Original Article

The possibilities for dynamic stability assessment during gait: A review of the literature

LUCIA BIZOVSKA¹; ZDENEK SVOBODA²; MIROSLAV JANURA³

^{1,2,3} Department of Natural Sciences in Kinanthropology, Faculty of Physical Culture, Palacky University Olomouc, CZECH REPUBLIC

Published online: September 28, 2015

(Accepted for publication september 10, 2015)

DOI:10.7752/jpes.2015.03074;

Abstract:

Falls are highly common causes of health problems and injuries, especially in the elderly population. Fall risk can be predicted from fall history, questionnaires, and clinical and instrumental tests in both static and dynamic conditions. During the last decade, dynamic stability assessment during gait has been widely discussed because the majority of falls occur in dynamic conditions. There are many different approaches for dynamic stability assessment; therefore, this study aimed to summarise articles related to stability assessment during gait in relation to fall risk and fall history. Three databases were searched, and 23 articles met the inclusion and exclusion criteria. This review was focused on studies of continuous human gait in laboratory environments; therefore, articles that discussed models, robots or measurements during daily life activities were excluded. The most frequently used variables to determine gait stability and variability were short-term and long-term local dynamic stability exponents and spatial-temporal gait characteristics. According to the results of our analysis, direct relationships with fall history and fall risk determined using clinical tests and questionnaires was found for nonlinear variables and spatial-temporal gait variables and their variability. Nonlinear variables were sufficient for distinguishing patients with musculoskeletal and neurological disorders from healthy subjects and, in combination with the variability of spatial-temporal gait characteristics, were sufficient for distinguishing various age groups.

Keywords: walking, fall risk, fall history, variability, nonlinear analysis

Introduction

Falls are very common causes of a variety of health problems, especially in the elderly. Falls lead to 20% to 30% of unintentional injuries (Scuffham, Chaplin, & Legood, 2003) and are responsible for 40% of deaths caused by injury (Rubenstein, 2006). The most frequent fall related injuries are hip fractures. As a consequence, half of the people suffering from such an injury are not able to return to the same mobility level as before the injury. Fall rate is gender related. Females fall more frequently than males; however, the rate of fatal falls is significantly higher in males above 65 years of age (Stevens, 2005). In addition, when assessing health-related quality of life, elderly fallers showed significantly lower scores than elderly non-fallers (Stenhagen, Ekström, Nordell, & Elmståhl, 2014).

The main risk factors for falls were divided into four groups: behavioural, biological, environmental and socioeconomic (World Health Organisation [WHO], 2007). According to Stenhagen, Ekström, Nordell and Elmståhl (2013), three health indicators can be used to predict falls globally in the elderly – reduced mobility, heart dysfunction and functional impairment; furthermore, an individual risk factor for falls is neuroleptic drugs.

In assessing fall risk, three approaches have been used – questionnaires and clinical and instrumental tests. Questionnaires mostly include questions regarding fall history, medications, psychological condition, vision, hearing, mobility and cognition problems and alcohol intake (Stapleton et al. 2009; Joint commission resources, 2008). Hamacher, Singh, van Dieen, Heller and Taylor (2011) stated that a number of limitations are associated with questionnaires, especially self-reports. Regarding clinical evaluations of fall risk, the Timed Up and Go Test is the most frequently used motor performance test, followed by other exams reported in literature (for review see Howcroft, Kofman, & Lemaire, 2013), including the Tinetti assessment tool, Berg balance scale, one legged stance, physical performance test and others. There is evidence that fall risk cannot be predicted by motor performance tests alone in healthy persons and in active elderly persons (Laessoe, Hoeck, Simonsen, Sinkjaer, & Voigt, 2007).

For instrumental assessment of fall risk, mainly static and dynamic posturography evaluations of persons in static and dynamic conditions, respectively, have been used. In recent years, stability assessments during gait have often been discussed because the majority of falls occur in dynamic conditions. Thus, gait

stability assessment is the focus of this review. There are several approaches to assessing dynamic stability during gait, and they require different walking speeds and walking distances and different numbers of trials. To study balance during gait, stability and variability parameters can be used. Stability is defined as the ability to preserve functional locomotion even if the locomotion is disturbed or control errors are present (England & Granata, 2007). Moreover, stability parameters can provide information about noise present during locomotion (Hamacher et al., 2011). Variability results from the noise present during a locomotion task and the noise present in the environment (Hamacher et al., 2011) and can be related to basic motor control and to age-related and pathological changes in locomotion (Gaouelle et al., 2013).

Many different approaches for variability and stability gait assessment exist, including assessments of spatial-temporal and kinematic gait characteristics and their standard deviations and coefficients of variation, assessments of accelerometric signal characteristics and nonlinear analyses, such as recurrence quantification analysis, Floquet analysis and local dynamic stability analysis. Thus, it may be difficult for a researcher to choose the optimal balance assessment approach for a particular purpose. This review aims to summarise the currently published articles on gait stability assessment to recommend a suitable and effective method for analysing dynamic stability during gait.

Methods

Search strategy

An electronic literature search was performed to find all articles related to dynamic stability assessment during gait in relation to fall risk published between 01/2005 and 01/2015. Three databases were searched – Web of Science, PubMed and Medline – using the following key word combinations: (gait OR walking) AND “dynamic stability” AND human AND “fall risk”. A targeted search for relevant articles was also performed. Only original research articles were included in the study. The titles and abstracts were assessed to identify articles that were inappropriate for this review. Because this review aimed to discuss dynamic stability during continuous level walking and only human-related gait events measured strictly in laboratory environments, articles assessing humanoid robots or models, locomotion episodes during daily life and initiation or termination of gait were excluded.

Data extraction

A customised data extraction form was developed. The following data, when present, were extracted: authors, publication year and characteristics of each of the sample groups that participated in the study, including sample size, gender, age, height, weight, and diagnosis. In addition faller identification; fall history assessment, if available; characteristics of the study design, including measurement devices, walking surface, duration and velocity of gait, if performed; unnatural changes in gait characteristics, such as slip perturbations; and data analyses, including data filtering, number of gait cycles, computed variables and key results, if studied, were also extracted. If orbital or local dynamic stability was computed, information regarding the state space reconstruction was also extracted.

Results

Search yield

The initial search of all databases revealed 59 results. Four other articles were identified by a targeted search using the reference lists of the related articles. After discarding duplicates and applying the exclusion criteria, 23 studies were included for further analysis. The search process is shown in Fig. 1.

Fall risk and fall history assessment

Fall history was assessed in 17.4% of studies. A retrospective evaluation was used in 13.0% of those studies, and a combination of retrospective and prospective assessments was only used in one study. Clinical assessment was reported in 21.7% of the studies.

Participants

When comparing sample size, one study included less than 10 participants in each experimental group, one study included less than 10 participants in one of the experimental groups, and all others studies (91.3%) included 10 or more subjects in all experimental groups. The largest study included a total of 134 participants. The gender compositions of the experimental groups were reported by 78.3% of studies: two studies enrolled only female subjects, and all other studies included both male and female participants. In regards to age, 65.2% of studies included subjects up to 65 years of age, 17.4% studies included subjects above 65 years of age and the other studies (17.4%) included a combination of young and middle-aged adults and elderly persons. Information regarding body mass index (BMI) was not provided by any studies; thus, BMI was computed for all studies from the mean weights and mean heights of each of the study groups. According to our calculations, BMI ranged from 21 to 30 kg.m⁻², which corresponds to a normal or overweight population. In regards to health condition, 69.6% of studies included healthy participants, 17.4% studies included healthy subjects as a control group in addition to patients, and the other studies only included patients. Reported diagnoses included unilateral transtibial

amputation, cognitive impairment, stroke, peripheral vestibular disorder, multiple sclerosis and other neurological and musculoskeletal problems.

Fig 1: Search yield with inclusion and exclusion criteria for this review

Measurement devices

Some of the studies did not strictly assess gait characteristics but instead combined gait stability or variability assessments with functional magnetic resonance imaging (Bruijn, Van Impe, Duysens, & Swinnen, 2014) or bone density assessments (Bhatt, Espy, Yang, & Pai, 2011). For the purpose of this review, only the gait related methods and parameters will be discussed.

Motion capture systems or inertial sensors, such as accelerometers and gyroscopes, were used by 91.3% of studies. Force plates placed on the ground or as part of a treadmill were used in 26.1% of studies, and computer assisted rehabilitation environment (CAREN) was used in 2 studies. One study used a dynamometer and goniometer, and one study used a force-sensitive resistor. As the only measurement device, motion capture systems were used in 16.7% of studies, accelerometers were used in 22.2% of studies and force plates were used in 11.1% of studies. A combination of a motion capture system and CAREN or force plates was used in 22.2% of studies.

Walking condition

Participants walked either overground or on a treadmill; one study used a combination of both walking conditions. Participants walked at their preferred walking speed in 56.5% of studies, and a combination of various velocities was assessed in 8.7% of studies. Additionally, 8.7% of studies used a walking speed 4 km/h. In one study, participants walked 1 m/s, and in one other study participants walked 1.4 m/s. Two of the studies assessed the fastest possible walking velocity. Gait speed was computed individually for each subject using leg length in one study, and one study did not provide clear information about walking velocity.

In 78.2% of studies, the walking surface was firm and stable. One study tested subjects walking on a soft surface and two studies tested walking after perturbations. In addition, participants were asked to perform a verbal dual task (letter fluency) in one study, and one study aimed to assess dynamic stability during gait with walking conditions that were different – wider/narrower/longer/shorter steps – than those preferred by the participant. In 17.4% of studies, trip perturbations were created.

Regarding measurement duration, trials were performed with durations ranging from a few seconds to 25 minutes, depending on the subsequent analysis. The reported walking distances ranged from 10 – 160 m, and this mostly reported by studies that did not use a treadmill.

Data analysis

The first parameter extracted was the number of steps or strides used for further analysis. Depending on the mathematic analysis methods used in the studies, the number of steps ranged from 1 to 350, with most above 40. Regarding data filtering, 52.2% of studies did not filter their data or did not specify their filtering process. All studies that specified their data filtering process used lowpass filter type Butterworth or Chebyshev I. Finite

impulse response filtering was used in one study, and Woltring filter routine was implemented in one study. The order of the filters ranged from zero to ten, and cut-off frequencies were chosen depending on the input data. For the marker data recorded using motion capture systems, the cut-off frequencies ranged from 4.5 to 25 Hz, and for the accelerometric data the cut-off frequencies ranged from 10 to 50 Hz. Data from force plates were filtered with cut-off frequencies of 6 or 50 Hz.

The most frequently used variables to quantify dynamic stability were variables describing local dynamic stability – Lyapunov exponents (LE). Short term LE were computed in 60.9% of studies, and long-term LE were computed in 30.4% of studies. Maximum Floquet multipliers (FM), as orbital stability variables, were computed in 13.0% of studies. In 21.7% of studies, LE or FM were computed as the only variables. Temporal gait parameters, such as step time, stride time and double support time, were computed in 30.4% of studies, and spatial gait variables, such as step or stride length and step width, were computed in 34.8% of studies. Cadence was assessed in 21.7% of studies. Regarding time series recorded using inertial sensors, only 13.0% of studies computed variables, such as root means square or peak acceleration and mean angular velocity, that characterised the signal. Other studies used the time series as an input for nonlinear or detrended fluctuation analysis. Regarding variability parameters, coefficients of variation and standard deviations were computed from temporal or spatial gait characteristics in 30.4% studies. Centre of pressure (COP), centre of mass (COM), energy, foot clearance, spectral and other characteristics were computed in 56.5% of studies; however, each of these variable was assessed by no more than three studies.

If local or orbital stability was assessed, we extracted information regarding state space construction, time delay and embedding dimensions. LE (short- or long-term), FM or both were computed in 60.9% of studies, and of those studies, each study that computed FM used kinematic marker data to construct the state space. Short-term LE was computed using kinematic marker data in 28.6% of these studies, using accelerations or angular velocities from inertial sensors in 64.3% of these studies and using COP trajectory in one study. For long-term LE, which was computed in 50.0% of these studies, accelerometric and marker kinematic data were used equally in 42.9% of these studies and COP trajectory was used in one study. To calculate embedding dimensions, global false nearest neighbour analysis was performed in all studies that clearly stated their computation algorithm. The embedding dimension values differed between the various measurement devices. Dimension 6 was used for COP trajectory data, dimension 5 or 6 was used for accelerometric data, and dimension 5 was used for kinematic data. Regarding time delay computation, two possible approaches were found –an autocorrelation function based on an algorithm introduced by Rosenstein et al. (1993) and a first minimum of average mutual information function, which was used more frequently. Because time delays were generally computed from each time series separately for each subject and each trial and then averaged, the values differed for the various time series recorded using various devices.

Discussion

Dynamic stability assessment and its relationship with fall risk and fall history is thoroughly discussed in the literature. Although a prospective approach for fall history assessment is recommended, in the majority of studies, a retrospective approach was used. Additionally, the methodology for dynamic stability assessment during gait is not uniform. Bruijn, Meijer, Beek and van Dieën (2014) in their review discussed validity and computation of currently most often used methods for dynamic stability assessment. To date, the relationship between variables describing dynamic stability during gait and fall risk or fall history has not been discussed, therefore, this study summarised information available in the literature regarding the methodologies used to assess dynamic stability during gait in relation to fall risk.

Factors influencing gait dynamics

There are many factors that have a direct or indirect relationship with dynamic stability. One of the main causes of changes in gait features are participants' characteristics. There is evidence that age influences dynamic stability, as determined using nonlinear techniques (Bruijn et al., 2014; Kang & Dingwell, 2008). Gait variables deducted from COP or COM movement have also been shown to influence dynamic stability (Bizovska et al., 2014; Krasovsky et al., 2012). Studies have shown increased values of variables that describe gait stability or variability with increasing age, which suggests that aging causes a decreasing ability to maintain locomotion stability. A review by Hamacher et al. (2011) studied kinematic variables obtained using motion capture systems. They found variables that effectively distinguished between various age-groups – variability of step width, stride time and velocity. A similar relationship between nonlinear gait analysis and aging has been discussed widely in the literature (Buzzi, Stergiou, Kurz, Hageman, & Heidel, 2003; Terrier & Reynard, 2015). Study results have suggested that variability in spatial-temporal gait characteristics is suitable for distinguishing elder adults from younger adults and that local and orbital stability can also be useful for this purpose.

BMI was not used as a classification criterion in any of the studies examined here. To the best of our knowledge, no studies that assessed the relationship of BMI with dynamic stability during gait have been published. In static conditions, a direct relationship of BMI with postural stability has been documented (Błaszczuk, Cieślinska-Swider, Plewa, Zahorska-Markiewicz, & Markiewicz, 2009; Kovacikova et al., 2014; Ku, Abu Osman, Yusof, & Wan Abas, 2012). The results have shown that overweight and obese people

exhibited worse postural control than normal-weight participants. Because an obvious relationship between BMI and stability in static conditions has been found, future studies should also assess the possible influence of BMI on dynamic stability during gait.

Regarding gender, the majority of studies used both male and female participants, but there were also studies that included strictly female participants. None of the articles discussed in this review studied gender-related differences in gait stability. Although, elder females are more fall-prone than elder males, studies should assess both genders so that their findings can be generalised to both genders.

Five of the studies discussed here assessed healthy subjects in comparison to patients with musculoskeletal, vestibular or neurological problems (Beurskens, Wilken, & Dingwell, 2014; Lamothe et al., 2011; Lee & Chou, 2006; Reynard, Vuadens, Deriaz, & Terrier, 2014). Healthy subjects and patients with neurological problems could be distinguished using LE as a stability indicator (Reynard et al., 2014). The results showed higher short-term LEs computed from accelerations in anterior-posterior, medial-lateral and vertical directions in patients, which indicates lower dynamic stability in patients. LE and FM were insufficient to distinguish between healthy participants and high-functioning participants with transtibial amputation (Beurskens et al., 2014). However, other supportive studies showed that FM and LE could be used to distinguish between patients with musculoskeletal and neurological disorders (Kurz, Arpin, & Corr, 2012; Marghitu & Hobatho, 2001). When comparing cognitively impaired and intact subjects, significant differences between groups were found in phase variability index, scaling exponents and root mean square of medial-lateral acceleration only when a dual task was performed (Lamothe et al., 2011). Patients with complaints of imbalance during walking or with a history of falls exhibited significantly different COM-COP inclination angles than healthy controls (Lee & Chou, 2006). When comparing healthy participants with patients with unilateral peripheral vestibular disorder during perturbed walking, patients showed a decreased ability to maintain stability after perturbations, which can be interpreted as a higher fall risk (McCrum et al., 2014). From these results, it can be assumed that local dynamic stability is sufficient for distinguishing between patients with neurological problems and healthy subjects, and variables describing gait stability after perturbations seem to be efficient for recognising potential fallers.

Other factors influencing the stability and variability of gait include the condition of the walking surface (Chang, Sejdic, Wright, & Chau, 2010), stability of the walking surface (Beurskens et al., 2014; McAndrew, Wilken, & Dingwell, 2011), visual feedback (Beurskens et al., 2014; McAndrew et al., 2011), changes in step characteristics (Young & Dingwell, 2012) and perturbations (Bhatt et al., 2011; Kajrolkar, Yang, Pai, & Bhatt, 2014; Krasovsky et al., 2012; McCrum et al., 2014). Chang, Sejdic, Wright and Chau (2010) tested gait stability on different surfaces, firm and soft, using LE and variability parameters as indicators. According to their results, LE was able to differentiate between surfaces, while variability of spatial and accelerometric characteristics were not. Beurskens et al. (2014) and McAndrew et al. (2011) tested gait dynamics in a destabilising environment using the CAREN system. When comparing unperturbed and perturbed walking patterns, perturbed walking exhibited significantly different mean and variability values of spatial-temporal gait characteristics and increased FM and short-term LE (Beurskens et al., 2014). McAndrew et al. (2011) showed that changes in LE and FM values computed from variables for different directions were related to the direction of the perturbation. Interestingly, for FM computed from the velocity of the lower trunk in the vertical direction, perturbed walking showed a smaller FM than unperturbed walking. Nonlinear variables were also found to be sensitive to voluntary changes in steps characteristics (Young & Dingwell, 2012).

It is well known that gait speed can influence gait performance and most gait variables. The majority of studies used preferred walking speed when performing gait analysis. It is unclear whether the choice of preferred walking speed, which is generally different for subjects within a group, influences the computed results. There is much evidence that gait stability and variability differ when the velocity of locomotion differs (England & Granata, 2007; Kang & Dingwell, 2008; Krasovsky, Lamontagne, Feldman, & Levin, 2014; Stenum, Bruijn, & Jensen, 2014; Terrier & Deriaz, 2013). To ensure uniformity, we can propose that a defined walking speed should be used for gait analysis. On the other hand, walking with a defined walking speed other than the participant's preferred walking speed could influence locomotion patterns, which could result in unnatural or altered walking patterns and, therefore, could have a negative impact on the computed results.

Relationship between fall risk and dynamic stability

Fall risk assessments using clinical tests or questionnaires about fall history were performed in nine studies. Prospective or retrospective approaches were used to examine fall history. Retrospective assessments of fall history are not sufficiently accurate or reliable because information about falls, their causes and consequences, are hard to remember in detail for 6, 12 and 24 months. In addition, subjects are examined after falls; thus, the impact of falls rather than fall risk is measured after a fall. A prospective approach is recommended by Lamb, Jørstad-Stein, Hauer and Becker (2005). Nevertheless, retrospective fall history assessment was the most frequently used method reported in the literature (Howcroft et al., 2013). Researchers related fall risk or fall history with local dynamic stability (Lockhart & Liu, 2008; Toebes, Hoozemans, Furrer, Dekker, & van Dieën, 2012), means and standard deviations or coefficients of variations of spatial-temporal gait characteristics (Konig, Taylor, Armbrrecht, Dietzel, & Singh, 2014), COM-COP inclination angles (Lee & Chou,

2006), multiscale entropy and recurrence quantification analysis of anterior-posterior accelerometric signal (Riva, Toebe, Pijnappels, Stagni, & van Dieën, 2013) and COM movement patterns as a response to perturbations (Krasovsky et al., 2012). In the literature, variability of kinematic parameters, mostly in combination with spatial-temporal gait variables, was used to differentiate between fallers and non-fallers (Barak, Wagenaar, & Holt, 2006; Hausdorff, Edelberg, Mitchell, Goldberger, & Wei, 1997; Miyoshi, Kinugasa, Urushihata, & Yuki, 2011). FM also seems to be an effective tool for gait assessment in relation to fall risk (Riva, Bisi, & Stagni, 2013). In future research, a prospective approach should be used when assessing fall history and its relationship with dynamic stability during gait and a combination of clinical tests and instrumental methods should be considered as both of these approaches provide information about fall risk.

Data analysis with nonlinear approaches

Nonlinear analyses included computation of FM, local divergence exponents, LE, and variables computed using recurrence quantification analysis. FM is able to quantify orbital stability of periodic, or mostly periodic, systems, while LE is used to assess local stability in not strictly periodic, and often chaotic, systems. However, both of these approaches necessitate a large number of gait cycles for analysis; thus, longer locomotion periods must be recorded. Recurrence quantification analysis is a multidimensional nonlinear analysis that can provide a quantification of the deterministic structure, the non-stationarity or irregularity, of the system (Riley & Turvey, 2002; Riva, Bisi, & Stagni, 2014).

Although LE and FM are widely used, the methodology for data recording and analysis of LE and FM varies. First, data filtering varies between studies and devices. For the computation of both types of exponents, some authors filtered the signal using a low-pass Butterworth filter or Chebyshev type I filter with cut-off frequencies ranging from 6 and 50 Hz. Some authors did not filter the recorded signals because of application of linear filtering to nonlinear signals (Riva, Grimpampi, Mazza, & Stagni, 2014). Thus, comparing results between studies is difficult when the data are analysed differently.

The studies examined in this review used stride counts that range from 35 steps for short-term LE computation to 175 for LE or FM computation. Riva et al. (2014) studied the minimal number of strides required for gait stability and variability measures to ensure accuracy and reliability. For short-term LE calculated for acceleration in all directions, the number of strides ranged from 63 to 105. For long-term LE, 138 to 146 strides were used, and for FM, most studies used 137 strides.

The methodology for nonlinear analyses is highly variable from data recording to data analysis. In future research, all methods should be discussed and analysed more deeply. A uniform approach for each method in regards to the reliability and accuracy of the measurement device being implemented for gait analysis should be proposed to allow results to be compared between studies without inaccuracies.

Conclusions

This study summarised articles related to stability assessment during gait. The conclusions of this review of the literature are as follows:

For fall risk assessment, instrumental methods or a combination of the clinical tests and questionnaires should be used. A prospective approach should be used for fall history assessment. The most influential factors in dynamic stability and variability of gait are age, health, walking surface and walking speed. Nonlinear variables and variability of spatial-temporal gait characteristics are effective for distinguishing different age groups. Nonlinear variables are sufficient for distinguishing patients with musculoskeletal or neurological disorders from healthy subjects. Direct relationships between fall history or fall risk and nonlinear variables and spatial-temporal gait variables and their variability were determined using clinical tests and questionnaires. In future research, the relationships between dynamic stability during gait and body mass index and gender should be investigated. A uniform methodology for each nonlinear technique should be implemented.

Acknowledgements

The study was supported by a research grant from the Czech Science Foundation (grant no. 15-13980S) "Assessment of gait performance variability as indicator of fall risk".

Conflict of interest

There is no conflict of interest.

References

- Barak, Y., Wagenaar, R. C., & Holt, K. G. (2006). Gait characteristics of elderly people with a history of falls: a dynamic approach. *Physical Therapy*, 86(11), 1501-1510.
- Beurskens, R., Wilken, J. M., & Dingwell, J. B. (2014). Dynamic stability of individuals with transtibial amputation walking in destabilizing environments. *Journal of Biomechanics*, 47(7), 1675-1681.
- Bhatt, T., Espy, D., Yang, F., & Pai, Y. C. (2011). Dynamic gait stability, clinical correlates, and prognosis of falls among community-dwelling elder adults. *Archives of Physical Medicine and Rehabilitation*, 92(5), 799-805.

- Bizovska, L., Svoboda, Z., Kutilek, P., Janura, M., Gaba, A., & Kovacikova, Z. (2014). Variability of centre of pressure movement during gait in young and middle-aged women. *Gait & Posture*, 40(3), 399-402.
- Błaszczyk, J. W., Cieślinska-Swider, J., Plewa, M., Zahorska-Markiewicz, B., & Markiewicz, A. (2009). Effects of excessive body weight on postural control. *Journal of Biomechanics*, 42(9), 1295-1300.
- Bruijn, S. M., Van Impe, A., Duysens, J., & Swinnen, S. P. (2014). White matter microstructural organization and gait stability in older adults. *Frontiers in Aging Neuroscience*, 6, 104.
- Buzzi, U. H., Stergiou, N., Kurz, M. J., Hageman, P. A., & Heidel, J. (2003). Nonlinear dynamics indicates aging affects variability during gait. *Clinical Biomechanics*, 18(5), 435-443.
- Chang, M. D., Sejdic, E., Wright, V., & Chau, T. (2010). Measures of dynamic stability: Detecting differences between walking overground and on a compliant surface. *Human Movement Science*, 29(6), 977-986.
- England, S. A., & Granata, K. P. (2007). The influence of gait speed on local dynamic stability of walking. *Gait & Posture*, 25(2), 172-178.
- Gaouelle, A., Mégrot, F., Presedo, A., Husson, I., Yelnik, A., & Penneçot, G.-F. (2013). The gait variability index: A new way to quantify fluctuation magnitude of spatiotemporal parameters during gait. *Gait & Posture*, 38(3), 461-465.
- Hamacher, D., Singh, N. B., Van Dieën, J. H., Heller, M. O., & Taylor, W. R. (2011). Kinematic measures for assessing gait stability in elderly individuals: a systematic review. *Journal of the Royal Society Interface*, 8(65), 1682-1698.
- Hausdorff, J. M., Edelberg, H. K., Mitchell, S. L., Goldberger, A. L., & Wei, J. Y. (1997). Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of Physical Medicine and Rehabilitation*, 78(3), 278-283.
- Hilfiker, R., Vaney, C., Gattlen, B., Meichtry, A., Deriaz, O., Lugon-Moulin, V., ... Terrier, P. (2013). Local dynamic stability as a responsive index for the evaluation of rehabilitation effect on fall risk in patients with multiple sclerosis: a longitudinal study. *BMC Research Notes*, 6, 260.
- Howcroft, J., Kofman, J., & Lemaire, E. D. (2013). Review of fall risk assessment in geriatric populations using inertial sensors. *Journal of Neuroengineering and Rehabilitation*, 10(1), 91.
- Joint Commission Resources (2008) *Reducing the risk of patient harm resulting from falls: Toolkit for implementing national patient safety goal 9*.
- Kajrolkar, T., Yang, F., Pai, Y. C., & Bhatt, T. (2014). Dynamic stability and compensatory stepping responses during anterior gait-slip perturbations in people with chronic hemiparetic stroke. *Journal of Biomechanics*, 47(11), 2751-2758.
- Kang, H. G., & Dingwell, J. B. (2008). Effects of walking speed, strength and range of motion on gait stability in healthy older adults. *Journal of Biomechanics*, 41(14), 2899-2905.
- Konig, N., Taylor, W. R., Armbrrecht, G., Dietzel, R., & Singh, N. B. (2014). Identification of functional parameters for the classification of older female fallers and prediction of 'first-time' fallers. *Journal of the Royal Society Interface*, 11(97).
- Kovacikova, Z., Svoboda, Z., Neumannova, K., Bizovska, L., Cuberek, R., & Janura, M. (2014). Assessment of postural stability in overweight and obese middle-aged women. *Acta Gymnica*, 44(3), 149-153.
- Krasovsky, T., Banina, M. C., Hacmon, R., Feldman, A. G., Lamontagne, A., & Levin, M. F. (2012). Stability of gait and interlimb coordination in older adults. *Journal of Neurophysiology*, 107(9), 2560-2569.
- Krasovsky, T., Lamontagne, A., Feldman, A. G., & Levin, M. F. (2014). Effects of walking speed on gait stability and interlimb coordination in younger and elder adults. *Gait & Posture*, 39(1), 378-385.
- Ku, P. X., Abu Osman, N. A., Yusof, A., & Wan Abas, W. A. (2012). Biomechanical evaluation of the relationship between postural control and body mass index. *Journal of Biomechanics*, 45(9), 1638-1642.
- Kurz, M. J., Arpin, D. J., & Corr, B. (2012). Differences in the dynamic gait stability of children with cerebral palsy and typically developing children. *Gait & Posture*, 36(3), 600-604.
- Laessoe, U., Hoeck, H. C., Simonsen, O., Sinkjaer, T., & Voigt, M. (2007). Fall risk in an active elderly population – can it be assessed? *Journal of Negative Results in Biomedicine*, 6, 2.
- Lamb, S. E., Jørstad-Stein, E. C., Hauer, K., Becker, C. (2005). Development of a common outcome data set for fall injury prevention trials: the Prevention of Falls Network Europe consensus. *Journal of the American Geriatrics Society*, 53(9), 1618-1622.
- Lamoth, C. J., van Deudekom, F. J., van Campen, J. P., Appels, B. A., de Vries, O. J., & Pijnappels, M. (2011). Gait stability and variability measures show effects of impaired cognition and dual tasking in frail people. *Journal of Neuroengineering and Rehabilitation*, 8, 2.
- Lee, H. J., & Chou, L. S. (2006). Detection of gait instability using and center of pressure inclination the center of mass angles. *Archives of Physical Medicine and Rehabilitation*, 87(4), 569-575.
- Lockhart, T., & Liu, J. (2008). Differentiating fall-prone and healthy adults using local dynamic stability. *Ergonomics*, 51(12), 1860-1872.
- Marghitu, D. B., & Hobatho, M. C. (2001). Dynamics of children with torsional anomalies of the lower limb joints. *Chaos, Solitons & Fractals*, 12(13), 2411-2419.
- 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(4), 644-649.

-
- McCrum, C., Eysel-Gosepath, K., Epro, G., Meijer, K., Savelberg, H. H., Brüggemann, G. P., & Karamanidis, K. (2014). Deficient recovery response and adaptive feedback potential in dynamic gait stability in unilateral peripheral vestibular disorder patients. *Physiological Reports*, 2(12).
- Miyoshi, H., Kinugasa, T., Urushihata, T., & Yuki, S. (2011). Relationship between stride time variability of walking and fall experience in middle aged and elderly woman. *Japanese Journal of Physical Fitness and Sports Medicine*, 60(1), 121-132.
- Reynard, F., Vuadens, P., Deriaz, O., & Terrier, P. (2014). Could local dynamic stability serve as an early predictor of falls in patients with moderate neurological gait disorders? A reliability and comparison study in healthy individuals and in patients with paresis of the lower extremities. *Plos One*, 9(6).
- Reynard, P., & Terrier, P. (2014). Local dynamic stability of treadmill walking: Intrasection and week-to-week repeatability. *Journal of Biomechanics*, 47(1), 74-80.
- Riley, M. A., & Turvey, M. T. (2002). Variability and determinism in motor behavior. *Journal of Motor Behavior*, 34(2), 99-125.
- Riva, F., Bisi, M. C., & Stagni, R. (2013). Orbital stability analysis in biomechanics: A systematic review of a nonlinear technique to detect instability of motor tasks. *Gait & Posture*, 37(1), 1-11.
- Riva, F., Bisi, M. C., & Stagni, R. (2014). Gait variability and stability measures: Minimum number of strides and within-session reliability. *Computers in Biology and Medicine*, 50, 9-13.
- Riva, F., Grimpampi, E., Mazza, C., & Stagni, R. (2014). Are gait variability and stability measures influenced by directional changes? *Biomedical Engineering Online*, 13.
- Riva, F., Toebe, M. J. P., Pijnappels, M., Stagni, R., & van Dieën, J. H. (2013). Estimating fall risk with inertial sensors using gait stability measures that do not require step detection. *Gait & Posture*, 38(2), 170-174.
- Rosenblatt, N. J., & Grabiner, M. D. (2010). Measures of frontal plane stability during treadmill and overground walking. *Gait & Posture*, 31(3), 380-384.
- Rosenstein, M. T., Collins, J. J., & De Luca, C. J. (1993). A practical method for calculating largest Lyapunov exponents from small data sets. *Physica D: Nonlinear Phenomena*, 65(1-2), 117-134.
- Rubenstein, L. Z. (2006). Falls in elder people: epidemiology, risk factors and strategies for prevention. *Age Ageing*, 35(S2), ii37-ii41.
- Scuffham, P., Chaplin, S., & Legood, R. (2003). Incidence and costs of unintentional falls in elder people in the United Kingdom. *Journal of Epidemiology and Community Health*, 57(9), 740-744.
- Stapleton, C., Hough, P., Bull, K., Hill, K., Greenwood, K., & Oldmeadow, L. (2009). Four-item fall risk screening tool for subacute and residential care: The first step in falls prevention. *Australasian Journal on Ageing*, 28 (3), 139-143.
- Stenhagen, M., Ekström, H., Nordell, E., & Elmstahl S. (2013) Falls in the general elderly population: a 3- and 6- year prospective study of risk factors using data from the longitudinal population study 'Good ageing in Skane'. *BMC Geriatrics*, 13, 81.
- Stenhagen, M., Ekström, H., Nordell, E., & Elmstahl, S. (2014). Accidental falls, health-related quality of life and life satisfaction: A prospective study of the general elderly population. *Archives of gerontology and geriatrics*, 58(1), 95-100.
- Stenum, J., Bruijn, S. M., & Jensen, B. R. (2014). The effect of walking speed on local dynamic stability is sensitive to calculation methods. *Journal of Biomechanics*, 47(15), 3776-3779.
- Stevens, J. A. (2005). Falls among elder adults: risk factors and prevention strategies. *Journal of Safety Research*, 36(4), 409-411.
- Terrier, P., & Deriaz, O. (2013). Non-linear dynamics of human locomotion: effects of rhythmic auditory cueing on local dynamic stability. *Frontiers in physiology*, 4, 230.
- Terrier, P., & Reynard, F. (2015). Effects of age on the variability and stability of gait: A cross-sectional treadmill study in healthy individuals between 20 and 69 years of age. *Gait & Posture*, 41(1), 170-174.
- Toebe, M. J. P., Hoozemans, M. J. M., Furrer, R., Dekker, J., & van Dieën, J. H. (2012). Local dynamic stability and variability of gait are associated with fall history in elderly subjects. *Gait & Posture*, 36(3), 527-531.
- World Health Organization. (2007). *WHO Global report on falls prevention in elder age*, Geneva, Switzerland: WHO Press.
- Young, P. M. M., & Dingwell, J. B. (2012). Voluntarily changing step length or step width affects dynamic stability of human walking. *Gait & Posture*, 35(3), 472-477.
-