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Review Article

Instrumented Analysis of Spatial Temporal Gait Variability as a Marker of Falls Risk to Assist Clinical Practice: A Brief Review

Abstract

Spatial temporal gait variability has developed into a measure of interest in clinical gait analysis. It is capable of providing unique insight into rhythmic stability of human gait and may be a sensitive biomarker of falls risk. Several lines of evidence support the use of spatial temporal gait variability as a clinical measure. The purpose of this review is to provide a brief, practical review, of spatial temporal gait variability. This review discusses how gait variability data is obtained, examines previous studies reporting gait variability as a marker of falls in a range of clinical populations and identifies approaches to implement this measure into clinical practice. In summary, it is suggested that spatial temporal gait variability is a sensitive measure of gait function that can assist clinical practice and delivery of therapy services.

Introduction

Regaining independent mobility is a common rehabilitation goal for many clinical populations including stroke survivors, amputees and patients recovering from various orthopedic surgeries such as total knee arthroplasty. Sensitive measures which quantify characteristics of gait are therefore of significant value for clinicians. Analysis of gait can assist clinical practice by identifying functional impairments which can be used as therapeutic targets and inform selection of appropriate rehabilitation strategies to optimize recovery of gait function. Measures of gait function can be categorized as spatial temporal (e.g. step time, step length), kinematic (the geometry of motion), kinetic (measures of force, joint moments) or energy expenditure (metabolic cost of walking). Utilizing one, or a combination of these measures will provide valuable information on gait characteristics which is likely to assist clinical practice.

The performance of gait involves coordinated action of muscles acting at the hip, knee and ankle joints to move the centre of gravity forward in a controlled manner. It is produced by the locomotor system which integrates inputs from the primary motor cortex (M1), cerebellum and basal ganglia,

with addition of feedback from the visual, vestibular and proprioceptive systems producing motor commands to execute coordinated muscle firing and limb movement [1]. The result is a highly consistent walking pattern with little variation in gait parameters from stride-to-stride [1]. However, abnormalities or injury of the locomotor system can result in a variable walking pattern [2-4]. In recent years there has been growing interest in the fluctuation of spatial temporal gait parameters from stride-to-stride as it may be that they are important biomarker of gait function. Variability in spatial temporal gait measures was originally considered to represent noise within the locomotor system without having any physiological significance. However, gait variability is now believed to reflect the underlying motor control of gait and appears to be sensitive to different pathological or ageing conditions [1]. The purpose of this review is to introduce gait variability as a sensitive, quantitative measure of gait function and discuss its potential to assist clinical practice.

Gait variability may be a sensitive marker of falls risk

Gait variability quantifies fluctuations in the regularity of gait patterns which are relatively stable in healthy adults when walking over level ground [5,6]. Some level of variability in gait

is acceptable, and may in fact be beneficial for movement in space. For example, the ability to vary gait patterns may allow for stepping over obstacles or slight changes in direction to avoid hazards [7-9]. However, in stable testing environments, gait patterns should be relatively consistent. It is thought that a more variable gait pattern may cause the centre of pressure to move over or beyond the base of support in a relatively uncontrolled and unstable fashion which may predispose an individual to experience a fall [10]. Falls assessment is an important focus for many health services. Intrinsic risk factors for falls include age, chronic disease, gait and balance instability, decreased vision, altered mental status and medication use [11]. Many, if not all, of these factors would likely be prevalent in many patients groups that utilize acute hospital services, rehabilitation facilities, community services and aged care facilities. Therefore, there is a strong clinical requirement for sensitive tools to assess falls risk and spatial temporal gait variability may be an appropriate biomarker. Sensitive measures to predict falls risk or discriminate falls history have substantial value given the negative consequences and significant cost on the health care system associated with falls [12,13]. Experiencing a fall has been associated with functional limitations, institutionalization, decline in independence, reduced confidence and self-imposed restriction of activity [12,14-16]. The activity limitations and participation restrictions associated with falls highlights the importance of identifying sensitive measures of gait function, such as spatial temporal gait variability, which are associated with falls history and falls risk.

Assessment and analysis of spatial temporal gait variability

Spatial temporal gait variability can be assessed using various techniques. Often considered the 'gold standard', 3D motion capture systems are able to record locomotion with high precision in purpose built laboratory settings. Motion capture systems use multiple cameras positioned to track location of reflective markers placed on specific landmarks of an individual. Subsequent identification of heel strike and toe off within the system software allows analysis of spatial temporal data, while kinematic and kinetic data can also be derived (analysis of gait kinetics requires additional force measurement, e.g. ground reaction force plates). While 3D motion captures systems provide a rich source of information, they are relatively expensive and often require purpose built laboratory facilities. Furthermore, 3D motion capture systems can require considerable time to both collect and process gait data. As a result, lower-cost, portable systems are frequently used. One of the most common methods currently used is computerized walkways [17]. Systems often come in a variety of lengths, are portable, and record spatial temporal parameters from embedded pressure sensors which detect foot position as the participant walks across the walkway. Alternative approaches include gyroscopes [18] or tri-axial accelerometers

[19,20] worn on the participant to record spatial temporal gait parameters while they mobilize. Importantly, test-retest reliability appears similar between various assessment tools [18,21,22], providing some level of confidence that the choice of assessment tool will not affect reliability of spatial temporal gait parameters.

Currently there does not appear to be a standardized metric used to report spatial temporal gait variability in the literature, with studies reporting a mixture of standard deviation and coefficient of variation as a measure of variability. As a result, caution should be applied when comparing spatial temporal variability between studies to ensure that the metrics compared (standard deviation or coefficient of variation) are the same. The advantage of standard deviation is that it is not as strongly influenced by the mean value of the spatial temporal measure compared to the coefficient of variation. Coefficient of variation is calculated as the standard deviation divided by the mean. Therefore, a subject with larger step length but the same standard deviation would have a smaller coefficient of variation. However, the advantage of using coefficient of variation is that it is a dimensionless unit allowing comparison with other variability measures (e.g. step length variability and step time variability) and across studies. It has been suggested future studies report both standard deviation and coefficient of variation as measures to quantify gait variability [17]. Given relative advantages and disadvantages of these methods, this appears to be a reasonable suggestion. Furthermore, no matter which metric for variability is reported, pooling left and right step measurements to determine variability may obscure underlying asymmetries, particularly for patients groups where impairments are unilateral (e.g. stroke survivors, amputees). Reporting spatial temporal variability for each limb with respect to the relative to the underlying pathology is recommended (e.g. paretic and non-parietic limb for stroke, or amputated and non-amputated limb for amputees).

In order to reliably assess variability of spatial temporal gait parameters, a number of steps should be recorded. As a result, variability of spatial temporal parameters recorded with motion capture systems or computerized walkways involve repeated walk trials across an active data collection area. A recent review suggested a minimum of 12 steps are collected to improve reliability of data [17]. However, earlier previous studies have recommended up to 120 steps be recorded to reliably measure variability [19,23]. Increasing the number of steps recorded during data collection may be achieved by repeating individual walk trials with a participant stopping, turning 180 degrees, and again walking over or across the data collection area (see Figure 1). This approach, while practical, has technical limitations. It is generally considered that continuous walking may be more accurate, as short interrupted walks do not allow spatial temporal rhythms to stabilize. Indeed, gait variability measured from short interrupted walks has been shown to be higher than continuous walk test protocols [24] and likely

reflects stabilization of spatial temporal gait parameters at either the beginning or end of the walk trial as the participant initiates walking and decelerates at the end of the trial. It could be argued that walking during everyday activities predominantly occurs over short bursts, so testing in a manner reflecting this provides a greater representation of everyday walking. However, if the purpose of testing is to identify abnormalities in spatial temporal rhythms, then artificially introducing variability may not be appropriate. Therefore, the most appropriate method may be to utilize continuous walking approaches or extending lead in and out lengths so that spatial temporal rhythms can stabilize (Figure 1).

While it is likely that a greater number of steps recorded would provide a stronger, and more reliable, estimate of spatial temporal variability, consideration should be given to the patient population to ensure that fatigue induced by the desire for high step counts does not affect the measure of gait variability [25]. For example, older adults [26], people with a high metabolic cost of walking (e.g. patients with diabetes mellitus [27]), or those with abnormal biomechanics (e.g. stroke survivors [28] or amputees [29]) are unlikely to be able to perform a high volume of walking within a short period of time and may fatigue quickly during gait analysis. The introduction of fatigue would likely alter spatial temporal parameters and result in reduced gait speed which may result

in an increased variability. Further supporting this suggestion, it is known that for an individual subject, variation in gait speed between individual walk trials is a potential confounder of gait variability findings [30–33]. While previous work has investigated speed normalization of gait parameters in adults walking at a range of speeds [31,34], only one study has translated this approach to investigate the effect on variability of spatial temporal parameters [33]. This study demonstrated that variability of spatial temporal parameters was significantly different compared to variability parameters normalized for gait speed, with those normalized for speed providing a more sensitive assessment of gait function. However, gait speed may differentially affect measure of spatial-temporal gait variability. In patients with Parkinson's disease it was shown that gait speed affected the measure of stride time variability, but had no effect on swing time variability [35]. Variations in speed may affect accurate interpretation of spatial temporal gait variability measures, however further work is required to thoroughly investigate the effect of gait speed on measures of spatial temporal gait variability. It may be that approaches of normalizing data for speed are particularly appropriate for populations where fatigue is likely to influence measures of spatial temporal variability.

Evidence supporting gait variability as a marker of falls

Several studies have demonstrated the clinical utility of gait variability as a functional biomarker. Perhaps the largest area of research has investigated gait variability as a marker of falls, with greater spatial temporal gait variability associated with increased falls, or risk of falls. A search of the literature in PubMed and CINAHL using keywords 'gait variability' AND 'falls' found several studies in a range of clinical populations including older adults [36–40], lower-limb amputees [33,41,42], stroke [3], Parkinson's disease [2], Huntington's disease [43], patients with peripheral neuropathy [44] and mild cognitive impairment/dementia [38]. The broad nature of these pathological populations demonstrates the wide potential to utilise gait variability as a biomarker of falls risk in various clinical settings.

Interestingly, the specific spatial temporal gait variability measures associated with falls appears quite diverse both within, and across, different patient groups (Table 1). For example, in older adults, one prospective and one retrospective study reported that stride time variability was a predictor of falls [37,38], others reported swing time and stride length variability were predictors of falls risk [36,40], while another reported step width variability was associated with falls history [39]. Similarly, retrospective studies with lower-limb amputees have reported that falls history was associated with greater amputated limb swing-time variability [42], non-amputated limb step time variability [41] and greater amputated limb step time, step length and step width variability [33]. This variance in the measures identified may reflect the strong collinearity

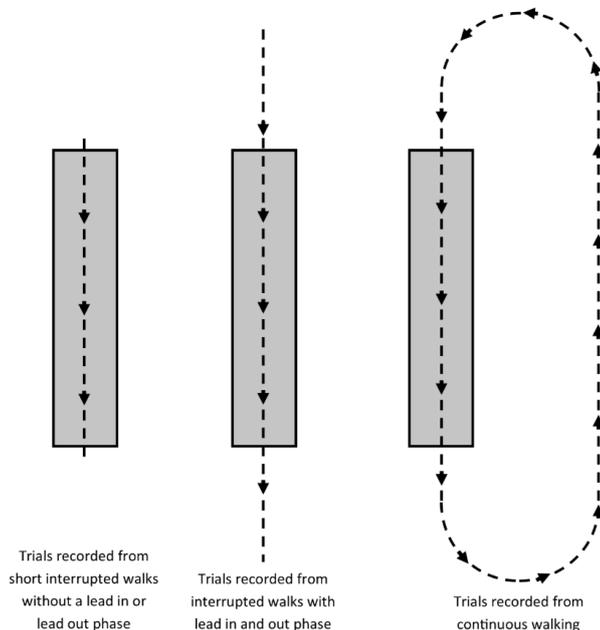


Figure 1: Examples of data collection methods. The active area for data collection is shown with a grey rectangle and may represent a computerised walkway or recording zone for motion capture systems. Left) Walk trials recorded from short interrupted walks without lead in or out phases may overestimate gait variability as spatial temporal parameters may need to stabilise during gait initiation and may be affected if the participant decelerates at the end of the walk trial. Centre) Extension of lead in and out phases would allow stabilisation of spatial temporal patterns prior to entering the data collection area, alleviating effects of gait initiation and cessation on data collection. Right) Data recorded from continuous walking would also alleviate effects of gait initiation and cessation.

Table 1: Summary of studies using instrumented analysis of spatial temporal gait variability to identify falls risk.

Author (year)	Population	Sample size	Data collection method	Gait analysis tool	Walk distance	Key spatial temporal variability marker of falls risk
Vergheze <i>et al.</i> , 2009	Older adults (>70 years)	597	Prospective	GAITRite™	2 trials over 4.6m mat	Swing time, Stride length
Hausdorff <i>et al.</i> , 2001	Older adults (>70 years)	52	Prospective	Wearable sensor	6 minutes	Stride time
Allali <i>et al.</i> , 2016	Older adults (>60 years)	1161	Retrospective	GAITRite™	Multi-site study with walk distances ranging from 1-6 trials over 4.6-7.9m mat	Stride time
Brach <i>et al.</i> , 2005	Older adults (>65 years)	503	Retrospective	GAITRite™	2 trials over 4m mat	Step Width
Maki 1997	Older adults (aged 62-96 years)	75	Prospective	Wearable sensor	1 trial, 8m	Stride length
Hordacre <i>et al.</i> , 2015	Transibial amputees	45	Retrospective	GAITRite™	10 trials over 4.9m mat	Step time, Step length, Step width
Parker <i>et al.</i> , 2013	Transibial amputees	34	Retrospective	GAITRite™	8 trials over 6.1m mat	Step time (non-amputated limb)
Vanicek <i>et al.</i> , 2009	Transibial amputees	11	Retrospective	3D motion capture	12 trials over 10m area	Swing time (amputated limb)
Srikanth <i>et al.</i> , 2009	Stroke	294	Prospective	GAITRite™	6 trials over 4.2m mat	Average variability of stride length, stride time and step width
Schaafsma <i>et al.</i> , 2003	Parkinson's disease	32	Retrospective	Wearable sensor	4 trials over 20m	Stride time
Grimbergen <i>et al.</i> , 2008	Huntington's disease	45	Retrospective	GAITRite™	3 trials, length not stated	Stride length
Wuehr <i>et al.</i> , 2014	Peripheral neuropathy	18	Retrospective	GAITRite™	1 trial over 6.7m mat	Stride time

between spatial temporal parameters. For example, there is likely to be a strong correlation between step length, step time and swing time. Nevertheless, further work is required to identify appropriate outcome measure selection as analysis of all potential spatial temporal gait variability measures may increase the risk of 'false positive' statistical errors (Type I error).

It should also be acknowledged that analysis of spatial temporal gait variability may have wider implications for rehabilitation clinicians beyond being a biomarker for falls risk. It has previously been reported that higher levels of gait variability are associated with frailty [45] and fear of falling [46] in older adults. Recently, gait variability was found to differentiate older adults with mobility and cognitive impairment, and predict those with future cognitive decline [47]. Furthermore, increased step time variability was found to be associated with a greater burden of subclinical brain vascular abnormalities as identified with magnetic resonance imaging [48]. Assessment of gait variability has the potential to be a sensitive, objective measure, of global function in rehabilitation, providing further support to suggest that it should be strongly considered in clinical practice.

Potential clinical utility

Spatial temporal gait variability is a measure which can clearly assist clinical practice. In this review it has been highlighted that spatial temporal gait variability is a sensitive measure

of human motor control [1]. Previous studies have identified correlations with falls history [2,3,33,38,39,41-44] or ability to predict falls [36,37,40]. Given this significant implications that experiencing a fall has on both the individual [12,14-16] and also clinical services [12,13], the translational potential for spatial temporal gait variability should be investigated. It is likely that gait variability can assist clinical practice in several ways. For example, spatial temporal gait variability could be used as a tool to screen patients on admission to clinical services to help characterize falls risk and apply appropriate falls prevention strategies. In addition, screening with gait variability could be used to identify appropriate treatment targets. Abnormalities in gait would be objectively identified and treatment approaches could be implemented to normalize gait function. This may assist streamlining of rehabilitation and therapy services for patients who require specific gait interventions. Furthermore, therapy may be applied which is capable of restoring measures of gait variability to normal levels. Previous studies have demonstrated that dual task training in older adults [49], treadmill training in Parkinson's disease [50] and pharmacological interventions in Parkinson's disease [51] were directly able to improve gait variability measures. Finally, gait variability could be used as a clinical outcome measure to demonstrate effectiveness of therapy and services. This would be achieved by quantifying changes in gait function from admission to discharge (or beyond) and may be particularly important given the increased demand for evidenced based practice and demonstrating effectiveness of

therapy services.

It should be acknowledged that there may be barriers to assessing spatial temporal gait variability in clinical practice. Perhaps most obvious is availability of appropriate equipment such as motion capture systems or computerized walkways. However, with advances in technology, it is likely that small, portable systems, worn on a participant may become more readily available, assisting clinical translation. Furthermore, there may be some level of processing required to analyze spatial temporal data. This is perhaps most problematic for 3D motion capture systems as computerized walkways, such as the GAITRite™, come with appropriate software to automate much of the analysis. Finally, appropriate selection of spatial temporal variability measure appears to lack clarity at this stage. As demonstrated in table 1, a wide range of measures have been identified both within and across patients groups. Until specific measures are identified with further studies, it may be difficult to select specific spatial temporal gait variability measures for each patient group. It may be that a combination of spatial temporal gait variability measures is appropriate. Measures such as the Gait Variability Index (GVI) have already been investigated and found to be a sensitive measure of gait function and mobility deficits [52]. However, given the potential clinical significance that gait variability has as a marker of falls, it is suggested that difficulty in pre-selecting an appropriate gait measure should not preclude the analysis from being conducted.

Future directions

This review has demonstrated that spatial temporal gait variability is an important measure of gait function that should be considered for clinical use as a marker of falls risk. To continue developing and facilitating clinical utility of this tool, further research is required to identify appropriate metrics (e.g. step time variability, step length variability) and variability parameters (e.g. coefficient of variation, standard deviation). Future work should also consider identifying the minimum number of steps required to obtain a reliable measure of gait variability. While it is generally acknowledged that a greater number of steps provides a stronger estimate of variability, this approach is somewhat impractical given the potential to induce fatigue in clinical populations. Finally, it is suggested that future studies should continue to investigate the predictive capacity of spatial temporal gait variability to predict falls risk with prospective studies as this is likely to have significant value for clinical services. It may be that gait variability could be combined with additional outcomes measures to form an algorithm to provide a strong predicative tool to reliably inform clinicians of falls risk.

Conclusion

Spatial temporal gait variability is a sensitive measure of gait function capable of identifying falls risk or discriminating

based on history of falls in a range of clinical populations. As such, gait variability has significant potential to assist clinical practice as a sensitive marker of falls. Clinical services should further investigate implementing gait variability as a standard assessment to identify falls risk and potential therapeutic targets. It is suggested that this would assist delivery of therapy and identification of patients requiring falls precautions.

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