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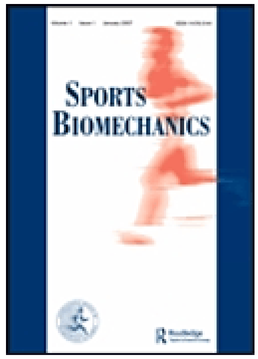

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A narrative review of potential measures of dynamic stability to be used during outdoor locomotion on different surfaces

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Abstract

Dynamic stability of locomotion plays an important role in running injuries, particularly during trail running where ankle injuries occur frequently. Several studies have investigated dynamic stability of locomotion using wearable accelerometer measurements. However, no study has reviewed how dynamic stability of locomotion is quantified using accelerometry. Therefore, the present review aims to synthetise the methods and findings of studies investigating stability related parameters measured by accelerometry, during locomotion on various surfaces, and among asymptomatic participants. A systematic search of studies associated with locomotion was conducted. Only studies including assessment of dynamic stability parameters based on accelerometry, including at least one group of asymptomatic participants, and conditions that occur during trail running were considered relevant for this review. Consequently, all retrieved studies used a non-obstructive portable accelerometer or an inertial measurement unit. Fifteen studies used a single tri-axial accelerometer placed above the lumbar region allowing outdoor recordings. From trunk accelerations, a combination of index of cycle repeatability and signal dispersion can adequately be used to assess dynamic stability. However, as most studies included indoor conditions, studies addressing the biomechanics of trail running in outdoor conditions are warranted.

Word count: 186

Key words: Biomechanics, Outdoor measurement; Gait; Trail running

Introduction

During trail running, the main component is non-paved stable or unstable surface such as grass, mud, rock, sand, and snow, and no more than 20% is asphalt (Malliaropoulos, Mertyri, & Tsaklis, 2015). Trail running involves uphill, downhill, and horizontal trails. Trail running is often performed over long distances, i.e. the so-called ultra-marathons (>42.195 km and up to 330 km) (Malliaropoulos et al., 2015; Vernillo et al., 2017). Because of the harsh conditions, such races are considered highly challenging from a physiological, neuromuscular and biomechanical standpoint (Millet et al., 2009, 2011). Consequently, periods of running are intertwined with periods of walking (Librett, Yore, & Schmid, 2006; Millet et al., 2011; Vernillo et al., 2017; Williamson, 2016). Unstable natural terrain surfaces might provoke ankle instability which again may cause severe stress around the ankle joint (Malliaropoulos et al., 2015). In addition, in a retrospective study 38 out of 114 ultra-distance runners reported previously sustained lateral ankle injuries from running (Hiemstra & Naidoo, 2009). Furthermore, the ankle is the region most often injured (36%), and ankle injuries are predominant in trail tracks compared with road tracks (Bishop & Fallon, 1999). Some researchers have investigated protective factors for trail running injuries and found that stability shoes, personalised training, and running accommodation in mountain environments could lead to a decreased injury rate (Khodaee et al., 2011; Malliaropoulos et al., 2015). However, no studies have investigated the dynamic stability in outdoor and natural conditions even though it is generally considered an important aspect of trail environments (Degache et al., 2014; Schütte et al., 2016). Actually, the trail environment consists of both stable and unstable surfaces resulting in predictable and unpredictable perturbations (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012; Vercruyssen, Tartaruga, Horvais, & Brisswalter, 2016). Further, the transitions between walking and running (Millet et al., 2011; Williamson, 2016) result in frequent disruptions challenging the stability of the running pattern (Chang, Sejdić, Wright, & Chau, 2010; Gates et al., 2012; Marigold & Patla, 2002).

Analyses of the dynamic stability of the running pattern are usually made using 3D motion capture systems. Motion analysis using reflective markers is considered a *gold standard* in the determination of movement variations (Cole et al., 2014). However, restrictions often apply such as small calibrated spaces, transportation difficulties, and ambient light noise (Cole et al., 2014). Accelerometers can collect data over long distances, they are lightweight and easily wearable allowing biomechanical recordings in real-world environments (Cole et al., 2014; Moe-Nilssen, 1998a; Villumsen, Madeleine, Birk, Holtermann, & Samani, 2017). Further, accelerometers have been used during prolonged outdoor trail investigations (Chelius et al., 2011; Giandolini, Pavailler, Samozino, Morin, & Horvais, 2015). Accelerometry has proven to be a reliable method to estimate variations during locomotion on both predictable and unpredictable irregular surfaces (Cole et al., 2014; Crowley, Madeleine, & Vuillerme, 2016; Kobsar, Osis, Hettinga, & Ferber, 2014; Moe-Nilssen, 1998c). Moreover, using accelerometry in outdoor settings may prove useful in identifying and correcting trail runners' technique and thus may have the potential to prevent injuries (Lee, Sutter, Askew, & Burkett, 2010; Schütte, Maas, Exadaktylos, & Berckmans, 2015). After removing the confounding effects of both the gravity measurement and accelerometer orientation, the method enables accelerations to be expressed relative to vertical (VT), mediolateral (ML), and anteroposterior (AP) directions (Moe-Nielsen, 1998a) and to assess the dynamic stability of locomotion.

Dynamic stability during locomotion is typically analysed by normalising and averaging data from independent strides. However, focusing on the events that occur during an average stride implicitly implies that each stride is generated independently of the past and future strides and that stride-to-stride variations are random. Therefore, a complete description of locomotor control requires an understanding of how movements are controlled from one stride to the next (Dingwell, Cusumano, Cavanagh, & Sternad, 2001). This fundamental control task of locomotion is defined as maintaining dynamic stability. In this review, dynamic stability is defined as the ability to maintain variability, symmetry, regularity, or complexity during locomotion on stable or unstable terrain (Schütte, Seerden, Venter, & Vanwanseele, 2018). The traditional measures of dynamic stability are often divided into groups based on the size of the perturbation. The first group of measures reflect the ability to recover from small perturbations, such as the maximum Lyapunov exponent and the maximum Floquet multiplier (Bruijn, Meijer, Beek, & van Dieen, 2013). The second group of measures reflect the ability to recover from large or external perturbations, such as assessments of accelerometric signal characteristics, coefficients of variation, and nonlinear analyses (Bizovska, Svoboda, & Janura, 2015; Bruijn et al., 2013). Of note, the ability to overcome local perturbations may be independent of the ability to overcome external perturbations such as unstable surfaces (Bruijn et al., 2013; McAndrew, Wilken, & Dingwell, 2011).

It is important to understand that during trail running many different scenarios occurs. The runner meets frequent surface changes, including compliant, irregular and flat surfaces. At the same time, running is often intertwined with walking due to the harsh conditions. Therefore, the present review aims to synthetise the methods and findings of studies investigating dynamic stability related parameters measured by accelerometry during walking and running on various surfaces among asymptomatic participants. We hypothesised that the synthesis of the retrieved studies would provide a scientific basis to assemble a novel method for future trail running studies. As such, a better knowledge and understanding of the adaptations to various surface types are of major importance for injury prevention and performance optimisation in trail running.

Method

Search strategy

In this narrative review, an electronic search was conducted in the Scopus, PubMed, and MEDLINE databases (March 2019). Due to the limited amount of scientific literature on 'trail running', search terms related to locomotion on flat, ascending and descending terrain as well as uneven surfaces or obstacles also reflecting trail running were included. The search terms were combined and resulted in the following string: trail running OR ultra-running OR running OR walking AND dynamic stability AND unstable OR irregular OR destabilising AND surface AND accelerometry OR accelerometer OR IMU OR inertial measurement unit (IMU) AND asymptomatic. The purpose of the search was to find all articles in which accelerometry is used to measure the stability of asymptomatic participants under conditions that may occur in trail running. These conditions include both running and walking on stable and unstable surfaces.

Study selection

The primary studies were considered relevant for this review if (1) the assessment of dynamic stability parameters was based on accelerometry, (2) at least one group of asymptomatic participants took part, (3) the studies were conducted in conditions occurring during trail running. This includes both walking and running, flat and uneven surfaces as well as obstacles. Only full-texts in English indexed from 1960 to 2019 were included in the search. A manual search for relevant articles was also performed based on the reference lists of the retrieved articles. Because this review aimed to discuss dynamic stability related parameters during locomotion on various surfaces types, articles investigating locomotion on different surfaces were targeted during this process.

Coding of studies

All of the included studies were coded for the following variables: study characteristics (author(s), title and year of publication); participant characteristics (number of participants, gender, age, and physical condition); accelerometry (type of accelerometer, placement, sampling frequency, and sensing range); locomotion condition (indoor or outdoor and surface type); gait speed; and outcome parameters (inter-step or inter-stride variability, signal dispersion methods, as well as motion and displacement).

Figure 1. Near Here

Results

Search yield

Initially, the keyword search yielded a total of 1438 articles. Due to the limited number of articles specifically investigating dynamic stability during trail running (4 out of 1438), conditions transferable to trail running were included in this review. The selection process based on the inclusion criteria resulted in 13 relevant articles. Additionally, a manual search based on the included studies was made. Four articles were added resulting in a total of 17 experimental studies. None of the retrieved studies directly assessed dynamic stability during trail running. The selection process is illustrated in Fig. 1.

Table 1. Near here

Participants

The reviewed articles tested participants with varying numbers (from two to 102 participants), ages, and physical characteristics. All studies included at least one experimental group of asymptomatic participants. Thirteen studies included an experimental group composed of young participants (<30 years old) (Boey, Aeles, Schütte, & Vanwanseele, 2017; Cole et al., 2014; Dixon et al., 2018; Iosa et al., 2012; Kavanagh, Barrett, & Morrison, 2004; Menant, Steele, Menz, Munro, & Lord, 2011; Menz, Lord, & Fitzpatrick, 2003; Mifsud, Kristensen, Villumsen, Hansen, & Kersting, 2014; Moe-Nilssen, 1998b, 1998c; Schütte et al., 2016; Schütte, Seerden, Venter, & Vanwanseele, 2018; van Schooten, Rispens, Elders, van Dieën, & Pijnappels, 2014).

Gait conditions

The experimental procedures included five running conditions and 13 walking conditions, as shown in Table 1.

Surface inclination and type: Nine locomotion studies, i.e., seven on walking and two on running were conducted exclusively on a flat surface (Auvinet et al., 2002; Bachasson et al., 2016; Floor-Westerdijk, Schepers, Veltink, Asseldonk, & Buurke, 2012; Henriksen, Lund, Moe-Nilssen, Bliddal, & Danneskiod-Samsøe, 2004; Iosa et al., 2012; Kavanagh et al., 2004; Mifsud et al., 2014; Schütte et al., 2018; van Schooten et al., 2014), whereas eight studies, i.e., six on walking and two on running were performed on both uneven terrain and a flat surface (Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c; Schütte et al., 2016). The irregular surface conditions consisted of either (1) an irregular woodchip trail (Boey et al., 2017; Schütte et al., 2016), (2) an irregular surface with wooden blocks hidden underneath a layer of turf (Cole et al., 2014; Menant et al., 2011; Menz et al., 2003) or rubber plates underneath foam (Moe-Nilssen, 1998c), (3) an irregular brick walkway (Dixon et al., 2018) (4) newly fallen snow (Moe-Nilssen, 1998b), or (5) a compliant surface (Cole et al., 2014).

Locomotion speed: Self-selected walking speed was used in 11 studies (Auvinet et al., 2002; Bachasson et al., 2016; Cole et al., 2014; Dixon et al., 2018; Floor-Westerdijk et al., 2012; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b; van Schooten et al., 2014). Three running studies applied fixed running speeds (Boey et al., 2017; Mifsud et al., 2014; Schütte et al., 2018) and two studies were performed at self-selected running speed (Boey et al., 2017; Schütte et al., 2016).

Walking or running distance: The required walking or running distance varied between studies. For the majority of walking studies, the gait track length was between 7 and 40 m (Angelis, Bragoni, & Paolucci, 2012; Auvinet et al., 2002; Bachasson et al., 2016; Cole et al., 2014; Dixon et al., 2018; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998c) Only two studies used a track length of 400 m and above (Boey et al., 2017; van Schooten et al., 2014). For the running studies, the track length varied between 90 and 3200 m (Boey et al., 2017; Schütte et al., 2016, 2018). All studies with a track length ≤ 90 m recorded several trails for both walking and running.

Accelerometer

Fifteen studies used tri-axial accelerometers (Auvinet et al., 2002; Bachasson et al., 2016; Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c, Schütte et al., 2016, 2018; van Schooten et al., 2014) and two studies used accelerometry integrated in an IMU (Floor-Westerdijk et al., 2012; Mifsud et al., 2014). Sampling frequencies varied from 50 to 1024 Hz and sensing range from ± 19.6 to ± 539.5 m/s^2.

Method of fixation: In 15 studies, either an accelerometer unit or IMU was fixed to the trunk (Auvinet et al., 2002; Bachasson et al., 2016; Cole et al., 2014; Dixon et al., 2018; Floor-Westerdijk et al., 2012; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c, Schütte et al., 2016, 2018; van Schooten et al., 2014). Two studies used an extra accelerometer fixed to the head (Kavanagh et al., 2004; Menz et al., 2003) and one study used an accelerometer fixed to the tibia (Schütte et al., 2018). One study used a single accelerometer fixed to the tibia (Boey et al., 2017) and one study had an additional accelerometer on calcaneus along with a tibia fixed accelerometer (Mifsud et al., 2014).

Signal processing: Five studies using a trunk accelerometer or IMU applied a trigonometric correction of the acceleration signal Moe-Nielssen (1998a) to compensate for lumbar curvature (Cole et al., 2014; Henriksen et al., 2004; Kavanagh et al., 2004; Schütte et al., 2016, 2018). The most common filter used among the included studies was a zero-lag 4th order low-pass Butterworth filter with a cut-off frequency between 8-50 Hz (Cole et al., 2014; Dixon et al., 2018; Schütte et al., 2016, 2018) or a zero-lag 2nd order low-pass Butterworth filter with a cut-off frequency between 10-60 Hz (Boey et al., 2017; Floor-Westerdijk et al., 2012; Mifsud et al., 2014). Accelerometry-based measures were computed in windows of different lengths. The majority of studies used windows described in steps ranging from four to 60 consecutive steps (Angelis et al., 2012; Auvinet et al., 2002; Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Kavanagh et al., 2004; Menant et al., 2011; Schütte et al., 2016, 2018; van Schooten et al., 2014). Other studies used windows described in meters (Henriksen et al., 2004; Menz et al., 2003; Moe-Nilssen, 1998c) or in seconds (Bachasson et al., 2016). All studies used the middle period of the required walking or running distance to secure computation of parameters in a steady pace.

Figure 2. Near Here

Outcomes assessing inter-step or inter-stride variability

Some of the studies did not strictly assess gait stability, such as margin of stability. Instead, these studies assessed the gait characteristics and variability from the acceleration signal, which have been used in literature to describe gait stability as illustrated in Figure 2. Table 2 shows that analyses of the complexity, rhythmicity and smoothness of the acceleration signal were performed. Step time variability (Menant et al., 2011; Menz et al., 2003), acceleration amplitude variability (Menz et al., 2003; van Schooten et al., 2014), and coefficient of variation of stride time (Bachasson et al., 2016) were used as indexes of repeatability of cycles. Several studies used autocorrelation to assess the variability between steps and strides by analysing the acceleration signal regularity from a factor of periodicity between consecutive steps (Bachasson et al., 2016; Dixon et al., 2018; Schütte et al., 2016). This method is not only an index of step–to-step variation in length and time but also an index of acceleration amplitude variation. Another similar waveform analysis describing the harmonic ratio in a signal was also utilised (Auvinet et al., 2002; Iosa et al., 2012; Menz et al., 2003). The sample entropy method was used by three of the studies to quantify the fluctuations of the acceleration signal (Bachasson et al., 2016; Schütte et al., 2016, 2018). Sample entropy is an analysis evaluating the repeatability of the pattern of the acceleration signal (Richman & Moorman, 2000). See Appendix for more details on computational aspects related to the outcomes of dynamic stability.

Outcomes assessing signal dispersion

The majority of studies included the amplitude of the acceleration (i.e. root mean square - RMS) in their analysis (Bachasson et al., 2016; Cole et al., 2014; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c). Some studies also computed the resultant acceleration RMS (Dixon et al., 2018; Henriksen et al., 2004) and ratio of acceleration RMS (Schütte et al., 2016, 2018). This provided an understanding of the entire signal as well as the ratio of the signal amplitude across VT, ML, and AP directions, respectively. The RMS of the acceleration reflects the average amplitude of the signal with high value associated with impaired stability (Menant et al., 2011). The ratio of acceleration RMS serves as an indicator of how much each direction contributes to the movement. Higher RMS trunk accelerations are reported when walking on irregular surface in ML (Menant et al., 2011; Menz et al., 2003) and in AP direction (Menant et al., 2011; Menz et al., 2003; Schütte et al., 2016) compared with walking on a flat surface. It has been suggested that the RMS of acceleration could differ between walking on flat and uneven terrains (Moe-Nilssen, 1998c). Menz et al. (2003) reported a difference in RMS of acceleration between walking on an irregular and a regular surface confirming that this measure assesses dynamic stability (Moe-Nilssen, 1998c). See also Appendix for more details.

Table 2. Near Here

Discussion and Implications

This is the first review to analyse and evaluate studies, which have assessed dynamic stability during locomotion using accelerometry, with the intention of transferring these methods into an analysis of the dynamic stability during trail running. Our analysis showed that one accelerometer fixed to the trunk would be appropriate to use for monitoring dynamic stability during locomotion. Using a single trunk-fixed accelerometer, a combination of measures of cycle repeatability and signal dispersion can be computed to describe different aspects of dynamic stability. In the retrieved studies, measures of dynamic stability were mostly extracted from indoor recordings made over relatively short gait distances and on regular or artificial irregular surfaces. Overall, and in support of our hypothesis, the retrieved studies provided a scientific basis to assemble a novel method that could be used in trail running studies. These findings have direct implications for researchers and practitioners interested in outdoor assessments of trail running performance and injury prevention.

Initially, it should be acknowledged that no trail running studies were directly identified. However, in line with our hypothesis, the retrieved recordings and analysis methods can be transferred to locomotion conditions that occur during trail running. Schütte et al. (2016) investigated outside running on a 90 m woodchip trail, which approached the desired conditions. However, woodchip trails are rarely found in natural environments. Further, woodchip trails lack the random irregularities often encountered in real trail environments (Easthope et al., 2014). Therefore, it may be more valid and effective to assess dynamic stability during trail running in outdoor settings. However, tests in outdoor settings often affect the reproducibility due to the variety of environmental influences such as temperature, weather, and surface conditions (Easthope et al., 2014). Nevertheless, previous studies have successfully investigated parameters such as risk of injuries (Khodaee et al., 2011; Malliaropoulos et al., 2015), foot strike pattern (Giandolini et al., 2017, 2015; Horvais & Giandolini, 2013; Kasmer, Liu, Roberts, & Valadao, 2013), and fatigue (Easthope et al., 2010, 2014; Giandolini et al., 2017; Vercruyssen et al., 2016) during prolonged locomotion in outdoor trail environments. In line with outdoor investigations, research involving dynamic stability is yet to be examined in trail running conditions. Even though the included articles address non-trail investigations, biomechanical adaptations due to surface irregularities have been reported (Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c; Schütte et al., 2016). Based on the results from the included studies, it seems applicable to capture the dynamic stability from recordings made over a relatively short gait distance (Angelis et al., 2012; Auvinet et al., 2002; Bachasson et al., 2016; Cole et al., 2014; Dixon et al., 2018; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-

Nilssen, 1998c). Thus, the use of an irregular surface with wooden blocks hidden underneath a layer of turf may be an appropriate method to simulate trail running conditions in a laboratory environment (Cole et al., 2014; Menant et al., 2011; Menz et al., 2003). However, as these studies included walking conditions, it is necessary to reproduce the methods during running. Moreover, running would require a longer track length or more running trials to secure a sufficient number of steps. Optimally, measurements should take place in-situ, potentially during a trail running competition.

This literature review included eight studies investigating the effects of irregular or compliant surfaces or the effect of outdoor environments on dynamic stability. Six of these eight studies examined dynamic stability during walking questioning the generalisation of results during running on irregular surfaces. The influence of the transition between walking and running on dynamic stability has been investigated in several studies, showing that the dynamic stability decreases with an increase in speed (Dingwell & Marin, 2006; England & Granata, 2007; Jordan, Challis, Cusumano, & Newell, 2009; Mehdizadeh, Arshi, & Davids, 2014). It is well known that the gait speed influences the gait performance and gait biomechanical measures. Variations in the requirements to maintain dynamic stability during gait are also evident when the speed is changed (Kavanagh & Menz, 2008). During trail running, the runners adjust their gait speed constantly due to surface perturbations or slope changes. Therefore, it is important to consider the impact of speed on the included measures of gait variability. Twelve of the included studies used self-selected speed when performing the gait analysis. Moe-Nilssen and Helbostad (2004) have suggested to ask participants to move at a self-selected speed to account for the confounding effects of different gait speed. Using a single tri-axial accelerometer fixed to the trunk at L3 vertebrae level, estimations of step frequency, step length, measures of gait regularity and symmetry (Moe-Nilssen & Helbostad, 2004), and acceleration RMS (Henriksen et al., 2004) could be obtained using an unbiased autocorrelation procedure. Schütte et al. (2016) investigated the influence of speed on dynamic stability parameters during outdoor running on a woodchip trail surface using accelerometry autocorrelation procedures. The authors found that the surface effects were unaffected when speed was introduced as a confounding factor. Therefore, the authors of the current review suggest using self-selected speeds when measuring dynamic stability during trail running to use the natural rhythmicity of the upper body accelerations thus increasing the ecological validity.

In 15 studies, an accelerometer was fixed to the trunk. In 11 of those, a single tri-axial accelerometer was used. From the trunk movements, the majority of the included measures were related to cycle repeatability, signal dispersion, and displacements. However, some considerations must be made due to the low frequency and amplitude oscillations associated with trunk accelerations (Kavanagh & Menz, 2008). To avoid errors in the measured accelerations during trail running, the trunk accelerometers should have an appropriate sensing range, i.e., sensing range ≥ ±313.8 m/s^2 (Mitschke, Kiesewetter, & Milani, 2018) and be able to detect high frequencies, i.e., sampling frequency ≥ 100 Hz (Kavanagh & Menz, 2008). Regarding signal processing, the raw VT, ML, and AP signals from the accelerometer should be trigonometrically corrected to remove the static gravitational component and filtered using an appropriate filter to remove motion-related frequencies (i.e. <5-6 Hz). One limitation of using a single tri-axial accelerometer attached to the trunk is the lack of knowledge about the effect of the natural shock absorption mechanism of the foot and the compensating kinematic and kinetic strategies at the knee and hip joints (Menant et al., 2011). Thus, applying an additional accelerometer on the tibia or foot could contribute with knowledge of the damping effects occurring between the foot or shank and the trunk.

Nevertheless, a single trunk-fixed accelerometer can be used to calculate a combination of the index of cycle repeatability and signal dispersion to assess dynamic stability during locomotion. Four studies implemented autocorrelation procedures to assess dynamic stability (Auvinet et al., 2002; Bachasson et al., 2016; Dixon et al., 2018; Schütte et al., 2016). Autocorrelation procedures have been found to be sufficiently sensitive to measure the acceleration step and stride regularity during running on an outdoor surface (Schütte et al., 2016). Further, such procedures enable the elimination of unwanted variables of interest introduced with self-selected speeds (Moe-Nilssen & Helbostad, 2004). Sample entropy would be an appropriate method to characterise control mechanisms in human locomotion and can be seen as a measure of dynamic stability during running despite a relatively high computational cost (Arshi, Mehdizadeh, & Davids, 2015; Schutte, Aeles, De Beeck, van der Zwaard, Venter, & Vanwanseele, 2016). The computation of acceleration RMS and the autocorrelation-based coefficients reflecting step and stride regularity as well as symmetry can be advantageous since these outcomes enable the detection of asymmetrical stability patterns in various environments (Dixon et al., 2018; Schütte et al., 2016, 2018). The variability of cycles in a repeatable acceleration signal is also an indirect measure of dynamic stability. This measurement of deviations in the acceleration signal between steps allows the exploration of how a biological signal fluctuates from its equilibrium state. Interestingly, this index of regularity between participants can be normalised across walking or running speed and anthropometrics values (Moe-Nilssen & Helbostad, 2004; Schütte et al., 2016). The deviations in acceleration have even been used to classify athletes based on their training background (Kobsar et al., 2014). In the future, it would be beneficial to identify the influence of training on dynamic stability and injury risks.

This review has some limitations. Firstly, it should be mentioned the studies reviewed were not conducted in situ that is to say in natural environment. Secondly, the experimental protocols had substantial discrepancies, e.g., the size ranged from 2 to 102, surface conditions varied, and walking and running were performed at different speeds. However, our choice of studies is justified by the fact that trail running is a discipline which includes various surface types as well as locomotion types, i.e., walking and running are often intertwined (Librett et al., 2006; Millet et al., 2011; Vernillo et al., 2017; Williamson, 2016). The third limitation concerns the validity and reliability of accelerometers as gait assessment tools. Optoelectrical motion analysis methods are considered the *gold standard* to evaluate locomotion stability (Cole et al., 2014). Wearable sensors assessing dynamic gait stability on stable and unstable surfaces have been found to be a viable and valid measurement system compared with optoelectronic measurements (Bruijn et al., 2010; Byun, Han, Kim, & Kim, 2016; Cole et al., 2014; Teufl et al., 2018; van Schooten et al., 2014). Moreover, the reliability of collection of acceleration data has been found to be high when walking on stable and unstable surfaces (Henriksen et al., 2004; Moe-Nilssen, 1998c; van Schooten et al., 2014). Still, the reliability of dynamic stability measures based on wearable accelerometers or IMU recordings remains to be demonstrated in conditions including, e.g., long-distance outdoor locomotion on different types of surfaces.

Conclusion

The purpose of this narrative review was to evaluate the biomechanical assessments of dynamic stability during locomotion. As hypothesised, these findings can be applied to conditions occurring during trail running. A single tri-axial embedded accelerometer fixed to the trunk should be adequate for use in outdoor assessments. However, a combination of an accelerometer fixed on the shoe or tibia and a trunk accelerometer would be beneficial to capture the dampening effect of oscillations and accelerations between the foot or shank and the trunk. The recordings should be made at self-selected speeds to ensure natural rhythmicity of locomotion. With respect to measures of dynamic stability, we recommend to use autocorrelation procedures to capture indexes of variance such as step and stride regularity, step symmetry as well as acceleration RMS. Future studies identifying whether there is relationship between training background, biomechanical measures of stability and injury records are warranted.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Angelis, D. De, Bragoni, M., & Paolucci, S. (2012). Assessment of upper-body dynamic stability during walking in patients with subacute stroke. *Rehabilitation Research & Development*, *49*, 439–450.

Arshi, A. R., Mehdizadeh, S., & Davids, K. (2015). Quantifying foot placement variability and dynamic stability of movement to assess control mechanisms during forward and lateral running. *Journal of Biomechanics*, *48*, 4020–4025.

Auvinet, B., Berrut, G., Touzard, C., Moutel, L., Collet, N., Chaleil, D., & Barrey, E. (2002). Reference data for normal subjects obtained with an accelerometric device. *Gait and Posture*, *16*, 124–134.

Bachasson, D., Moraux, A., Ollivier, G., Decostre, V., Ledoux, I., Gidaro, T., … Hogrel, J. Y. (2016). Relationship between muscle impairments, postural stability, and gait parameters assessed with lower-trunk accelerometry in myotonic dystrophy type 1. *Neuromuscular Disorders*, *26*, 428–435.

Bishop, G. W., & Fallon, K. E. (1999). Musculoskeletal injuries in a six-day track race: ultramarathoner's ankle. *Clinical Journal of Sport Medicine*, *9*, 216–220.

Bizovska, L., Svoboda, Z., & Janura, M. (2015). The possibilities for dynamic stability assessment during gait: A review of the literature. *Journal of Physical Education and Sport*, *15*, 490–497.

Boey, H., Aeles, J., Schütte, K., & Vanwanseele, B. (2017). The effect of three surface conditions, speed and running experience on vertical acceleration of the tibia during running. *Sports Biomechanics*, *16*, 166–176.

Bruijn, S. M., Meijer, O. G., Beek, P. J., & van Dieen, J. H. (2013). Assessing the stability of human locomotion: a review of current measures. *Journal of The Royal Society Interface*, *10*.

Bruijn, S. M., Ten Kate, W. R. T., Faber, G. S., Meijer, O. G., Beek, P. J., & van Dieën, J. H. (2010). Estimating dynamic gait stability using data from non-aligned inertial sensors. *Annals of Biomedical Engineering*, *38*, 2588–2593.

Byun, S., Han, J. W., Kim, T. H., & Kim, K. W. (2016). Test-retest reliability and concurrent validity of a single tri-axial accelerometer-based gait analysis in older adults with normal cognition. *PLoS ONE*, 11, e0158956.

Chang, M. D., Sejdić, E., Wright, V., & Chau, T. (2010). Measures of dynamic stability: Detecting differences between walking overground and on a compliant surface. *Human Movement Science*, *29*, 977–986.

Chelius, G., Braillon, C., Pasquier, M., Horvais, N., Pissard-Gibollet, R., Espiau, B., & Azevedo Coste, C. (2011). A wearable sensor network for gait analysis: A 6-day experiment of running through the desert. *IEEE/ASME Transactions on Mechatronics*, *16*, 878–883.

Cole, M. H., van den Hoorn, W., Kavanagh, J. K., Morrison, S., Hodges, P. W., Smeathers, J. E., & Kerr, G. K. (2014). Concurrent validity of accelerations measured using a tri-axial inertial measurement unit while walking on firm, compliant and uneven surfaces. *PLoS ONE*, *9, e98395*.

Crowley, P., Madeleine, P., & Vuillerme, N. (2016). Effects of mobile phone use during walking: A review. *Critical Reviews in Physical and Rehabilitation Medicine*, *28*, 101–119.

Degache, F., van Zaen, J., Oehen, L., Guex, K., Trabucchi, P., & Millet, G. (2014). Alterations in postural control during the world's most challenging mountain ultra-marathon. *PLoS ONE*, *9, e84554*.

Dingwell, J. B., Cusumano, J. P., Cavanagh, P. R., & Sternad, D. (2001). Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. *Journal of Biomechanical Engineering*, *123*, 27-32.

Dingwell, J. B., & Marin, L. C. (2006). Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. *Journal of Biomechanics*, *39*, 444–452.

Dixon, P. C., Schütte, K. H., Vanwanseele, B., Jacobs, J. V, Dennerlein, J. T., & Schiffman, J. M. (2018). Gait adaptations of older adults on an uneven brick surface can be predicted by age-related physiological changes in strength. *Gait and Posture*, *61*, 257–262.

Easthope, C., Hausswirth, C., Louis, J., Lepers, R., Vercruyssen, F., & Brisswalter, J. (2010). Effects of a trail running competition on muscular performance and efficiency in well-trained young and master athletes. *European Journal of Applied Physiology*, *110*, 1107–1116.

Easthope, C., Nosaka, K., Caillaud, C., Vercruyssen, F., Louis, J., & Brisswalter, J. (2014). Reproducibility of performance and fatigue in trail running. *Journal of Science and Medicine in Sport*, *17*, 207–211.

England, S. A., & Granata, K. P. (2007). The influence of gait speed on local dynamic stability of walking. *Gait and Posture*, *25*, 172–178.

Floor-Westerdijk, M. J., Schepers, H. M., Veltink, P. H., Asseldonk, E. H. F. Van, & Buurke, J. H. (2012). Use of inertial sensors for ambulatory assessment of center-of-mass displacements during walking. *IEEE Transactions on Biomedical Engineering*, *59*, 2080–2084.

Gates, D. H., Wilken, J. M., Scott, S. J., Sinitski, E. H., & Dingwell, J. B. (2012). Kinematic strategies for walking across a destabilizing rock surface. *Gait and Posture*, *35*, 36–42.

Giandolini, M., Horvais, N., Rossi, J., Millet, G., Morin, J., & Samozino, P. (2017). Effects of the foot strike pattern on muscle activity and neuromuscular fatigue in downhill trail running. *Scandinavian Journal of Medicine and Science in Sports*, 27, 809-819.

Giandolini, M., Pavailler, S., Samozino, P., Morin, J.-B., & Horvais, N. (2015). Foot strike pattern and impact continuous measurements during a trail running race: proof of concept in a world-class athlete. *Footwear Science*, *7*, 127–137.

Henriksen, M., Lund, H., Moe-Nilssen, R., Bliddal, H., & Danneskiod-Samsøe, B. (2004). Test – retest reliability of trunk accelerometric gait analysis. *Gait and Posture*, *19*, 288–297.

Hiemstra, J., & Naidoo, N. (2009). Predisposing factors to lateral ankle injury in male comrades marathon runners. *South African Journal of Physiotherapy*, *65*, 21–27.

Hodt-billington, C., Helbostad, J. L., Vervaat, W., Rognsvåg, T., & Moe-Nilssen, R. (2011). Changes in gait symmetry, gait velocity and self-reported function following total hip replacement. *Journal of Rehabilitation Medicine*, *43*, 787–793.

Horvais, N., & Giandolini, M. (2013). Foot strike pattern during downhill trail running. *Footwear Science*, *5*, 26–27.

Iosa, M., Angelis, D. De, Bragoni, M., Paolucci, S., Fusco, A., Morone, G., … Paolucci, S. (2012). Assessment of upper-body dynamic stability during walking in patients with subacute stroke. *Rehabilitation Research & Development*, *49*, 439–450.

Jordan, K., Challis, J. H., Cusumano, J. P., & Newell, K. M. (2009). Stability and the time-dependent structure of gait variability in walking and running. *Human Movement Science*, *28*, 113–128.

Kasmer, M. E., Liu, X.-C., Roberts, K. G., & Valadao, J. M. (2013). The relationship of foot strike pattern, shoe type, and performance in a 50-km trail race. *Journal of Strength and Conditioning Research*, *30*, 1633–1637.

Kavanagh, J., Barrett, R., & Morrison, S. (2004). Upper body accelerations during walking in healthy young and elderly men. *Gait and Posture*, *20*, 291–298.

Kavanagh, J., & Menz, H. (2008). Accelerometry: A technique for quantifying movement patterns during walking. *Gait and Posture*, *28*, 1–15.

Khodaee, R., Myers, R., Spittler, J., Lee, J. A., Hill, J. C., & Yeakel, D. (2011). Risk factors for injuries in a high-altitude ultramarathon. *British Journal of Sports Medicine*, *45*, 355-356.

Kobsar, D., Osis, S. T., Hettinga, B. A., & Ferber, R. (2014). Classification accuracy of a single tri-axial accelerometer for training background and experience level in runners. *Journal of Biomechanics*, *47*, 2508–2511.

Lamoth, C. J. C., Ainsworth, E., Polomski, W., & Houdijk, H. (2010). Variability and stability analysis of walking of transfemoral amputees. *Medical Engineering and Physics*, *32*, 1009–1014.

Lee, J. B., Sutter, K. J., Askew, C. D., & Burkett, B. J. (2010). Identifying symmetry in running gait using a single inertial sensor. *Journal of Science and Medicine in Sport*, *13*, 559–563.

Librett, J. J., Yore, M. M., & Schmid, T. L. (2006). Characteristics of physical activity levels among trail users in a U.S. national sample. *American Journal of Preventive Medicine*, *31*, 399–405.

Malliaropoulos, N., Mertyri, D., & Tsaklis, P. (2015). Prevalence of injury in ultra trail running. *Human Movement*, *16*, 52–59.

Marigold, D. S., & Patla, A. E. (2002). Strategies for dynamic stability during locomotion on a slippery surface: effects of prior experience and knowledge. *Journal of Neurophysiology*, *88*, 339–353.

McAndrew, P. M., Wilken, J. M., & Dingwell, J. B. (2011). Dynamic stability of human walking in visually and mechanically destabilizing environments. *Journal of Biomechanics*, *44*, 644–649.

Mehdizadeh, S., Arshi, A. R., & Davids, K. (2014). Effect of speed on local dynamic stability of locomotion under different task constraints in running. *European Journal of Sport Science*, *14*, 791–798.

Menant, J., Steele, J., Menz, H., Munro, B., & Lord, S. (2011). Step time variability and pelvis acceleration patterns of younger and older adults: Effects of footwear and surface conditions. *Research in Sports Medicine*, *19*, 28–41.

Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. *Gait and Posture*, *18*, 35–46.

Mifsud, N. L., Kristensen, N. H., Villumsen, M., Hansen, J., & Kersting, U. G. (2014). Portable inertial motion unit for continuous assessment of in-shoe foot movement. *Procedia Engineering*, *72*, 208–213.

Millet, G. Y., Morin, J. B., Degache, F., Edouard, P., Feasson, L., Verney, J., & Oullion, R. (2009). Running from Paris to Beijing: Biomechanical and physiological consequences. *European Journal of Applied Physiology*, *107*, 731–738.

Millet, G. Y., Tomazin, K., Verges, S., Vincent, C., Bonnefoy, R., Boisson, R. C., … Martin, V. (2011). Neuromuscular consequences of an extreme mountain ultra-marathon. *PLoS ONE, e17059*.

Mitschke, C., Kiesewetter, P., & Milani, T. L. (2018). The effect of the accelerometer operating range on biomechanical parameters: Stride length, velocity, and peak tibial acceleration during running. *Sensors*, *18*, 130.

Moe-Nilssen, R. (1998a). A new method for evaluating motor control in gait under real-life environmental conditions. Part 1 : The instrument. *Clinical Biomechanics*, *13*, 320–327.

Moe-Nilssen, R. (1998b). A new method for evaluating motor control in gait under real-life environmental conditions. Part 2: Gait analysis. *Clinical Biomechanics*, *13*, 328–335.

Moe-Nilssen, R. (1998c). Test-retest reliability of trunk accelerometry during standing and walking. *Archives of Physical Medicine and Rehabilitation*, *79*, 1377–1385.

Moe-Nilssen, R., & Helbostad, J. L. (2004). Estimation of gait cycle characteristics by trunk accelerometry. *Journal of Biomechanics*, *37*, 121–126.

Richman, J., & Moorman, R. (2000). Physiological time-series analysis using approximate entropy and sample entropy. *American Journal of Physiology-Heart and Circulatory Physiology*, 278, 2039–2049.

Schütte, K. H., Aeles, J., De Beéck, T. O., van der Zwaard, B. C., Venter, R., Vanwanseele, B. (2016). Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry. *Gait and Posture*, *48*, 220–225.

Schütte, K. H., Maas, E. A., Exadaktylos, V., & Berckmans, D. (2015). Wireless tri-axial trunk accelerometry detects deviations in dynamic center of mass motion due to running-induced fatigue.

Plos ONE, 10, e0141957.

Schütte, K. H., Seerden, S., Venter, R., & Vanwanseele, B. (2018). Influence of outdoor running fatigue and medial tibial stress syndrome on accelerometer-based loading and stability. *Gait and Posture*, *59*, 222–228.

Teufl, W., Lorenz, M., Miezal, M., Taetz, B., Fröhlich, M., & Bleser, G. (2018). Towards inertial sensor based mobile gait analysis: Event-detection and spatio-temporal parameters. *Sensors*, *19*, 38.

van Schooten, K. S., Rispens, S. M., Elders, P. J. M., van Dieën, J. H., & Pijnappels, M. (2014). Toward ambulatory balance assessment: Estimating variability and stability from short bouts of gait. *Gait and Posture*, *39*, 695–699.

Vercruyssen, F., Tartaruga, M., Horvais, N., & Brisswalter, J. (2016). Effects of footwear and fatigue on running economy and biomechanics in trail runners. *Medicine and Science in Sports and Exercise*, *48*, 1976–1984.

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J. B., Samozino, P., Horvais, N., & Millet, G. Y. (2017). Biomechanics and physiology of uphill and downhill running. *Sports Medicine*, 47, 615-629.

Villumsen, M., Madeleine, P., Birk, M., Holtermann, A., & Samani, A. (2017). The variability of the trunk forward bending in standing activities during work vs . leisure time. *Applied Ergonomics*, *58, 273-280.*

Williamson, E. (2016). Nutritional implications for ultra-endurance walking and running events. *Extreme Physiology and Medicine*, *5*, 1–18.

Yentes, J., Hunt, N., Schmid, K., Kaipust, J., McGrath, D., & Stergiou, N. (2013). The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of Biomedical Engineering*, *41*, 349–365.

Appendix

The following appendix elaborates on the outcomes of dynamic stability included in the studies of this review.

Coefficient of variation

The coefficient of variation (CV%) is a way of expressing the within-participant variation and is calculated as follows:

$$CV\% = \frac{S}{\bar{X} * 100}$$

Letting S denote the standard deviation (SD) and $\bar{X}$ the mean. It is a measure of absolute reliability, unitless and is expressed in % (Moe-Nilssen, 1998c).

Harmonic ratio

The harmonic ratio is used to provide an indication of the smoothness of acceleration patterns. It is based on the premise that the unit of measurement from a continuous walking trial is a stride (i.e., two steps). Therefore, a stable, rhythmic gait pattern should consist of acceleration patterns that repeat in multiples of two within any given stride. Evaluation of the harmonic content of the acceleration signal in each direction is carried out using stride frequency as the fundamental frequency component. Using a finite Fourier series, the components of the acceleration signal that are 'in phase' (the even harmonics) are compared with the components that are 'out of phase' (odd harmonics), and a harmonic ratio is calculated by dividing the sum of the amplitudes of the even harmonics by the sum of the amplitudes of the odd harmonics (Menz et al., 2003).

Step time variability

The step time variability reflects the SD of the mean step time or the percent of mean step time (Menant et al., 2011). It is suggested that step time variability can reflect adaptability to challenging terrains (Moe-Nilssen & Helbostad, 2004).

Acceleration amplitude variability

The acceleration amplitude variability provides an indication of the repeatability of acceleration patterns from step to step. First, the steps are divided into individual steps by identifying the vertical peaks identifying steps. Then, the steps are averaged and normalised over time to obtain mean and SD values. Finally, the SDs are averaged to produce a number representing the absolute variability of the signal across an entire walking trial (Menz et al., 2003).

Step and/or stride regularity and symmetry (autocorrelation)

The inter-step and inter-stride regularity can be assessed using an unbiased autocorrelation procedure (Moe-Nilssen & Helbostad, 2004; Schütte et al., 2016). The autocorrelation function measures the similarity between the time series and a time-lagged replication defined by the phase shift in number of samples (Moe-Nilssen & Helbostad, 2004). The periodicity of the signal corresponds to the autocorrelation coefficients produced at peak values of the time-lagged replication of the signal (Moe-Nilssen & Helbostad, 2004). The zeroth shift is located centrally as the phase shift is identical in both positive and negative direction, and it is equal to a perfect replication of the gait cycle, indicated by a value of 1.0. The first neighbouring dominant peak amplitude indicates the inter-step regularity and the second the inter-stride regularity. The closeness of the dominant peak amplitudes to the zeroth shift amplitude reflects the regularity. A regularity of 1.0 reflects perfectly repeated cycles (Moe-Nilssen & Helbostad, 2004; Schütte et al., 2016). The closeness of inter-step and inter-stride regularity reflects the symmetry between steps and strides (Hodt-billington, Helbostad, Vervaat, Rognsvåg, & Moe-Nilssen, 2011). A perfect symmetry is indicated by a value equivalent to 1.0. The full mathematical algorithm is described in detail elsewhere (Moe-Nilssen & Helbostad, 2004).

Sample entropy

Sample entropy (SaEn) quantifies the regularity of a time series consisting of *N* data points by measuring the negative natural logarithm of the probability that two sequences of data points of length *m*, having repeated itself within a tolerance *r*, will also repeat itself for $m + 1$ points, without allowing self-matches (Richman & Moorman, 2000). SaEn has shown greater reliability with small data sets as often seen for gait studies (Yentes et al., 2013). A high SaEn value indicates a lower regularity of the time series. Regularity in a time series has been reported as an indication of dynamic stability in human movement (Arshi et al., 2015; Lamoth, Ainsworth, Polomski, & Houdijk, 2010). The mathematical non-linear logarithmic approach is described in detail elsewhere (Richman & Moorman, 2000).

Acceleration root mean square

Acceleration root mean square (RMS) is a measure of dispersion of the data relative to zero, as opposed to SD which is a measure of dispersion relative to the mean (Menz et al., 2003). Two different methods are used to compute RMS values: (1) the mean RMS is obtained averaging individual stride RMS values and (2) the overall RMS value is obtained over the entire walking/running trial without stride partitioning (Iosa et al., 2012). The acceleration RMS ratio is an indicator of the proportion of accelerations in each axis contributing to the overall movement and is calculated as the RMS of each axis relative to the resultant vector RMS (Schütte et al., 2015).

Table 1: Study characteristics of the 17 experimental studies, including participant characteristics (number of participants, gender, age, and physical condition), accelerometry (Type of accelerometer, placement, sampling frequency, and sensing range), gait condition (indoor/outdoor and surface type), and gait speed.

Study	Participants characteristics	Accelerometry	Gait condition	Gait speed
		Walking		
Auvinet et al., 2002	102 asymptomatic participants (50M/52F) Range 20-39 Y	Tri-axial accelerometry Fixed to the trunk (L3-L4 vertebrae) 50 Hz sampling frequency	Indoor walking on a flat surface	Walking at self-selected speed
Bachasson et al., 2016	20 asymptomatic participants (9/M/11F)* Mean age 40.5 Y	Tri-axial accelerometry Fixed to the trunk (L3-L4 vertebrae) 100 Hz sampling frequency ± 539.4 m/s² sensing range	Indoor walking on a flat surface	Walking at self-selected speed
Cole et al., 2014	12 asymptomatic younger participants (6M/6F) Mean age 22.8 Y*	Tri-axial accelerometry Fixed to the trunk (T12 vertebrae) 100 Hz sampling frequency	Indoor walking on a firm, compliant, and uneven surface (uneven surface comprised of hidden wooden blocks underneath a layer of foam and turf)	Walking at self-selected speed
Dixon et al., 2018	18 asymptomatic younger participants (10M/8F) Mean age 27.0 Y*	Tri-axial accelerometry Fixed to the trunk (L5 vertebrae) 128 Hz sampling frequency ± 58.8 m/s² sensing range	Indoor walking on a flat walkway and on an uneven brick walkway	Walking at self-selected speed
Floor-Westerdijk et al., 2012	8 asymptomatic male participants Mean age 62.3 Y	IMU (tri-axial accelerometry, gyroscope, and magnetometer) Fixed to the trunk (sacrum) and left and right shanks	Indoor walking on a flat surface	Walking at self-selected speed
Henriksen et al., 2004	20 asymptomatic participants (6M/14F) Mean age 35.2 Y	Tri-axial accelerometry Fixed to the trunk (L3 vertebrae) 250 Hz sampling frequency ± 26.5 m/s² sensing range	Indoor walking on a flat surface	Instructed to walk at three different speeds: 'normal walking speed', 'slowly', and 'as fast as you can, but do not run'
Iosa et al., 2012	15 asymptomatic younger participants (7M/8F) Mean age 29.0 Y*	Tri-axial accelerometry Fixed to the trunk (L3 vertebrae) 100 Hz sampling frequency No reported sensing range	Indoor walking on a flat surface	Walking at self-selected speed
Kavanagh et al., 2004	8 asymptomatic younger participants Mean age 23 Y*	Tri-axial accelerometry Fixed on posterior aspect of the head and to the trunk (L3 vertebrae) 512 Hz sampling frequency ± 19.6 m/s² sensing range	Indoor walking on a flat surface	Walking at self-selected speed
Menant et al., 2011	6 asymptomatic younger participants (1M/5F) Mean age 22.5 Y*	Tri-axial accelerometry Fixed to the trunk (Sacrum) 200 Hz sampling frequency ± 98.1 m/s² sensing range	Indoor walking on a flat linoleum surface and an uneven surface (uneven surface comprised of wooden blocks hidden between a bottom layer of foam and an upper layer of turf)	Walking at self-selected speed
Menz et al., 2003	30 asymptomatic participants (11M/19F) Mean age 29 Y	Tri-axial accelerometry Fixed on posterior aspect of the head and to the trunk (pelvis) 200 Hz sampling frequency ± 49 m/s² (head) ± 98.1 m/s² (pelvis) sensing range	Indoor walking on a flat walkway and on an uneven surface (uneven surface comprised of wooden blocks hidden between a bottom layer of foam and an upper layer of turf)	Walking at self-selected speed
Moe-Nilssen, 1998c	19 asymptomatic participants (4M/15F) Mean age 22.9 Y	Tri-axial accelerometry Fixed to the trunk (L3 vertebrae) 128 Hz sampling frequency ± 19.6 m/s² sensing range	Indoor walking on a flat walkway and on an uneven surface (uneven surface comprised of circular rubber plates hidden between two layers of rubber carpeting)	Walking at five different speeds (from very slowly to as fast as possible without running)
Moe-Nilssen, 1998b	2 asymptomatic female participants	Tri-axial accelerometry Fixed to the trunk (L3 vertebrae) 512 Hz sampling frequency ± 19.6 m/s² sensing range	Outdoor walking in 0.2 m newly fallen snow and on an indoor treadmill	Walking at three self-selected speeds in snow and five self-selected speeds on treadmill
van Schooten et al., 2014	20 asymptomatic participants Mean age 28.5 Y	Tri-axial accelerometry Fixed to the trunk (L5 vertebrae) 100 Hz sampling frequency ± 58.8 m/s² sensing range	Outdoor walking on a tarmac footpath	Walking at self-selected speed
		Running		
Boey et al., 2017	35 asymptomatic participants (18M/17F) 12 untrained runners (avg. 2km per week) Mean age 22.3 Y 12 recreational (avg. 18km per week) Mean age 22.3 Y 11 well-trained (avg. 74km per week) Mean age 25.4 Y	Tri-axial accelerometry Fixed on the tibia, 8 cm above the medial malleolus 1024 Hz sampling frequency ± 490.3 m/s² sensing range	Outdoor running on a concrete track, synthetic track, and a woodchip trail	Running at two different speeds: Self-selected speed and fixed at 3.06 m/s
Mifsud et al., 2014	17 asymptomatic male recreational runners (avg. 16.6 km/week) Mean age 28.6 Y	IMU (tri-axial accelerometry and gyroscope) Fixed on medial tibial aspect and calcaneus lateralis 800 Hz sampling frequency ± 156.9 m/s² sensing range and ± 800°/s	Indoor running on a flat surface	3.3 m/s running speed
Schütte et al., 2018	16 asymptomatic participants (10M/6F)* Mean age 20.1 Y	Tri-axial accelerometry Fixed on the tibia and on the trunk (L3-L5 vertebrae) 1024 Hz sampling frequency ± 490.3 m/s² sensing range	Outdoor running on a synthetic track surface	Maximal effort fatiguing run
Schütte et al., 2016	28 asymptomatic participants (14M/14F) Mean age 22.6 Y Recreational runners (avg. 9.6 km/week) Highly-trained runners (avg. 72.9 km/week)	Tri-axial accelerometry Fixed to the trunk (L3 vertebrae) 1024 Hz sampling frequency ± 490.3 m/s² sensing range	Outdoor running on a flat concrete road, synthetic track, and woodchip trail	Self-selected running speed on concrete road as control speed

*Study contains one or more test groups different from the presented experimental group in the table.

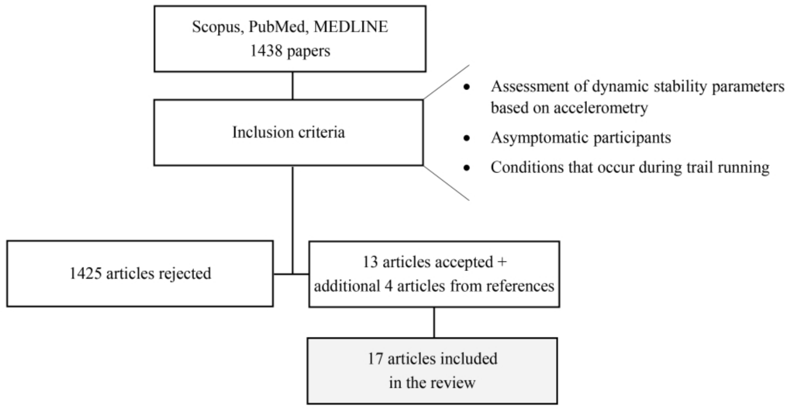
Table 2: Outcome parameters for dynamic stability assessment acquired from the 17 experimental studies divided into inter-step or inter-stride variability and signal dispersion.

Interstep or -stride variability	**Axis**	**Unit**	**Study**
Coefficient of variation of stride time	-	%	(Bachasson et al., 2016)
Harmonic ratio	VT, AP, ML	a.u.	(Auvinet et al., 2002; Iosa et al., 2012; Menz et al., 2003)
Step time variability	-	%	(Menant et al., 2011; Menz et al., 2003)
Acceleration amplitude variability	VT, AP, ML	m/s^2, g or a.u.	(Menz et al., 2003; van Schooten et al., 2014)
Step and/or stride regularity (autocorrelation)	VT, AP, ML	a.u.	(Auvinet et al., 2002; Bachasson et al., 2016; Dixon et al., 2018; Schütte et al., 2016, 2018)
Step and/or stride symmetry/asymmetry (autocorrelation)	-	%	(Auvinet et al., 2002; Bachasson et al., 2016)
Sample entropy	VT, AP, ML	a.u.	(Bachasson et al., 2016; Schütte et al., 2016, 2018)
Signal dispersion	**Axis**	**Unit**	**Study**
Acceleration RMS	VT, AP, ML	m/s^2, g or s^{-1} or a.u.	(Bachasson et al., 2016; Cole et al., 2014; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c)
Resultant acceleration RMS	-	a.u.	(Dixon et al., 2018; Henriksen et al., 2004)
Ratio of acceleration RMS	VT, AP, ML	a.u.	(Schütte et al., 2016, 2018)

Figures legends

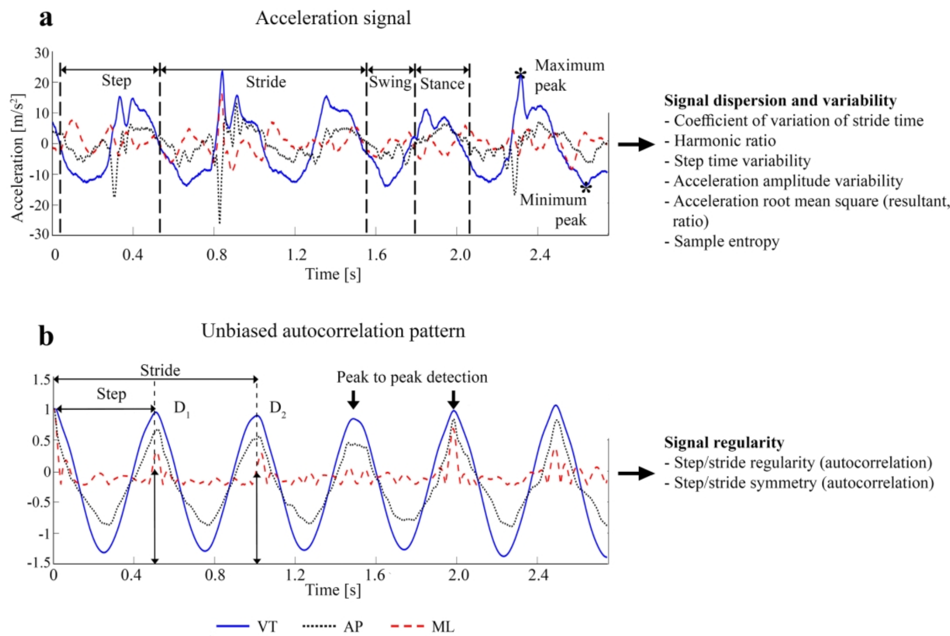
Fig. 1. Flowchart reporting study selection and inclusion criteria.

Fig. 2.a. Example of the outcome parameters extracted from an acceleration signal to represent dynamic stability. 2.b. Illustration of the outcome parameters extracted from an unbiased autocorrelation procedure applied to the acceleration signal in 2.a. The accelerometer data display running on irregular surface in outdoor conditions. VT: vertical (blue solid line), AP: anteroposterior (black dotted line), and ML: mediolateral (red dashed line) acceleration signals. See Table 2 for references using these outcomes.



Flowchart reporting study selection and inclusion criteria

338x190mm (300 x 300 DPI)



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209x141mm (300 x 300 DPI)