vertical velocities of the head-arms-trunk segment during STS compared to STW in young healthy male participants	9	9	0	21.8	(2.50)	NR	NR	1.703	(0.049)	65.10	(6.80)	3	NR
Magnan *et al* 1996	To determine how kinetic and spatial-temporal parameters during STS are modified with the additional task of gait-initiation during STW in young healthy male participants	9*	10	0	28.0	(6.00)	NR	NR	1.760	(0.050)	74.60	(11.40)	5	NR
Mezzarobba *et al* 2018	To determine if there are differences in postural control between progressively complex motor tasks (walking, GI, and STW) within participants with PD (±FOG) or age-matched healthy participants and thereby assess if PD motor profiles can be differentiated between those with, and without FOG	12	6	6	67.4	(8.70)	NR	NR	NR	NR	24.9‡	(3.9‡)	10	5
Silva *et al* 2013	To determine if the central nervous system requires longer to process information during STW (with the inclusion of a new task of GI) compared to STS by assessing anticipatory activation of muscle onset latencies in young healthy participants	12	12	0	24.5	(3.70)	NR	NR	1.720	(0.040)	70.92	(3.85)	–	5
All Studies	–	99	79%	21%	39.6	(16.30)	–	–	1.725	(0.071)	74.04	(10.72)	–	–

DOM – dominant; F – female; FOG – freezing-of-gait; GI – gait-initiation; M – male; NR - data "not reported"; PD – Parkinson's disease; STW – sit-to-stand; STW – sit-to-walk; STSW – sit-to-stand-and-walk; *Data analysed in this study based on n=9; †data refers to age range; ‡data refers to Body Mass Index (BMI) in kg/m^2

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Table 2: Included Studies' Protocol Constraint Characteristics and RTW Task Comparisons
Experimental protocol details with respect to movement tasks and within-study parameters

Study	Feet Position	Seat Height (%KH)	Seat Height (m)	Knee Angle (°)	Arm use	Tempo	Ecological Task	Lead Limb	RTW Subtask Comparisons
Buckley *et al* 2008	SS then maintained	NR	NR	105	Constrained to trunk	SS	Target or Object	SS then maintained	GI v STS v STW
Jones *et al* 2016	Standardised	100 & 120	–	–	NR	SS	UL Task	Dom and NonDom	STW v STSW
Kerr & Kerr 2001	Parallel	–	0.45	–	NR	SS	NR	SS then maintained	STS v STW
Kerr & Kerr 2002	Kept Constant	100	–	–	Constrained to trunk	SS	NR	NR	STS v STW
Kerr *et al* 2004	Parallel	100	–	–	Constrained to trunk	SS	NR	SS then maintained	STS v STW
Kouta *et al* 2006	Shoulder Width Apart	100	–	90	NR	SS	NR	NR	GI v STS v STW
Magnan *et al* 1996	SS	100	–	–	Constrained to trunk	SS	NR	SS then maintained	STS v STW
Mezzarobba *et al* 2018	SS then maintained	100	–	100	Constrained to waist	SS	NR	Left	GI v STW
Silva *et al* 2013	SS	NR	NR	90	NR	SS	NR	NR	STS v STW

Dom – dominant limb; GI – gait-initiation; NonDom – non-dominant limb; NR – data "not reported"; SS – self-selected; STS – sit-to-stand; STW – sit-to-walk; STSW – sit-to-stand-and-walk; UL – upper limb

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Table 3: Risk of Bias Within Studies

Consensus data are presented per quality domain for each paper with the inter-rater agreement shown as the κ statistic

	Risk of Bias Assessment Criteria								
Study	1. Inclusion criteria	2. Subject description	3. Exposure measurement	4. Condition Measurement	5. Confounders identified	6. Confounders managed	7. Outcome measurement	8. Statistical analyses	Overall Bias
Buckley *et al* 2008	0	1	0	0	0	0	0	0	1
Jones *et al* 2016	1	0	0	0	1	0	0	0	2
Kerr & Kerr 2001	1	1	0	0	2	1	1	0	6
Kerr & Kerr 2002	1	2	2	0	2	1	2	2	12
Kerr *et al* 2004	0	1	0	0	0	0	0	0	1
Kouta *et al* 2006	1	0	0	0	1	0	0	0	2
Magnan *et al* 1996	1	0	0	0	0	0	0	0	1
Mezzarobba *et al* 2018	0	0	0	0	0	0	0	0	0
Silva *et al* 2013	1	1	1	0	0	2	0	0	5
κ statistic	0.73	0.44	1.00	1.00	0.80	0.49	0.31	1.00	0.772

Scoring Code: 0 – Low bias; 1 – Unclear; 2 – High Bias

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Table 4: Effect sizes in biomechanical parameters unique to 1 study

Mean (SD) data for each RTW subtask are shown per biomechanical parameter with 95%CI around the effect-size g (Hedge's g). Individual parameters are shown for each study with studies listed in alphabetical order; parameters are described showing the RTW subtask comparison, the parameter type, measurement units with respect to movement event(s) associated with the respective parameter, and whether the parameter is consistent between the RTW subtasks (i.e. when the effect-size 95%CI includes the null value – the zero effect line.

Study		Parameter	Parameter Type (Units)	Event 1	Event 2	GI GI Mean (SD)	STS STS Mean (SD)	STW STW Mean (SD)	*g*	(95%CI)	*p*	Cons
Buckley *et al* 2008	1	Distance_Step Length (GI vs STW)	Distance Between Events (m)	Heel-off	Initial-contact	0.528 (0.048)	– –	0.581 (0.056)	-0.987	(-1.814 to -0.160)	0.019	N
Buckley *et al* 2008	2	Velocity_FirstStep Vel (GI vs STW)	Mean Velocity Between Events ($m.s^{-1}$)	Heel-off	Initial-contact	0.940 (0.173)	– –	1.080 (0.173)	-0.782	(-1.589 to 0.026)	0.058	Y
Buckley *et al* 2008	3	Distance_FirstStep Width (GI vs STW)	Distance Between Events (m)	Heel-off	Initial-contact	0.241 (0.065)	– –	0.282 (0.062)	-0.622	(-1.417 to 0.173)	0.125	Y
Buckley *et al* 2008	4	Distance_COP-BCOM_at Initial-Contact (GI vs STW)	Distance at Event (m)	Initial-contact	–	0.281 (0.037)	– –	0.337 (0.034)	-1.539	(-2.436 to -0.641)	0.001	N
Buckley *et al* 2008	5	Velocity_BCOM_Horizontal at Seat-off (STS vs STW)	Velocity at Event ($m.s^{-1}$)	Seat-off	–	– –	0.440 (0.069)	0.510 (0.069)	-0.977	(-1.803 to -0.151)	0.020	N
Jones et al 2016	6	Force_PeakGRF_Vertical (STS(W)* vs STW)	Max Force Between Events (%BW)	Movt-Onset	Seat-off	– –	130.0 (0.095)	136.0 (0.095)	-0.607	(-1.472 to 0.257)	0.169	Y
Jones *et al* 2016	7	Distance_COP-BCOM_at Upright (STS(W*) vs STW)	Distance at Event (m)	Upright	–	– –	0.020 (0.000)	0.140 (0.032)	-5.152	(-7.034 to -3.270)	0.000	N
Jones *et al* 2016	8	Distance_COP-BCOM_at GI-Onset (STS(W)* vs STW)	Distance at Event (m)	GI-onset	–	– –	0.020 (0.013)	0.050 (0.032)	-1.196	(-2.124 to -0.268)	0.012	N
Jones *et al* 2016	9	Time_GI-Onset to Swing Toe-off (GI Time) (STS(W)* vs STW)	Time Between Events (s)	GI-onset	Toe-off	– –	0.610 (0.095)	0.460 (0.095)	1.518	(0.541 to 2.495)	0.002	N
Jones *et al* 2016	10	Distance_Max COP-BCOM_Step1 (STS(W)* vs STW)	Max Dist Between Events (m)	Toe-off	Initial-contact	– –	0.250 (0.032)	0.260 (0.032)	-0.304	(-1.151 to 0.544)	0.483	Y
Jones *et al* 2016	11	Time_Step1 (STS(W)* vs STW)	Time Between Events (s)	Toe-off	Initial-contact	– –	0.440 (0.063)	0.400 (0.063)	0.607	(-0.257 to 1.472)	0.169	Y
Jones *et al* 2016	12	Distance_Max COP-BCOM_Step2 (STS(W)* vs STW)	Max Dist Between Event (m)	Initial-contact	Initial-contact2 (2nd)	– –	0.230 (0.032)	0.230 (0.032)	0.000	(-0.841 to 0.841)	1.000	Y
Jones *et al* 2016	13	Time_Step2 (STS(W)* vs STW)	Time Between Events (s)	Initial-contact	Initial-contact2 (2nd)	– –	0.620 (0.063)	0.580 (0.063)	0.607	(-0.257 to 1.472)	0.169	Y
Jones *et al* 2016	14	Distance_Max COP-BCOM_Step3 (STS(W)* vs STW)	Max Dist Between Events (m)	Initial-contact2 (2nd)	Initial-contact3 (3rd)	– –	0.260 (0.032)	0.260 (0.032)	0.000	(-0.841 to 0.841)	1.000	Y

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Study		Parameter	Parameter Type (Units)	Event 1	Event 2	GI GI Mean (SD)	STS STS Mean (SD)	STW STW Mean (SD)	*g*	(95%CI)	*p*	Cons
Jones *et al* 2016	15	Time_Step3 (STS(W)* vs STW)	Time Between Events (s)	Initial-contact2 (2^{nd})	Initial-contact3 (3^{rd})	– –	0.580 (0.032)	0.560 (0.032)	0.607	(-0.257 to 1.472)	0.169	Y
Jones *et al* 2016	16	Time_Movt-Onset to Step3 (Overall Movt Time) (STS(W)* vs STW)	Time Between Events (s)	Movt-Onset	Initial-contact3 (3^{rd})	– –	4.550 (0.569)	2.700 (0.253)	4.032	(2.469 to 5.59)	0.000	N
Jones *et al* 2016	17	Time_Go-Signal to Step3 (Overall Task Time) (STS(W)* vs STW)	Time Between Events (s)	Go-signal	Initial-contact3 (3^{rd})	– –	4.970 (0.569)	3.050 (0.285)	4.096	(2.515 to 5.677)	0.000	N
Kerr & Kerr 2001	18	Force_PeakGRF_Posterior (Braking) (STS vs STW)	Maximum Force Between Events (%BW)	Movt-Onset	Upright or Toe-off	– –	11.370 (2.130)	13.320 (3.620)	-0.623	(-1.582 to 0.335)	0.202	Y
Kerr & Kerr 2001	19	Force_PeakGRF_Anterior (Propulsive) (STS vs STW)	Maximum Force Between Events (%BW)	Movt-Onset	Upright or Toe-off	– –	0.260 (0.760)	1.430 (1.260)	-1.067	(-2.078 to -0.057)	0.038	N
Kerr & Kerr 2001	20	Time_Movt-Onset to PeakGRF_Anterior (STS vs STW)	Time Between Events (%Total Time)	Movt-Onset	PeakGRF_ Anterior	– –	30.040 (9.040)	35.780 (6.600)	-0.688	(-1.653 to 0.276)	0.162	Y
Kerr & Kerr 2001	21	Time_Movt-Onset to PeakGRF_Posterior (STS vs STW)	Time Between Events (%Total Time)	Movt-Onset	PeakGRF_ Posterior	– –	43.300 (3.000)	43.120 (5.620)	0.038	(-0.892 to 0.968)	0.936	Y
Kerr *et al* 2004	22	Force_PeakGRF_Mediolateral (STS vs STW)	Maximum Force Between Events (%BW)	Movt-Onset	Seat-off	– –	4.400 (0.580)	7.900 (0.985)	-4.199	(-5.601 to -2.797)	0.000	N
Kouta *et al* 2006	23	Time%_Movt-Onset to Peak HAT Vel_Horizontal (STS vs STW)	Proportional Time Between Events (%Total Time)	Movt-Onset	Peak HAT vel _Horizontal	– –	37.700 (2.400)	41.500 (4.800)	-0.957	(-1.899 to -0.014)	0.047	N
Kouta *et al* 2006	24	Time%_Movt-Onset to Peak BCOM Vel_Vertical (STS vs STW)	Proportional Time Between Events (%Total Time)	Movt-Onset	Peak BCOM Vel_Vertical	– –	67.900 (6.300)	66.600 (3.000)	0.252	(-0.635 to 1.139)	0.578	Y
Kouta *et al* 2006	25	Time%_Peak Swing GRF Vert to Swing Toe-off (GI vs STW)	Proportional Time Between Events (%Total Time)	Movt-Onset	Toe-off	54.900 (10.200)	– –	65.400 (10.100)	-0.988	(-1.935 to -0.041)	0.041	N
Kouta *et al* 2006	26	Distance_Total BCOM Displacememt_Horizontal (STS vs STW)	Distance Between Events (% of Height)	Movt-Onset	Upright	– –	0.183 (0.025)	0.329 (0.151)	-1.289	(-2.278 to -0.300)	0.011	N
Kouta *et al* 2006	27	Distance_Total BCOM Displacememt_Vertical (STS vs STW)	Distance Between Events (% of Height)	Movt-Onset	Upright	– –	0.167 (0.015)	0.159 (0.014)	0.527	(-0.375 to 1.428)	0.252	Y
Kouta *et al* 2006	28	Velocity_BCOM_Horizontal at Peak BCOM Vertical (STS vs STW)	Velocity at Event ($m.s^{-1}$)	Peak BCOM Vertical Velocity	–	– –	0.160 (0.060)	0.370 (0.180)	-1.495	(-2.519 to -0.472)	0.004	N
Kouta *et al* 2006	29	Velocity_Peak HAT_Horizontal before Seat-off (STS vs STW)	Maximum Velocity Between Events ($m.s^{-1}$)	Movt-Onset	Seat-off	– –	0.620 (0.090)	0.720 (0.110)	-0.950	(-1.893 to -0.008)	0.048	N

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Study		Parameter	Parameter Type (Units)	Event 1	Event 2	GI GI Mean (SD)	STS STS Mean (SD)	STW STW Mean (SD)	*g*	(95%CI)	*p*	Cons
Kouta *et al* 2006	30	Force_Stance-Limb PeakGRF_Vertical (GI vs STW)	Maximum Force Between Events (%BW)	Movt-Onset	Initial-contact	115.300 (4.100)	– –	108.200 (7.100)	1.170	(0.199 to 2.141)	0.018	N
Magnan *et al* 1996	31	Time_Movt-Onset to Peak BCOM Momentum_Horizontal (STS vs STW)	Time Between Events (s)	Movt-Onset	Peak BCOM Momentum Horizontal	– –	0.680 (0.120)	0.620 (2.110)	0.038	(-0.844 to 0.921)	0.932	Y
Magnan *et al* 1996	32	Time_Movt-Onset to Peak BCOM Momentum_Vertical (STS vs STW)	Time Between Events (s)	Movt-Onset	Peak BCOM Momentum Vertical	– –	1.110 (0.170)	1.020 (0.160)	0.521	(-0.380 to 1.422)	0.257	Y
Magnan *et al* 1996	33	Momentum_Peak BCOM_Horizontal (STS vs STW)	Max Momentum Between Events (kg.m.s^{-1})	Movt-Onset	Upright	– –	39.100 (6.000)	47.800 (7.400)	-1.234	(-2.214 to -0.253)	0.014	N
Magnan *et al* 1996	34	Momentum_Peak BCOM_Vertical (STS vs STW)	Max Momentum Between Events (kg.m.s^{-1})	Movt-Onset	Upright	– –	47.700 (6.800)	53.800 (8.300)	-0.768	(-1.960 to 0.154)	0.102	Y
Magnan *et al* 1996	35	Position_BCOM_AP_at Seat-off (STS vs STW)	Position at Event (m) AP direction	Seat-off	–	– –	-0.014 (0.035)	-0.012 (0.028)	-0.060	(-0.943 to 0.823)	0.894	Y
Magnan *et al* 1996	36	Position_COP_AP_at Seat-off (STS vs STW)	Position at Event (m) AP direction	Seat-off	–	– –	0.026 (0.023)	0.024 (0.031)	0.070	(-0.813 to 0.953)	0.877	Y
Magnan *et al* 1996	37	Force_Stance-Limb PeakGRF_Vertical (STS vs STW)	Maximum Force Between Events (%BW)	Movt-Onset	Peak BCOM Momentum Vertical	– –	59.260 (3.950)	57.300 (3.790)	0.484	(-0.415 to 1.382)	0.291	Y

Cons – consistent parameter; COP – centre-of-pressure; Distance_ – refers to a distance measurement parameter; Force_ – refers to a ground-reaction-force measurement parameter; GI – gait-initiation; GRF – ground-reaction-force; Max – maximum; Momentum_ – refers to a momentum measurement parameter; Movt – movement; NR – data "not reported"; Position_ – refers to a position in a certain direction measurement parameter; STS – sit-to-stand; STS(W) – sit-to-stand-and-walk; STW – sit-to-walk; Time_ – refers to a time-related measurement parameter; vel – velocity; Velocity_ – refers to a velocity measurement parameter; vert – vertical; vs – versus; *refers to data from STSW analogous to STS

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Table 5: Summary of all consistent kinematic and kinetic biomechanical parameters

RTW subtask comparisons of parameters with their respective RTW phase or event are shown with single-study (g) and combined (M) effect-sizes and 95%CIs which cross the line of zero-effect

No.	Phase/Event	Consistent Parameter	Study	RTW Subtask 1	RTW Subtask 2	Effect Size *g*	Effect Size *M*	95%CI	*p*
1	Rising	Time_Movement-Onset to Seat-off (Flexion Mom Time)	Buckley *et al* 2008 Jones *et al* 2016 Magnan et al 1996	STW STW STW	STS STS* STS	-0.079 0.152 0.121	0.055	(-0.423 to 0.533)	0.823
2	Rising	Time_ Movement -Onset to Peak BCOM Momentum_Horizontal	Magnan *et al* 1996	STW	STS	0.038	–	(-0.844 to 0.921)	0.932
3	Rising	Time_ Movement -Onset to Peak BCOM Momentum_Vertical	Magnan *et al* 1996	STW	STS	0.521	–	(-0.380 to 1.422)	0.257
4	Rising	Time_ Movement -Onset to PeakGRF_Anterior	Kerr and Kerr 2001	STW	STS	-0.688	–	(-1.653 to 0.276)	0.162
5	Rising	Time_ Movement -Onset to PeakGRF_Posterior	Kerr and Kerr 2001	STW	STS	0.038	–	(-0.892 to 0.968)	0.936
6	Rising	Time%_ Movement -Onset to Peak BCOM Velocity_Vertical	Kouta *et al* 2006	STW	STS	0.252	–	(-0.635 to 1.139)	0.578
7	Rising/Seat-off	Position_BCOM_AP_at Seat-off	Magnan *et al* 1996	STW	STS	-0.060	–	(-0.943 to 0.823)	0.894
8	Rising/Seat-off	Position_COP_AP_at Seat-off	Magnan et al 1996	STW	STS	0.070	–	(-0.813 to 0.953)	0.877
9	Rising	Velocity_Peak BCOM_Vertical	Buckley *et al* 2008 Jones *et al* 2016 Kouta *et al* 2006	STW STW STW	STS STS* STS	-0.551 -0.429 -0.228	-0.415	(-0.898 to 0.069)	0.093
10	Rising	Momentum_Peak BCOM_Vertical	Magnan *et al* 1996	STW	STS	-0.768	–	(-1.690 to 0.154)	0.102
11	Rising	Force_PeakGRF_Vertical	Jones *et al* 2016	STW	STS*	-0.607	–	(-1.472 to 0.257)	0.169
12	Rising	Force_Stance-Limb PeakGRF_Vertical	Magnan *et al* 1996	STW	STS	0.484	–	(-0.415 to 1.382)	0.291
13	Rising	Force_PeakGRF_Posterior (Braking)	Kerr and Kerr 2001	STW	STS	-0.623	–	(-1.582 to 0.335)	0.202
14	Rising	Distance_Total BCOM Displacememt_Vertical	Kouta *et al* 2006	STW	STS	0.527	–	(-0.375 to 1.428)	0.252
15	GI/Toe-off	Distance_COP-BCOM_at Toe-off	Buckley *et al* 2008 Jones *et al* 2016	STW STW	GI GI*	-0.514 0.299	-0.137	(-0.712 to 0.439)	0.642
16	Walking/Step1	Distance_Max COP-BCOM_Step1	Jones *et al* 2016	STW	STS*	-0.304	–	(-1.151 to 0.544)	0.483
17	Walking /Step1	Time_Step1	Jones *et al* 2016	STW	STS*	0.607	–	(-0.257 to 1.472)	0.169
18	Walking /Step1	Distance_FirstStep Width	Buckley *et al* 2008	STW	GI	-0.622	–	(-1.417 to 0.173)	0.125
19	Walking /Step1	Velocity_FirstStepBCOM Velocity	Buckley *et al* 2008	STW	GI	-0.782	–	(-1.589 to 0.026)	0.058
20	Walking /Step2	Distance_Max COP-BCOM_Step2	Jones *et al* 2016	STW	STS*	0.000	–	(-0.841 to 0.841)	1.000
21	Walking /Step2	Time_Step2	Jones *et al* 2016	STW	STS*	0.607	–	(-0.257 to 1.472)	0.169
22	Walking /Step3	Distance_Max COP-BCOM_Step3	Jones *et al* 2016	STW	STS*	0.000	–	(-0.841 to 0.841)	1.000
23	Walking /Step3	Time_Step3	Jones *et al* 2016	STW	STS*	0.607	–	(-0.257 to 1.472)	0.169

COP – centre-of-pressure; Distance_ – refers to a distance measurement parameter; Force_ – refers to a ground-reaction-force measurement parameter; GI – gait-initiation; GRF – ground-reaction-force; Momentum_ – refers to a momentum measurement parameter; Position_ – refers to a position in a certain direction measurement parameter; STS – sit-to-stand; STW – sit-to-walk; Time_ – refers to a time-related measurement parameter; Velocity_ – refers to a velocity measurement parameter; *refers to data from STSW analogous to STS

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