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A Novel Method of Analysis for Prolonged-Standing Data: Accounting for Joint and Muscle Discomfort

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Abstract

Background: The typical American worker spends about two-thirds of their work day standing. Prolonged standing has been found to be associated with acute and chronic adverse health outcomes. There is considerable variability among existing methods of analysis for prolonged-standing data, and therefore difficulty interpreting and comparing results across studies.

Purpose: The purpose of this study is to develop a bodyweight transfer analysis method that incorporates factors of both time and amplitude of loading. This method was then applied to actual prolonged-standing data, to understand how the results of this method are impacted by time spent standing, and how the results relate to previously-reported methods of analysis for weight shifting data.

Methods: Seven subjects (six male, one female) stood with each foot on one of two force plates for 6 h with a 5-min seated rest break between hours. Our new method identified two different types of events: fidgets and weight shifts. Center-of-pressure data were analyzed with the proposed method and three existing methods of analysis.

Results: Subjects utilized different quantities of fidgets and weight shifts over the course of the trials. Existing methods of analysis identified a wide range in number of events, with some methods consistently identifying more events than others. These existing methods significantly differed from the proposed method. Fidgets, weight shifts, and fidgets + weight shifts, as identified using the proposed method, had significant interactions with time, while only one of the existing methods showed a significant time interaction.

Conclusions: The conclusions drawn from analysis of prolonged standing center-of-pressure data can differ significantly depending on the method of analysis used. The method proposed here accounts for the different sources of discomfort and the tissue characteristics of these sources. Future work should explore the relationships between physiologic parameters and fidgets and weight shifts, so that appropriate clinical interventions can be identified.

Keywords

prolonged standing; occupational health; posture

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INTRODUCTION

The typical American worker spends 61% of their workday—approximately 5 h of an 8-h day—standing or walking (Bureau of Labor Statistics, 2016). It has been previously reported that prolonged standing is associated with acute adverse health outcomes, such as lower extremity joint compression, discomfort, muscle fatigue, and swelling (Balasubramanian, Adalarasu, & Regulapati, 2009; Canadian Centre for Occupational Health and Safety, 2014; Halim, Omar, Saman, & Othman, 2012; Krijnen, de Boer, Ader, & Bruynzeel, 1997a; Partsch, Winiger, & Lun, 2004). Chronic adverse health outcomes have also been reported to include cardiovascular insufficiency, osteoarthritis, and lower extremity edema (Canadian Centre for Occupational Health and Safety 2014; Krijnen, de Boer, Ader, & Bruynzeel, 1997b; McCulloch, 2002; Sudol-Szopinska, Panorska, Kozinski, & Blachowiak, 2011). Despite these findings, a recent review by Waters and Dick (2015) identified inconsistency among existing prolonged standing literature, and called for improved characterization of prolonged standing such that the biomechanical factors that may contribute to these adverse health effects can be better understood (Waters & Dick, 2015).

A commonly reported and important outcome measure during prolonged standing is the change in force distribution over time, often reported as weight shifts. Cham and Redfern (2001) studied weight shifts over 4 h of prolonged standing on different flooring types and found that subjective ratings of discomfort/fatigue differed significantly across flooring conditions in the last 2 h, while differences in the number of weight shifts were only significant in hour 4. A significant, positive relationship was found during hours 3 and 4 between the number of weight shifts performed and subjective discomfort/fatigue suggesting one performs more weight shifts as he or she becomes more uncomfortable/tired. Wiggermann and Keyserling (2013) found significant differences in subjective ratings of discomfort during the last hour of 4-h prolonged standing trials on commercially-available anti-fatigue mats when compared to standing on hard flooring. Like Cham and Redfern (2001), Wiggermann and Keyserling (2013) found a significant, positive correlation between the number of weight shifts performed and ratings of perceived discomfort. Further, weight shifting was found to increase significantly over time, with no significant association between flooring material and weight shifting identified, indicating that the time spent standing impacts weight shifting behavior and subjective discomfort more so than the flooring material being stood on. Work by Prado, Dinato, and Duarte (2011) found differences in the amplitude of weight transfers performed (0.1 × bodyweight to 0.5 × bodyweight vs. > 0.5 × bodyweight) between different age groups during 30-min unconstrained standing trials, with the younger cohort performing significantly more large-amplitude weight transfers than the older adults.

As previously stated, numerous investigators have found significant outcomes associated with events occurring during prolonged and/or unconstrained standing, however the methods by which they calculate these measures vary greatly (Table 1). Zhang, Drury, and Woolley (1991) first introduced the concept of classifying movements during prolong standing by defining a four-item visual scale for identifying the severity and presence of postural movements, ranging from “just noticeable movement” to “body center of gravity change with both feet changing location” (p. 178). Cham and Redfern (2001) defined a “weight shift" (CWS) as a change in the lateral center of pressure (COP) measurement greater than 10% of the total COP range seen for a given trial. Wiggermann and Keyserling (2013) defined the same term, "weight shift" (WWS), as a change in bodyweight distribution lasting 7.5 s or more between conditions where less than 20% bodyweight was endured by either leg or greater than 20% bodyweight was endured by both legs simultaneously. Prado et al. (2011) utilized the term "weight transfer" (PWT) to define any cumulative sum of vertical ground reaction forces greater than 0.5 × bodyweight that also surpassed a fixed drift parameter threshold. Though Prado et al. (2011) also identified a small amplitude weight transfer, only PWT with amplitudes greater than 0.5 × bodyweight are considered in the present analysis. The variety of methods for obtaining and presenting information on bodyweight distribution changes during prolonged standing makes it difficult to compare across studies (Redfern & Cham, 2000), compare between subjects (Prado et al., 2011), and most importantly, contextualize physiologically in terms of injury risk and prevention.

During prolonged standing, blood settles due to the effects of gravity, muscles fatigue as a combined result of circulatory insufficiencies and low-level contractions sustained over time to maintain the upright position, and cartilage deforms secondary to joint loading through weight bearing (Waters & Dick, 2015; Zhang et al., 1991). Wiggermann and Keyserling (2013) suggested that "weight shifting temporarily relieves pressure on the feet, allows replenishment of synovial fluid in joint cartilage, and decreases venous pooling in the lower extremities" (p. 772). Prado et al. (2011) suggested that "postural changes are […] a physiological response to reduce musculoskeletal fatigue and discomfort […] triggered by somatosensory information" (p. 96). Cham and Redfern (2001) related weight shifts to discomfort and fatigue, suggesting "as participants become increasingly tired, there is an overall increase in the number of weight shifts" (p. 388). Further, the same authors make note of controlling for skin temperature "related to edema formation and local blood flow during standing" (p. 390). It has been hypothesized that individuals voluntarily alter their COP distribution to affect the muscle tension and cartilage pressure that results from the above-mentioned effects of prolonged standing on muscles and cartilage (Wiggermann & Keyserling, 2013). A focus of previous work on the link between weight shifting and discomfort during prolonged standing has been on the muscle pump action; we propose that the cartilage loading that occurs plays an equally important role, and that individuals may utilize different weight shifting behaviors in response to these two different sources of discomfort.

The goal of the present study was thus to propose a bodyweight transfer analysis method that incorporates factors of both time and amplitude of loading. This analysis was then applied to 6 h of prolonged-standing data to understand how the results of this analysis method are impacted by time spent standing and how the results relate to previously-reported methods of analysis for weight shifting data. We hypothesized that the results from these various methods would differ in the number of events they identify and their significance across different domains. Further, we argue that the results from the proposed method provide meaningful context to movements identified during prolonged standing and their possible link to physiological sources of discomfort.

METHODS

Study Population

Seven healthy adults (one female, six males) were screened and consented to participate in the study. Mean (*SD*) participant demographics were as follows: age = 22.6 (2.6) years, height = 180.2 (8.3) cm, mass = 79.8 (14.1) kg, and BMI = 24.6 (3.9) kg/m^2. Subjects were included in the study if they had no history of dizziness or balance problems, osteoporosis, orthopedic problems within the last 3 years such as fractures or ligament tears, nor neurological, pulmonary, or cardiovascular health issues. Subjects self-verified that they were able to stand for 2–6 h and self-identified the proportion of each day spent standing (five reported 10–25%, two reported 25–50%). The same brand of polyvinyl chloride (PVC) soled work shoes and socks were provided to subjects to be worn during the testing session. Prolonged standing sessions were completed in the morning at the Medical Virtual Reality Center at the University of Pittsburgh's Eye and Ear Institute. Subjects were asked to not participate in exercise during the 48 h prior to each visit. The study protocol was approved by University of Pittsburgh's Institutional Review Board.

Procedure and Data Acquisition

Subjects stood with one foot on each of two 40 × 60 cm^2 balance plates (BP5050, Bertec Corporation, Columbus, OH) for 6 h. Subjects were allowed a 5-min seated rest period between each hour. The balance plates tracked postural changes during standing via force distribution at a sampling rate of 1000 Hz. Subjects were instructed to stand comfortably and maintain ground contact with both feet during the entire testing session. They were allowed to alter their weight distribution between legs but were not instructed to do so. Stance width was self-selected by each participant to be most representative of their natural standing posture. A standing desk was provided to subjects so they could perform a computer task of their choosing. Subjects were instructed to not lean on the desk, but were allowed to place their hands on computer keyboard to interact with the task chosen. Sixth hour data was missing for one subject, so the final analysis was performed on 41 h of data (6 h for six subjects and 5 h for one subject).

Data Analysis

Data were down sampled with MATLAB Version 2017a (The MathWorks Inc., Natick, MA) to 20 Hz for analysis. The vertical force output from each plate was analyzed to investigate the weight endured by the left and right feet during standing. The main variables of interest for this study were weight shifts (WS) and fidgets (F) as determined by the proposed method (Figure 1). A WS was identified when an individual changed the distribution of bodyweight endured by his or her dominant leg by greater than ± 10% bodyweight and sustained this change for at least 7.50 s (Wiggermann & Keyserling, 2013). An F was defined as the same change in bodyweight distribution lasting between 0.75 and 7.49 s. These two different movement types were identified with the theoretical backing that cartilage is made of a stiffer material than muscle tissue and therefore deforms more slowly (Athanasiou, Rosenwasser, Buckwalter, Malinin, & Mow, 1991; Bol, Leichesenring, Ernst, & Ehret, 2016; Collinsworth, Zhang, Kraus, & Truskey, 2002; Miramini, Smith, Zhang, & Gardiner, 2017). Further, whereas muscles rely on nutrients and oxygen from blood, cartilage is much more poorly vascularized (Fox & Bedi, 2009; Harms, 2000). For these reasons, it was considered reasonable to assume that faster movements (represented by F) may more closely relate to muscle discomfort and blood flow, while slower, sustained movements (represented by WS) may more closely relate to cartilage de-loading. All outputs were examined by two researchers for appropriateness of the identified events. If an F was identified on the transition into or out of a WS, it was manually removed from the dataset when erroneously identified as an isolated event. If a cluster of F events were identified without an appreciable change in bodyweight distribution between them, a single F was manually chosen as a representative for the event. Discrepancies between researchers were discussed with a third researcher until a consensus could be reached.

Statistical Analysis

All data were analyzed for identification of F, WS, CWS, WWS, and PWT (Cham & Redfern, 2001; Prado et al., 2011; Wiggermann & Keyserling, 2013). In order to determine if, for each method, the mean number of events identified (F, WS, CWS, WWS, and PWT) differed between time points (hours 1–6), one-way repeated measures ANOVAs were performed. In addition, one-way repeated measures ANOVAs were also performed to determine whether, within each hour, the mean number of CWS, WWS, and PWT separately differed from F, WS, and the combination of F and WS. For significant ANOVAs, post-hoc analyses were used to identify significant results.

RESULTS

Fidgeting and Weight Shifting Behaviors over Time

Force data from each subject were analyzed using the proposed method to identify F and WS during each hour. As shown in Figure 2, individuals utilize different quantities of F and WS during prolonged standing. For example, subjects a-e performed more F than WS in a given hour, while subjects f and g performed more WS than F.

For the number of F, WS, and total movements, a significant main effect of time was observed ($p = 0.033$, $p = 0.0059$, $p < 0.001$, respectively; Figure 3). Post-hoc analysis revealed a significantly higher number of F at hour 5 of standing, WS at hour 3, and total movements at hour 3.

Each subject's data were also analyzed using three existing analysis methods (Cham & Redfern, 2001; Prado et al., 2011; Wiggermann & Keyserling, 2013). For each method, there were no significant main effects of time for CWS ($p = 0.232$) nor PWT ($p = 0.112$), but there was a significant main effect of time for WWS ($p = 0.0368$). Post-hoc analyses show a significantly higher number of WWS starting at hour 4.

Comparison of Methods

Hour 4 data for two different subjects are displayed in Figure 4. Each method of analysis identified a different number of events for the same data (Figures 4 and 5), with CWS generally yielding the largest amount, WWS the smallest amount, and PWT a moderate amount falling somewhere between WWS and CWS for a given sample of data. However, while total counts of events identified by each method differed, there was some overlap regarding where in the data that the events were identified (i.e., there were few instances in the data where only one method identified an event at a given time point). Visual inspection of Figure 4 also reveals a marked difference in the shape of the bodyweight distribution trace when comparing between the two subjects. The shape of the trace shows how often the individual was changing his or her bodyweight distribution, and by how much; metrics captured by F and WS.

Differences between existing methods and the developed F and WS method were explored within each hour of prolonged standing. CWS was found to be significantly different than F, WS, and total movements for each hour spent standing (Table 2; Figure 5). PWT was not found to be significantly different than F, WS, or total movements. WWS was found to be significantly different than F and total movements for each hour spent standing but was not different than WS (Table 2; Figure 5).

DISCUSSION

We developed a novel bodyweight transfer analysis method for use during standing that takes into account both time and amplitude of loading. The results of the current study indicate that the proposed method, and the three existing methods of analysis for body weight transferring during prolonged-standing data, each provide results that differ from one another. Much of previous prolonged-standing literature has discussed the relationship between bodyweight transfers and discomfort (Cham & Redfern, 2001; Prado et al., 2011; Wiggermann & Keyserling, 2013). However, the results of our study imply that inferences drawn about the relationship between bodyweight transfers and discomfort are made less meaningful by the inconsistency across methods.

The number of events identified across methods (F, WS, CWS, WWS, and PWT), as seen in Figures 3 and 5, indicate that variability exists not only across methods but also within each method. Large standard errors were observed, likely attributed to between-subject differences and the small sample size used in this analysis. Certain methods tend to identify a larger number of events (CWS, PWT) than other methods (WWS, WS), and with a greater amount of spread. The different time, frequency, and amplitude thresholds for each method play a role in this observed difference.

When all analysis methods are applied to the same data, there is overlap in terms of when events are identified. This indicates that the methods output similar results, despite different threshold requirements to identify an event. Time was found to be a significant main effect only for F, WS, F + WS, and WWS. The hours at which these effects were found to be significant differed by method. Because of this, certain time points are given meaning when utilizing one method, while other time points are given the same meaning when a different method of analysis is used. Therefore, the conclusions we draw from the data differ significantly based on the method used. Importantly, occupational recommendations for workers who perform prolonged standing will vary based on which method was used for analysis (Ebben, 2003; Marras & Karwowski, 2006; van Dieen & Oude Vrielink, 1998).

With each method of analysis offering a different picture of the data, it can be difficult to reconcile which method provides the most utility. Studying weight-shifting behaviors and discomfort during prolonged standing seeks to infer something about the types of movements people perform to relieve the discomfort occurring at joints and in muscles (Wiggermann & Keyserling, 2013). Each tissue type (cartilage or muscle tissue) experiences loading cycles as a result of the time-dependent strain characteristics of the tissue and the speed at which the loads are applied or removed. Cartilage deformation is more sensitive to time under prolonged compression when compared to muscle tissue (Athanasiou et al., 1991; Bol et al., 2016; Collinsworth et al., 2002; Miramini et al., 2017). Therefore, a faster movement (F) may be more indicative of a muscle-relieving movement, whereas a slower, prolonged movement (WS) may be more indicative of a cartilage-relieving movement. Our proposed method accounts for the different sources of discomfort and the time-dependent strain characteristics of each tissue type.

It is important to note that the theory linking F to muscle relief and WS to cartilage relief is just that. More work should be done to look at the responses of these tissues with different amplitude and duration movements to better understand their effects. Also, the sample used in the present analysis was primarily young adult males of a healthy weight who spend as much as 25%–50% of their day standing or walking. While this may not be representative of the typical occupational cohort who are exposed to prolonged standing, the merits of the proposed analysis method are in the different types of movements accounted for and the theoretical framework which supports the need for these outcomes (F, WS).

Our proposed method identifies postural changes in ways similar to those previously presented, but classifies them in ways that provide more information about the time and magnitude of the postural strategy used. Furthermore, the proposed method lends itself to a better understanding of what amount of weight may be tolerated by the body before postural adjustment is initiated, as well as how long it takes to make that adjustment. As can be seen in Figure 2, some individuals tend to rely more on quick movements (“primary fidgeters”), while others tend to rely more on slower, prolonged movements (“primary shifters”) to relieve discomfort. Having the two different kinds of events identifiable by the proposed method gives insight into the types of movements the individual is making, and not just how many movements are occurring. If the individual’s strategy changes, the proposed method is able to identify these changes.

Further exploring the type of strategy used may give useful information about the etiology of the individual’s discomfort and, by extension, direct subject-specific interventions. Examples include pressure relief footwear/flooring to help off-load cartilage (Lewinson et al., 2017) vs. endurance-focused strength program to aid with circulation (Hughes, Ueda, & Casey, 2016). Future work should explore physiological parameters as they relate to WS and F, such that clinical and occupational interventions can be most appropriately applied.

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OCCUPATIONAL APPLICATIONS

Prolonged standing, often required in healthcare, factory, and retail jobs, is associated with adverse health effects. In the present study, we introduce a novel method for analyzing prolonged-standing data, which accounts for time-dependent strain characteristics of both cartilage and muscle tissue to identify two different types of weight distribution change events. Compared to existing methods for analyzing this type of data, our proposed method provides more information about the amplitude and temporal quality of the movements occurring. If a worker were to stand on a surface that measures postural sway during a typical work day, this analysis method could identify the types of movements an individual makes, and help infer sources of discomfort. By understanding the movement strategy utilized, the most appropriate work environment adaptations can be put into place to decrease discomfort. These environmental adaptations may have downstream effects on worker satisfaction and days on disability.

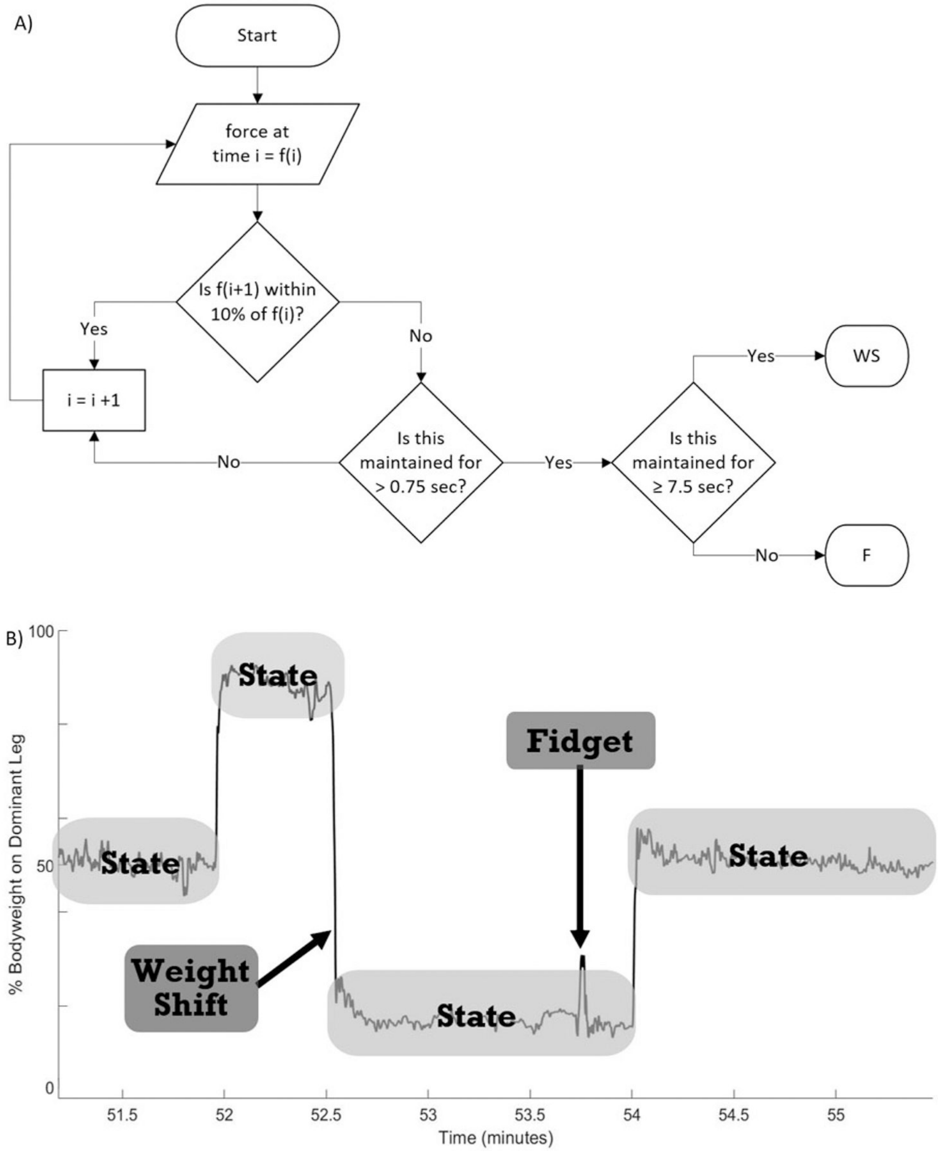

FIGURE 1.

(A) Logic used for proposed method. (B) Visual representation of weight shifts and fidgets as defined by the proposed method – a change from one state (a window of ±10% bodyweight) to another lasting at least 7.50 s (weight shift), or out of and back into a state over a time span of greater than 0.75 s but less than 7.50 s (fidget).

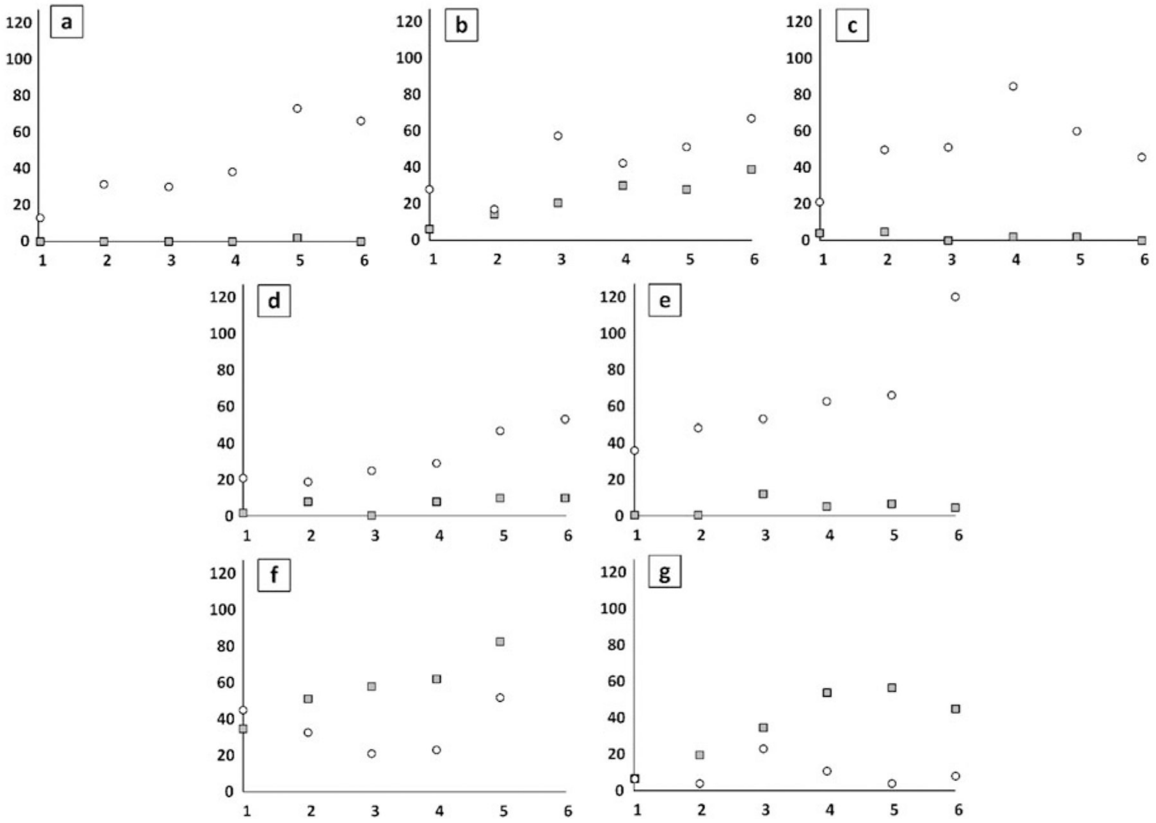

FIGURE 2.

Number of events identified per hour for each of the seven subjects (a–g), with white circles denoting the number of F and gray squares denoting number of WS.

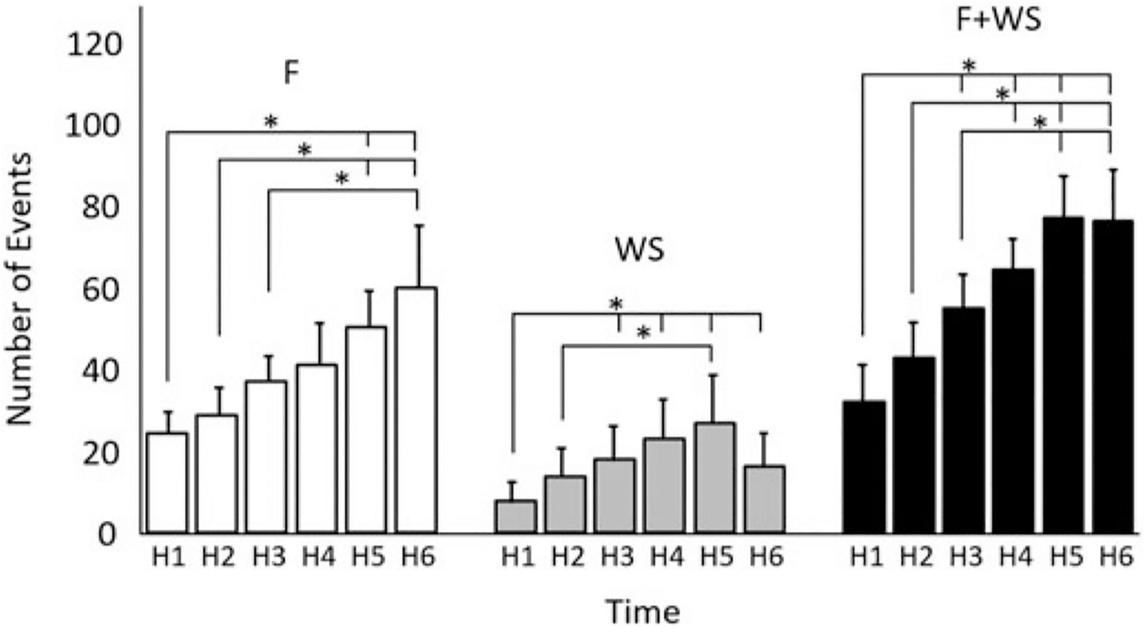

FIGURE 3.

Mean number of events identified across all subjects within each hour (HX). F, WS, and total events (F + WS) shown in white, gray, and black, respectively. Error bars represent standard errors. Significant results of post hoc paired comparisons are provided (* denotes significantly different number of events between hours).

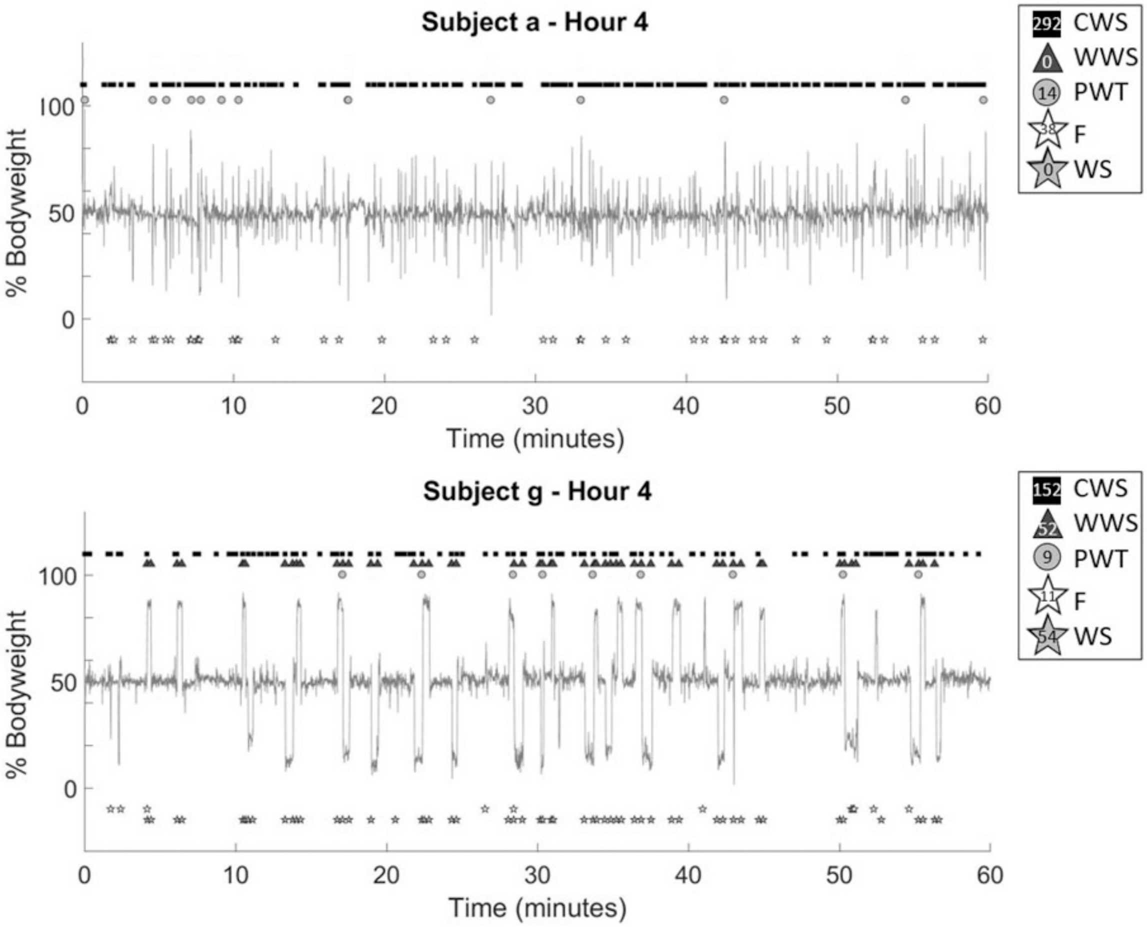

FIGURE 4.

Percent bodyweight on the dominant leg by time for 1 h of data for two different subjects. Events identified by each of the four analysis methods are denoted by circles (PWT), triangles (WWS), squares (CWS), or pentagrams (white = F, grey = WS) with totals for the hour summarized on the right side of the graph.

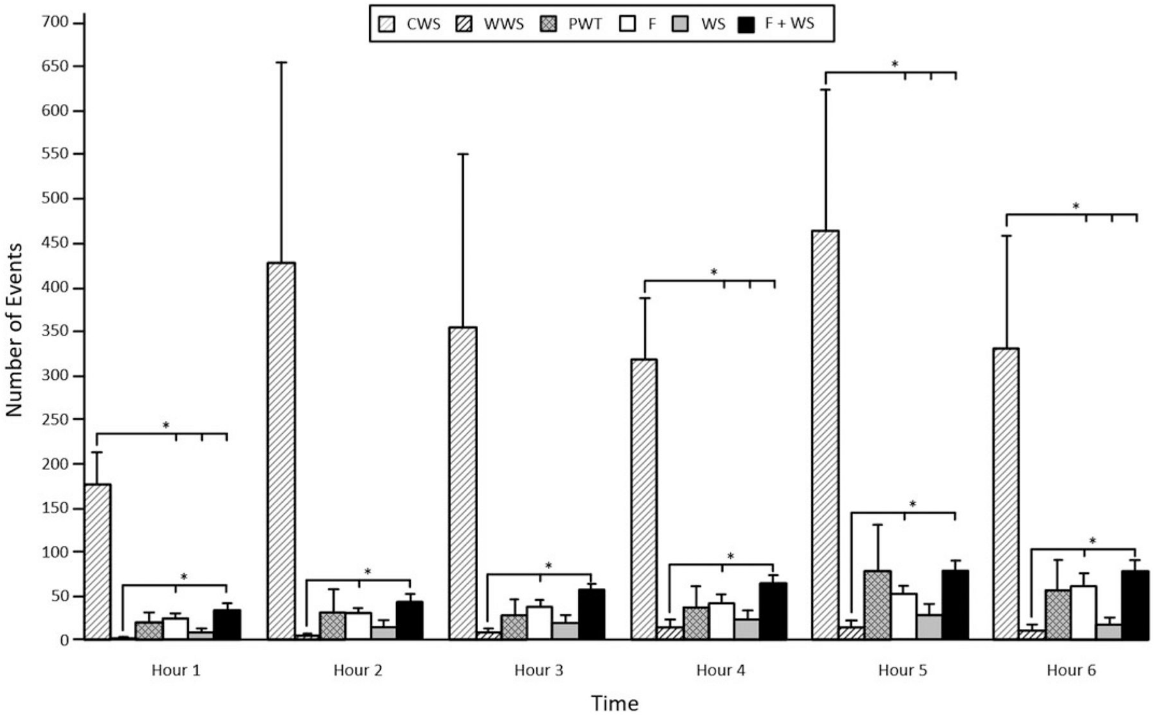

FIGURE 5.

Mean number of events identified per hour for each method. CWS, WWS, and PWT are shown in white with gray diagonal lines, white with black diagonal lines, and gray with black hash, respectively. F, WS, and total events (F + WS) are shown in white, gray, and black, respectively. Error bars represent standard errors. Significant results of post hoc tests are provided (* denotes significantly different number of events between methods).

TABLE 1.

Summary of different methods explored for analyses of prolonged-standing data.

Method	Output variable	Criteria
Cham and Redfern (2001)	Cham weight shift (CWS)	Time: N/A Amplitude: change in lateral center of pressure > 10% of total range observed during trial
Wiggermann and Keyserling (2013)	Wiggermann weight shift (WWS)	Time: ≥ 7.5 s Amplitude: change between states • <20% bodyweight on dominant leg • <20% bodyweight on non-dominant leg • >20% bodyweight on both legs simultaneously
Prado et al. (2011)	Prado weight transfer (PWT)	Time: N/A Amplitude: > 50% bodyweight as determined by cumulative sum of vertical ground reaction force Other: fixed drift parameter must also be surpassed

TABLE 2.

Statistical comparisons of the number of events identified by existing methods vs. the number of F, WS, or total events (F + WS) identified by proposed method within each hour.

Time	CWS	WWS	PWT
Hour 1	[*]$p < 0.0001$	[*]$p < 0.0001$	$p = 0.12$
	$F = 16.75$	$F = 14.93$	$F = 2.22$
	F, WS, F + WS	F, F + WS	
Hour 2	$p = 0.06$	[*]$p = 0.0006$	$p = 0.61$
	$F = 3.00$	$F = 9.38$	$F = 0.62$
		F, F + WS	
Hour 3	$p = 0.09$	[*]$p = 0.0001$	$p = 0.12$
	$F = 2.55$	$F = 12.41$	$F = 1.72$
		F, F + WS	
Hour 4	[*]$p < 0.0001$	[*]$p = 0.003$	$p = 0.31$
	$F = 14.16$	$F = 6.74$	$F = 1.29$
	F, WS, F + WS	F, F + WS	
Hour 5	[*]$p = 0.004$	[*]$p = 0.0005$	$p = 0.55$
	$F = 6.34$	$F = 9.72$	$F = 0.72$
	F, WS, F + WS	F, F + WS	
Hour 6	[*]$p = 0.02$	[*]$p = 0.001$	$p = 0.22$
	$F = 4.72$	$F = 9.17$	$F = 1.63$
	F, WS, F + WS	F, F + WS	

In each cell, the p-value, F-value, and post hoc results are provided.

[*] Significantly different number of events was identified between methods.