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

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19 **Abstract**

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

35 **Word count: 186**

36

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

39 **Introduction**

40 During trail running, the main component is non-paved stable or unstable surface such as grass,
41 mud, rock, sand, and snow, and no more than 20% is asphalt (Malliaropoulos, Mertyri, & Tsaklis,
42 2015). Trail running involves uphill, downhill, and horizontal trails. Trail running is often
43 performed over long distances, i.e. the so-called ultra-marathons (>42.195 km and up to 330 km)
44 (Malliaropoulos et al., 2015; Vernillo et al., 2017). Because of the harsh conditions, such races are
45 considered highly challenging from a physiological, neuromuscular and biomechanical standpoint
46 (Millet et al., 2009, 2011). Consequently, periods of running are intertwined with periods of
47 walking (Librett, Yore, & Schmid, 2006; Millet et al., 2011; Vernillo et al., 2017; Williamson,
48 2016). Unstable natural terrain surfaces might provoke ankle instability which again may cause
49 severe stress around the ankle joint (Malliaropoulos et al., 2015). In addition, in a retrospective
50 study 38 out of 114 ultra-distance runners reported previously sustained lateral ankle injuries from
51 running (Hiemstra & Naidoo, 2009). Furthermore, the ankle is the region most often injured (36%),
52 and ankle injuries are predominant in trail tracks compared with road tracks (Bishop & Fallon,
53 1999). Some researchers have investigated protective factors for trail running injuries and found
54 that stability shoes, personalised training, and running accommodation in mountain environments
55 could lead to a decreased injury rate (Khodaei et al., 2011; Malliaropoulos et al., 2015). However,
56 no studies have investigated the dynamic stability in outdoor and natural conditions even though it
57 is generally considered an important aspect of trail environments (Degache et al., 2014; Schütte et
58 al., 2016). Actually, the trail environment consists of both stable and unstable surfaces resulting in
59 predictable and unpredictable perturbations (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012;
60 Vercruyssen, Tartaruga, Horvais, & Brisswalter, 2016). Further, the transitions between walking
61 and running (Millet et al., 2011; Williamson, 2016) result in frequent disruptions challenging the

62 stability of the running pattern (Chang, Sejdić, Wright, & Chau, 2010; Gates et al., 2012; Marigold
63 & Patla, 2002).

64 Analyses of the dynamic stability of the running pattern are usually made using 3D motion
65 capture systems. Motion analysis using reflective markers is considered a *gold standard* in the
66 determination of movement variations (Cole et al., 2014). However, restrictions often apply such as
67 small calibrated spaces, transportation difficulties, and ambient light noise (Cole et al., 2014).
68 Accelerometers can collect data over long distances, they are lightweight and easily wearable
69 allowing biomechanical recordings in real-world environments (Cole et al., 2014; Moe-Nilssen,
70 1998a; Villumsen, Madeleine, Birk, Holtermann, & Samani, 2017). Further, accelerometers have
71 been used during prolonged outdoor trail investigations (Chelius et al., 2011; Giandolini, Pavailler,
72 Samozino, Morin, & Horvais, 2015). Accelerometry has proven to be a reliable method to estimate
73 variations during locomotion on both predictable and unpredictable irregular surfaces (Cole et al.,
74 2014; Crowley, Madeleine, & Vuillerme, 2016; Kobsar, Osis, Hettinga, & Ferber, 2014; Moe-
75 Nilssen, 1998c). Moreover, using accelerometry in outdoor settings may prove useful in identifying
76 and correcting trail runners' technique and thus may have the potential to prevent injuries (Lee,
77 Sutter, Askew, & Burkett, 2010; Schütte, Maas, Exadaktylos, & Berckmans, 2015). After removing
78 the confounding effects of both the gravity measurement and accelerometer orientation, the method
79 enables accelerations to be expressed relative to vertical (VT), mediolateral (ML), and
80 anteroposterior (AP) directions (Moe-Nielsen, 1998a) and to assess the dynamic stability of
81 locomotion.

82 Dynamic stability during locomotion is typically analysed by normalising and averaging data
83 from independent strides. However, focusing on the events that occur during an average stride
84 implicitly implies that each stride is generated independently of the past and future strides and that
85 stride-to-stride variations are random. Therefore, a complete description of locomotor control

86 requires an understanding of how movements are controlled from one stride to the next (Dingwell,
87 Cusumano, Cavanagh, & Sternad, 2001). This fundamental control task of locomotion is defined as
88 maintaining dynamic stability. In this review, dynamic stability is defined as the ability to maintain
89 variability, symmetry, regularity, or complexity during locomotion on stable or unstable terrain
90 (Schütte, Seerden, Venter, & Vanwanseele, 2018). The traditional measures of dynamic stability are
91 often divided into groups based on the size of the perturbation. The first group of measures reflect
92 the ability to recover from small perturbations, such as the maximum Lyapunov exponent and the
93 maximum Floquet multiplier (Bruijn, Meijer, Beek, & van Dieen, 2013). The second group of
94 measures reflect the ability to recover from large or external perturbations, such as assessments of
95 accelerometric signal characteristics, coefficients of variation, and nonlinear analyses (Bizovska,
96 Svoboda, & Janura, 2015; Bruijn et al., 2013). Of note, the ability to overcome local perturbations
97 may be independent of the ability to overcome external perturbations such as unstable surfaces
98 (Bruijn et al., 2013; McAndrew, Wilken, & Dingwell, 2011).

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

108

109

110 **Method**

111 *Search strategy*

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

122

123 *Study selection*

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

133

134 *Coding of studies*

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

141

142 Figure 1. Near Here

143

144 **Results**

145 *Search yield*

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

153

154 Table 1. Near here

155

156 *Participants*

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

165

166 *Gait conditions*

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

169 **Surface inclination and type:** Nine locomotion studies, i.e., seven on walking and two on
170 running were conducted exclusively on a flat surface (Auvinet et al., 2002; Bachasson et al., 2016;
171 Floor-Westerdijk, Schepers, Veltink, Asseldonk, & Buurke, 2012; Henriksen, Lund, Moe-Nilssen,
172 Bliddal, & Danneskiold-Samsøe, 2004; Iosa et al., 2012; Kavanagh et al., 2004; Mifsud et al., 2014;
173 Schütte et al., 2018; van Schooten et al., 2014), whereas eight studies, i.e., six on walking and two
174 on running were performed on both uneven terrain and a flat surface (Boey et al., 2017; Cole et al.,
175 2014; Dixon et al., 2018; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c;
176 Schütte et al., 2016). The irregular surface conditions consisted of either (1) an irregular woodchip
177 trail (Boey et al., 2017; Schütte et al., 2016), (2) an irregular surface with wooden blocks hidden
178 underneath a layer of turf (Cole et al., 2014; Menant et al., 2011; Menz et al., 2003) or rubber plates
179 underneath foam (Moe-Nilssen, 1998c), (3) an irregular brick walkway (Dixon et al., 2018) (4)
180 newly fallen snow (Moe-Nilssen, 1998b), or (5) a compliant surface (Cole et al., 2014).

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

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

195

196 *Accelerometer*

197 Fifteen studies used tri-axial accelerometers (Auvinet et al., 2002; Bachasson et al., 2016; Boey
198 et al., 2017; Cole et al., 2014; Dixon et al., 2018; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh
199 et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c, Schütte et al.,
200 2016, 2018; van Schooten et al., 2014) and two studies used accelerometry integrated in an IMU
201 (Floor-Westerdijk et al., 2012; Mifsud et al., 2014). Sampling frequencies varied from 50 to 1024
202 Hz and sensing range from ± 19.6 to ± 539.5 m/s².

203 **Method of fixation:** In 15 studies, either an accelerometer unit or IMU was fixed to the trunk
204 (Auvinet et al., 2002; Bachasson et al., 2016; Cole et al., 2014; Dixon et al., 2018; Floor-Westerdijk

205 et al., 2012; Henriksen et al., 2004; Iosa et al., 2012; Kavanagh et al., 2004; Menant et al., 2011;
206 Menz et al., 2003; Moe-Nilssen, 1998b, 1998c, Schütte et al., 2016, 2018; van Schooten et al.,
207 2014). Two studies used an extra accelerometer fixed to the head (Kavanagh et al., 2004; Menz et
208 al., 2003) and one study used an accelerometer fixed to the tibia (Schütte et al., 2018). One study
209 used a single accelerometer fixed to the tibia (Boey et al., 2017) and one study had an additional
210 accelerometer on calcaneus along with a tibia fixed accelerometer (Mifsud et al., 2014).

211 **Signal processing:** Five studies using a trunk accelerometer or IMU applied a trigonometric
212 correction of the acceleration signal Moe-Nielssen (1998a) to compensate for lumbar curvature
213 (Cole et al., 2014; Henriksen et al., 2004; Kavanagh et al., 2004; Schütte et al., 2016, 2018). The
214 most common filter used among the included studies was a zero-lag 4th order low-pass Butterworth
215 filter with a cut-off frequency between 8-50 Hz (Cole et al., 2014; Dixon et al., 2018; Schütte et al.,
216 2016, 2018) or a zero-lag 2nd order low-pass Butterworth filter with a cut-off frequency between 10-
217 60 Hz (Boey et al., 2017; Floor-Westerdijk et al., 2012; Mifsud et al., 2014). Accelerometry-based
218 measures were computed in windows of different lengths. The majority of studies used windows
219 described in steps ranging from four to 60 consecutive steps (Angelis et al., 2012; Auvinet et al.,
220 2002; Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Kavanagh et al., 2004; Menant et al.,
221 2011; Schütte et al., 2016, 2018; van Schooten et al., 2014). Other studies used windows described
222 in meters (Henriksen et al., 2004; Menz et al., 2003; Moe-Nilssen, 1998c) or in seconds (Bachasson
223 et al., 2016). All studies used the middle period of the required walking or running distance to
224 secure computation of parameters in a steady pace.

225

226 **Figure 2.** Near Here

227

228 ***Outcomes assessing inter-step or inter-stride variability***

229 Some of the studies did not strictly assess gait stability, such as margin of stability. Instead, these
230 studies assessed the gait characteristics and variability from the acceleration signal, which have
231 been used in literature to describe gait stability as illustrated in Figure 2. Table 2 shows that
232 analyses of the complexity, rhythmicity and smoothness of the acceleration signal were performed.
233 Step time variability (Menant et al., 2011; Menz et al., 2003), acceleration amplitude variability
234 (Menz et al., 2003; van Schooten et al., 2014), and coefficient of variation of stride time (Bachasson
235 et al., 2016) were used as indexes of repeatability of cycles. Several studies used autocorrelation to
236 assess the variability between steps and strides by analysing the acceleration signal regularity from
237 a factor of periodicity between consecutive steps (Bachasson et al., 2016; Dixon et al., 2018;
238 Schütte et al., 2016). This method is not only an index of step-to-step variation in length and time
239 but also an index of acceleration amplitude variation. Another similar waveform analysis describing
240 the harmonic ratio in a signal was also utilised (Auvinet et al., 2002; Iosa et al., 2012; Menz et al.,
241 2003). The sample entropy method was used by three of the studies to quantify the fluctuations of
242 the acceleration signal (Bachasson et al., 2016; Schütte et al., 2016, 2018). Sample entropy is an
243 analysis evaluating the repeatability of the pattern of the acceleration signal (Richman & Moorman,
244 2000). See Appendix for more details on computational aspects related to the outcomes of dynamic
245 stability.

246

247 ***Outcomes assessing signal dispersion***

248 The majority of studies included the amplitude of the acceleration (i.e. root mean square - RMS)
249 in their analysis (Bachasson et al., 2016; Cole et al., 2014; Henriksen et al., 2004; Iosa et al., 2012;
250 Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-Nilssen, 1998b, 1998c). Some
251 studies also computed the resultant acceleration RMS (Dixon et al., 2018; Henriksen et al., 2004)
252 and ratio of acceleration RMS (Schütte et al., 2016, 2018). This provided an understanding of the

253 entire signal as well as the ratio of the signal amplitude across VT, ML, and AP directions,
254 respectively. The RMS of the acceleration reflects the average amplitude of the signal with high
255 value associated with impaired stability (Menant et al., 2011). The ratio of acceleration RMS serves
256 as an indicator of how much each direction contributes to the movement. Higher RMS trunk
257 accelerations are reported when walking on irregular surface in ML (Menant et al., 2011; Menz et
258 al., 2003) and in AP direction (Menant et al., 2011; Menz et al., 2003; Schütte et al., 2016)
259 compared with walking on a flat surface. It has been suggested that the RMS of acceleration could
260 differ between walking on flat and uneven terrains (Moe-Nilssen, 1998c). Menz et al. (2003)
261 reported a difference in RMS of acceleration between walking on an irregular and a regular surface
262 confirming that this measure assesses dynamic stability (Moe-Nilssen, 1998c). See also Appendix
263 for more details.

264

265

Table 2. Near Here

266

267 **Discussion and Implications**

268 This is the first review to analyse and evaluate studies, which have assessed dynamic stability
269 during locomotion using accelerometry, with the intention of transferring these methods into an
270 analysis of the dynamic stability during trail running. Our analysis showed that one accelerometer
271 fixed to the trunk would be appropriate to use for monitoring dynamic stability during locomotion.
272 Using a single trunk-fixed accelerometer, a combination of measures of cycle repeatability and
273 signal dispersion can be computed to describe different aspects of dynamic stability. In the retrieved
274 studies, measures of dynamic stability were mostly extracted from indoor recordings made over
275 relatively short gait distances and on regular or artificial irregular surfaces. Overall, and in support
276 of our hypothesis, the retrieved studies provided a scientific basis to assemble a novel method that

277 could be used in trail running studies. These findings have direct implications for researchers and
278 practitioners interested in outdoor assessments of trail running performance and injury prevention.

279

280 Initially, it should be **acknowledged** that no trail running studies were directly identified.
281 However, in line with our hypothesis, the retrieved recordings and analysis methods can be
282 transferred to locomotion conditions that occur during trail running. Schütte et al. (2016)
283 investigated outside running on a 90 m woodchip trail, which approached the desired conditions.
284 However, woodchip trails are rarely found in natural environments. Further, woodchip trails lack
285 the random irregularities often encountered in real trail environments (Easthope et al., 2014).
286 Therefore, it may be more valid and effective to assess dynamic stability during trail running in
287 outdoor settings. However, tests in outdoor settings often affect the reproducibility due to the
288 variety of environmental influences such as temperature, weather, and surface conditions (Easthope
289 et al., 2014). Nevertheless, previous studies have successfully investigated parameters such as risk
290 of injuries (Khodaei et al., 2011; Malliaropoulos et al., 2015), foot strike pattern (Giandolini et al.,
291 2017, 2015; Horvais & Giandolini, 2013; Kasmer, Liu, Roberts, & Valadao, 2013), and fatigue
292 (Easthope et al., 2010, 2014; Giandolini et al., 2017; Vercruyssen et al., 2016) during prolonged
293 locomotion in outdoor trail environments. In line with outdoor investigations, research involving
294 dynamic stability is yet to be examined in trail running conditions. Even though the included
295 articles address non-trail investigations, biomechanical adaptations due to surface irregularities have
296 been reported (Boey et al., 2017; Cole et al., 2014; Dixon et al., 2018; Menant et al., 2011; Menz et
297 al., 2003; Moe-Nilssen, 1998b, 1998c; Schütte et al., 2016). Based on the results from the included
298 studies, it seems applicable to capture the dynamic stability from recordings made over a relatively
299 short gait distance (Angelis et al., 2012; Auvinet et al., 2002; Bachasson et al., 2016; Cole et al.,
300 2014; Dixon et al., 2018; Kavanagh et al., 2004; Menant et al., 2011; Menz et al., 2003; Moe-

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

308
309 This literature review included eight studies investigating the effects of irregular or compliant
310 surfaces or the effect of outdoor environments on dynamic stability. Six of these eight studies
311 examined dynamic stability during walking questioning the **generalisation** of results during running
312 on irregular surfaces. The influence of the transition between walking and running on dynamic
313 stability has been investigated in several studies, showing that the dynamic stability decreases with
314 an increase in speed (Dingwell & Marin, 2006; England & Granata, 2007; Jordan, Challis,
315 Cusumano, & Newell, 2009; Mehdizadeh, Arshi, & Davids, 2014). It is well known that the gait
316 speed influences the gait performance and gait biomechanical measures. Variations in the
317 requirements to maintain dynamic stability during gait are also evident when the speed is changed
318 (Kavanagh & Menz, 2008). During trail running, the runners adjust their gait speed constantly due
319 to surface perturbations or slope changes. Therefore, it is important to consider the impact of speed
320 on the included measures of gait variability. Twelve of the included studies used self-selected speed
321 when performing the gait analysis. Moe-Nilssen and Helbostad (2004) have suggested to ask
322 participants to move at a self-selected speed to account for the confounding effects of different gait
323 speed. Using a single tri-axial accelerometer fixed to the trunk at L3 vertebrae level, estimations of
324 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 $\geq \pm 313.8 \text{ m/s}^2$ (Mitschke, Kiesewetter, & Milani, 2018) and be able to detect high frequencies, i.e., sampling frequency $\geq 100 \text{ Hz}$ (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. $< 5\text{-}6 \text{ Hz}$). 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.

348

349 Nevertheless, a single trunk-fixed accelerometer can be used to calculate a combination of the
350 index of cycle repeatability and signal dispersion to assess dynamic stability during locomotion.
351 Four studies implemented autocorrelation procedures to assess dynamic stability (Auvinet et al.,
352 2002; Bachasson et al., 2016; Dixon et al., 2018; Schütte et al., 2016). Autocorrelation procedures
353 have been found to be sufficiently sensitive to measure the acceleration step and stride regularity
354 during running on an outdoor surface (Schütte et al., 2016). Further, such procedures enable the
355 elimination of unwanted variables of interest introduced with self-selected speeds (Moe-Nilssen &
356 Helbostad, 2004). Sample entropy would be an appropriate method to characterise control
357 mechanisms in human locomotion and can be seen as a measure of dynamic stability during running
358 despite a relatively high computational cost (Arshi, Mehdizadeh, & Davids, 2015; Schutte, Aeles,
359 De Beeck, van der Zwaard, Venter, & Vanwanseele, 2016). The computation of acceleration RMS
360 and the autocorrelation-based coefficients reflecting step and stride regularity as well as symmetry
361 can be advantageous since these outcomes enable the detection of asymmetrical stability patterns in
362 various environments (Dixon et al., 2018; Schütte et al., 2016, 2018). The variability of cycles in a
363 repeatable acceleration signal is also an indirect measure of dynamic stability. This measurement of
364 deviations in the acceleration signal between steps allows the exploration of how a biological signal
365 fluctuates from its equilibrium state. Interestingly, this index of regularity between participants can
366 be normalised across walking or running speed and anthropometrics values (Moe-Nilssen &
367 Helbostad, 2004; Schütte et al., 2016). The deviations in acceleration have even been used to
368 classify athletes based on their training background (Kobsar et al., 2014). In the future, it would be
369 beneficial to identify the influence of training on dynamic stability and injury risks.

370

371 This review has some limitations. Firstly, it should be mentioned the studies reviewed were not
372 conducted in situ that is to say in natural environment. Secondly, the experimental protocols had

373 substantial discrepancies, e.g., the size ranged from 2 to 102, surface conditions varied, and walking
374 and running were performed at different speeds. However, our choice of studies is justified by the
375 fact that trail running is a discipline which includes various surface types as well as locomotion
376 types, i.e., walking and running are often intertwined (Librett et al., 2006; Millet et al., 2011;
377 Vernillo et al., 2017; Williamson, 2016). The third limitation concerns the validity and reliability of
378 accelerometers as gait assessment tools. Optoelectrical motion analysis methods are considered the
379 *gold standard* to evaluate locomotion stability (Cole et al., 2014). Wearable sensors assessing
380 dynamic gait stability on stable and unstable surfaces have been found to be a viable and valid
381 measurement system compared with optoelectronic measurements (Bruijn et al., 2010; Byun, Han,
382 Kim, & Kim, 2016; Cole et al., 2014; Teufl et al., 2018; van Schooten et al., 2014). Moreover, the
383 reliability of collection of acceleration data has been found to be high when walking on stable and
384 unstable surfaces (Henriksen et al., 2004; Moe-Nilssen, 1998c; van Schooten et al., 2014). Still, the
385 reliability of dynamic stability measures based on wearable accelerometers or IMU recordings
386 remains to be demonstrated in conditions including, e.g., long-distance outdoor locomotion on
387 different types of surfaces.

388

389 **Conclusion**

390 The purpose of this narrative review was to evaluate the biomechanical assessments of dynamic
391 stability during locomotion. As hypothesised, these findings can be applied to conditions occurring
392 during trail running. A single tri-axial embedded accelerometer fixed to the trunk should be
393 adequate for use in outdoor assessments. However, a combination of an accelerometer fixed on the
394 shoe or tibia and a trunk accelerometer would be beneficial to capture the dampening effect of
395 oscillations and accelerations between the foot or shank and the trunk. The recordings should be
396 made at self-selected speeds to ensure natural rhythmicity of locomotion. With respect to measures

397 of dynamic stability, we recommend to use autocorrelation procedures to capture indexes of
398 variance such as step and stride regularity, step symmetry as well as acceleration RMS. Future
399 studies identifying whether there is relationship between training background, biomechanical
400 measures of stability and injury records are warranted.

401

402

403 **Disclosure statement**

404 No potential conflict of interest was reported by the authors.

405

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562

564 **Appendix**

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

567 ***Coefficient of variation***

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

$$570 \text{ CV\%} = \frac{S}{\bar{X}} * 100$$

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

573 ***Harmonic ratio***

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

583 ***Step time variability***

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

587 ***Acceleration amplitude variability***

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

593 ***Step and/or stride regularity and symmetry (autocorrelation)***

594 The inter-step and inter-stride regularity can be assessed using an unbiased autocorrelation
595 procedure (Moe-Nilssen & Helbostad, 2004; Schütte et al., 2016). The autocorrelation function
596 measures the similarity between the time series and a time-lagged replication defined by the phase
597 shift in number of samples (Moe-Nilssen & Helbostad, 2004). The periodicity of the signal
598 corresponds to the autocorrelation coefficients produced at peak values of the time-lagged
599 replication of the signal (Moe-Nilssen & Helbostad, 2004). The zeroth shift is located centrally as
600 the phase shift is identical in both positive and negative direction, and it is equal to a perfect
601 replication of the gait cycle, indicated by a value of 1.0. The first neighbouring dominant peak
602 amplitude indicates the inter-step regularity and the second the inter-stride regularity. The closeness
603 of the dominant peak amplitudes to the zeroth shift amplitude reflects the regularity. A regularity of
604 1.0 reflects perfectly repeated cycles (Moe-Nilssen & Helbostad, 2004; Schütte et al., 2016). The
605 closeness of inter-step and inter-stride regularity reflects the symmetry between steps and strides
606 (Hodt-billington, Helbostad, Vervaat, Rognsvåg, & Moe-Nilssen, 2011). A perfect symmetry is
607 indicated by a value equivalent to 1.0. The full mathematical algorithm is described in detail
608 elsewhere (Moe-Nilssen & Helbostad, 2004).

609 ***Sample entropy***

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

619 *Acceleration root mean square*

620 Acceleration root mean square (RMS) is a measure of dispersion of the data relative to zero, as
621 opposed to SD which is a measure of dispersion relative to the mean (Menz et al., 2003). Two
622 different methods are used to compute RMS values: (1) the mean RMS is obtained averaging
623 individual stride RMS values and (2) the overall RMS value is obtained over the entire
624 walking/running trial without stride partitioning (Iosa et al., 2012). The acceleration RMS ratio is an
625 indicator of the proportion of accelerations in each axis contributing to the overall movement and is
626 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 (9M/11F)* Mean age 40.5 Y	Tri-axial accelerometry Fixed to the trunk (L3-L4 vertebrae) 100 Hz sampling frequency ± 539.4 m/s ² 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/s ² 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/s ² 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/s ² 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/s ² 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/s ² (head) ± 98.1 m/s ² (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/s ² 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/s ² 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/s ² 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/s ² 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/s ² 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/s ² 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/s ² 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.

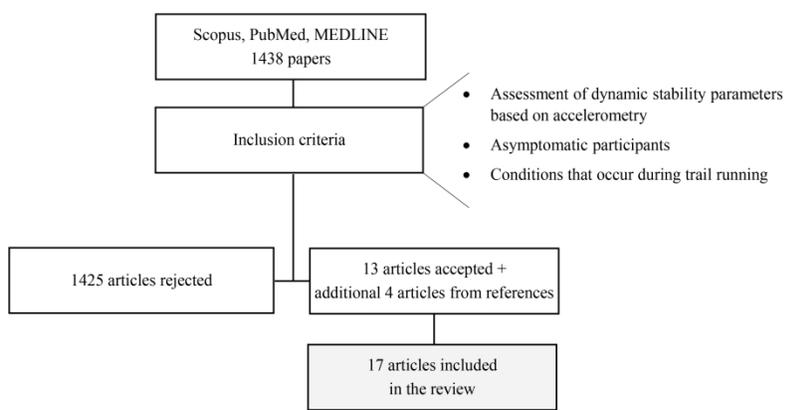
Table 2: Outcome parameters for dynamic stability assessment acquired from the 17 experimental studies divided into inter-step or inter-stride variability and signal dispersion.

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)

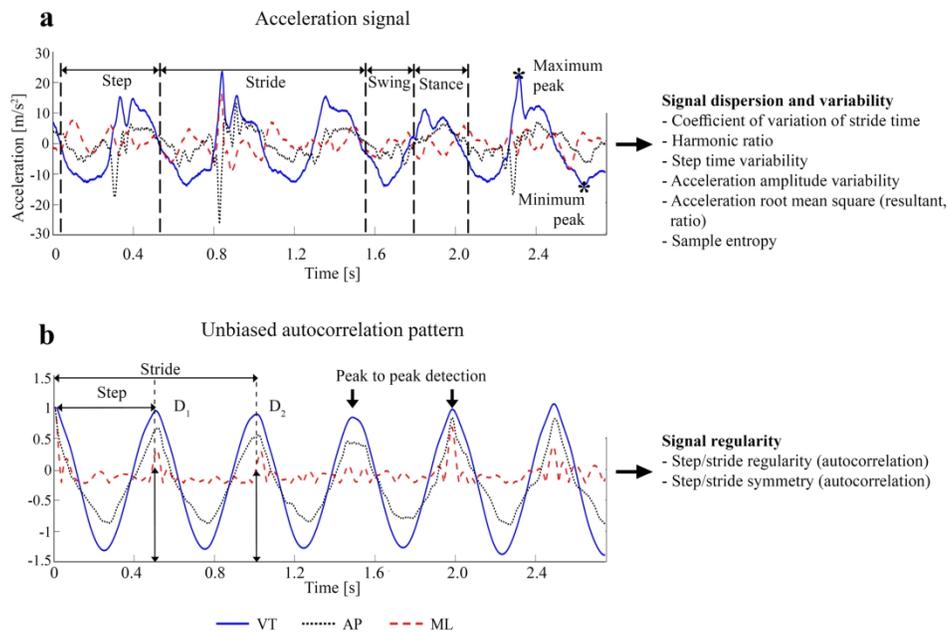


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209x141mm (300 x 300 DPI)