Interpreting Spatiotemporal Parameters, Symmetry, and Variability in Clinical Gait Analysis

Arnaud Gouelle and Fabrice Mégrot

Abstract

Spatiotemporal parameters (STP) are widely studied variables in clinical gait analysis. Yet they often remain underutilized despite the rich information they provide about organization and control of the patient's progress. Building on them requires a broad knowledge of the "normal" gait, before to being able to understand the impact of pathological disorders. We hope to provide information to better grasp and understand the STP while highlighting important points.

Through this chapter, we will introduce basics of the gait cycle, before considering the components for which the STP may be informative: rhythm, pace, phases, postural control, asymmetry, and variability. We will define main parameters for each component and discuss their use regarding state of the art. Then factors influencing STP will be addressed to understand how these parameters change during life, when a child learns to walk or when the advance in age-affected gait in the elderly, as well as the influence of diseases. Indeed, various pathologies affect the walk, and the most relevant STP are not always the same. We will consider Friedreich ataxia, which is a neurodegenerative disease, in which combination of cerebellar, pyramidal syndromes, and axonal neuropathy cause a rapid degeneration of the walking ability and therefore lead to various observable gait patterns. We will also illustrate how PST can be useful to

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document the most appropriate time for a patient to change from one assistive device to another.

The final portion will aim to give paths for clinical interpretation while thinking about the concepts of limitation and adaptation.

Keywords
Clinical gait • Spatiotemporal • Interpretation • Variability • Symmetry

Contents

Introduction

Spatiotemporal parameters (STP) are one of the most studied variables in clinical gait analysis. Yet they often remain underutilized despite the rich information they can provide about the organization and control of the progress of the patient. At first sight, gait parameters are simple to formulate and easy to calculate. Building on them requires a broad knowledge of the "normal" gait, before to being able to understand the impact of pathological disorders. Indeed, behind their apparent simplicity is hidden all of the complexity to read parameters that are intrinsically linked to each other that depend on many personal (e.g., age, sex) and environmental (e.g., recording protocol, computational algorithms) factors. For example, taking into account only the walking speed to assess the results of a rehabilitation protocol will have little meaning because the speed is dependent on both cadence and stride length. Following the evolution of the gait of a child without considering the growth will inevitably lead to misinterpretation. Similarly, assessing only mean values will obscure an important part of the information on disturbances and regulations, visible through the variability.

Analyzing STP requires experience and training, as well as knowledge of the factors that influence them. We hope this chapter provides information to better grasp and understand the spatiotemporal parameters while highlighting important points.

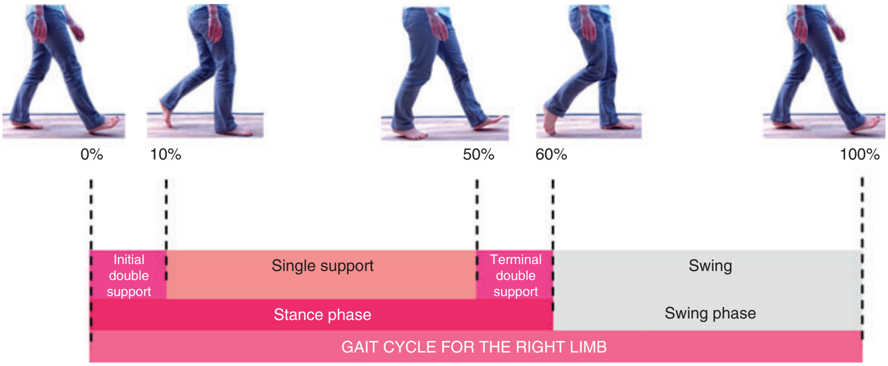

Fig. 1 Different phases of gait cycle illustrated for the right lower limb

We first discuss the basics of the gait cycle, before considering each of the components for which the STP may be informative. Then we will see how these parameters change during life or are affected by disease. The final portion will aim to give the reader paths for clinical interpretation.

Basics for Gait Analysis

Gait Cycle (See Kirtley 2006; Perry and Burnfield 2010; Whittle 2007)

The gait cycle (Fig. 1), defined as the time from the occurrence of a particular event – by convention the initial foot contact with the ground – until the next occurrence of the same event for the same lower limb, is the fundamental unit of gait. While this term may be an important parameter itself, the gait cycle is usually standardized so that the initial contact of the foot is at 0% (beginning of cycle), and the next contact of the same foot is 100% (end of cycle). This process of time normalization makes it easier to compare between individuals, within individuals, and between cycles of the two limbs. The detailed description of events and phases that takes place within a gait cycle depends on the approach to the work.

The simplest approach subdivides the cycle according to the periods of contact of the feet with the ground, distinguishing two phases, the stance phase and the swing phase, which alternate for each limb during walking. This involves adding an additional event to the gait cycle, when the foot leaves the ground. A gait cycle is composed of a support phase (0–60% of the cycle) followed by a swing phase (60–100% of the cycle) for each left and right lower limbs.

The observation of both spatial and temporal characteristics of lower limbs allows the introduction of additional phases. When only one limb is supported, it is called single support (10–50%), while the second limb is in swing phase. When both members are in stance phase, we speak about double support. The double support is often analyzed as an overall phase (20%), but in reality, it splits in a first double support at the time of loading (from 0% to 10% of the cycle) and a second at the end of support (50–60% of the cycle, often called pre-swing phase).

Reference Gait

The results of this decomposition of the gait cycle are spatial and temporal parameters. Sensitive by nature to walking speed and of course to the experimental settings, it is usual to study the STP in a framework as simple as possible. The reference gait consists of walking in healthy adults at spontaneous and stable state, that is to say, not taking into account either the acceleration phase or deceleration phase. It is preferably registered in a straight line and is not obstructed by obstacles. Obviously, this is not totally representative of a walk in everyday life, made up of adaptations and changes of pace, but is needed for the clinical use of STP. Other protocols can then be set up to identify other issues (walking at fast or slow rate, adding obstacles, turn around, double task, etc.) but we will not discuss them in this chapter.

State of the Art

While many STP can be found in the literature, they are all derived from a few basic parameters, reflecting the spatiality and the temporality of ground footwork. Depending on the methods of calculation, the systems used and on the object of study, other variables are derived from the raw data, including the temporal and stature standardization, ratio computation, and measures of dispersion. To simplify the interpretation, it is more convenient to group STP which reflect a same aspect of the gait and to focus on the individual analysis of each component before linking all.

Six domains can be considered based on the covariance between parameters: rhythm, pace, phases, postural control, asymmetry, and variability (see Verghese et al. 2007; Verlinden et al. 2013; Lord et al. 2013, 2014).

Rhythm: Variables Reflecting Gait Rhythm and Absolute Timing

Except for cadence and walk ratio, these parameters are the raw time values that reflect the walk of the patient. They are not directly used in this raw form, in seconds or milliseconds, which provides little information and of course is directly related to the frequency of locomotion. Analysis of the relative durations of each phase as a percentage of the total duration of the gait cycle is common and will be addressed in the component (see Phases: Duration of Gait Phases Relative to Gait Cycle Time (% GC)).

Rh1. Single support (s): period of time when only the current foot is in contact with the ground.

Rh2. Swing time (s): period of time while the foot is not in contact with the ground; is exactly equivalent as single support of the contralateral limb for the considered cycle.
Rh3. Stance time (s): period of time when the foot is in contact with the ground.
Rh4. Double support (s): initial and final parts of the stance phase when two feet are in contact with the ground; can be considered as a global time or differentiated as initial and terminal double support.
Rh5. Step time (s): period of time taken for one step measured from first contact of one foot to the first contact of following other foot.
Rh6. Stride time (s): total amount of time for the cycle; equivalent to two successive step time; this duration is used to express gait phases in a relative form (%).
Rh7. Cadence (steps/min): number of steps taken in a given time; the usual clinical units being steps per minute.
Rh8. Walk ratio: step length divided by cadence.

The cadence is given in steps per minute or in cycles per minute. Mathematically, cadence, which is a frequency (number of events per second), is calculated as the inverse of the cycle. It is then multiplied by a factor 60 to obtain a number of cycles per minute, or a factor 120 for the number of steps per minute.

The spontaneous cadence is usually between 98–138 steps/min for women and 91–135 steps/min for men 18–49 years old (Whittle 2007). Women offset a smaller step length with a higher cadence. Generally, an increased cadence is found, regardless of the gender, in adults smaller than the average population.

To normalize the cadence, it is advised to use the formula proposed by Hof (1996), taking into account the leg length and the acceleration g of gravity.

$$\text{Normalized cadence } \varphi = \frac{\dfrac{\text{cadence (steps/minute)}}{120}}{\sqrt{\dfrac{\text{g}}{\text{lower limb length (meters)}}}}$$

The walk ratio represents the relationship between the amplitude and the frequency of movement of the legs and is calculated as the mean step length divided by the cadence. In adults, it is relatively invariant through a speed range from very slow to very fast, that is, independent of the speed (Sekiya et al. 1996). Walking with an invariant walk ratio would be optimal in terms of energy expenditure, temporal variability, spatial variability, and attentional demand. It is, therefore, a particularly interesting parameter for the longitudinal monitoring of a patient, especially during rehabilitation, which provides information on the rhythmic organization of the gait.

The walk ratio, obtained from the step length in centimeters and the cadence in steps/minute, has a mean of 0.58 (0.06) in adults and decreases when the person tends to walk with fast small steps. Attention must be paid because these reference values change depending on the parameters (step length, cycle length), the units used (cm, m), and the possible standardization variables (leg length, height).

$$\text{Normalized walk ratio} = \frac{\text{normalized step length } \lambda}{\text{normalized cadence } \varphi}$$

Pace: Parameters Related to Speed and/or Measures of Length

The pace domain includes the parameters related to walking speed and displacement in the sagittal plane.

Pa1. Stride length (m or cm): the distance travelled by a person during one stride (or cycle); can be measured as the length between the rearmost point of the footprint (often heel) from one (heel) strike to the next (heel) strike on the same side.
Pa2. Step length (m or cm): distance between corresponding successive heel points of opposite feet, measured parallel to the direction of progression for the ipsilateral stride.
Pa3. Speed (m/s or cm/s): covered by the whole body in a given time

The stride length is the distance related to the gait cycle, but, in practice, the step length proves more informative because it assesses the symmetry between the two lower limbs. Obviously, the length is directly related to the lower limb length, and therefore it is particularly important to standardize the length to monitor the progress of a child/teenager. The step length for a side is partly dependent on the contralateral support because if this one is deficient, the foot will land to the ground faster and with less distance covered. Thus, it is often reduced in pathologies affecting the gait, while the cadence is increased to maintain a certain speed.

$$\text{Normalized step length } \lambda = \frac{\text{step length (meters)}}{\text{lower limb length (meters)}}$$

The step length is commonly computed according to the anteroposterior axis of progression. Hence, it is possible to observe a length of zero or negative if the rear foot is not brought beyond the front foot. It is also possible to focus on the overall travel length of the foot in space, often called raw step length, which is the real distance between two successive contacts (takes into account both anteroposterior and lateral distance).

The speed represents the overall performance of walking and is regarded as the sixth vital sign. It may simply be calculated as the distance traveled divided by the time required; however, it is also the product of step length and cadence.

In other words, it is possible to produce the same speed via multiple configurations ranging from fast small steps to slow long steps. Moreover, while the cadence increases linearly, the step length, which is more constrained by the physical aspect, increases logarithmically, changing greatly at low speed, but tending to stabilize at higher speeds. Only considering walking speed is not enough to properly analyze the progress of a subject over time.

A normal walking speed can thus result from adequate cadence and step length (healthy gait), as well as from small steps offset by increased cadence. If the compensation is insufficient, the speed will also be reduced.

Everyone has a preferential, spontaneous walking speed or rather a comfort speed zone, determined within plus or minus 1 km/h, in which there is no significant difference in energy cost. We can agree to a speed range of between 1.3 m/s and 1.6 m/s for adults. We must also keep in mind that being able to significantly change its walking speed, when necessary, affects the ability of a subject to adapt to different situations that may have to be managed during the daily life. The speed difference between the spontaneous pace and the rapid pace can thus be seen as a marker of functional reserves of a person and adaptability.

The normalized speed can be obtained simply as the product of the normalized step length by the normalized cadence.

$$\text{Normalized speed } \beta = \text{normalized step length } \lambda \times 2 \text{ normalized cadence } \varphi$$

The factor 2 is due to the initial use of the raw cadence in steps per minute. If cadence in cycles per second is used, no factor intervenes ($\beta = \lambda \times \phi$).

Phases: Duration of Gait Phases Relative to Gait Cycle Time (% GC)

Once expressed as a percentage of the cycle, the proportions of the various phases become easier to exploit; however, they vary again with walking speed (Fig. 2).

Ph1. Stance phase (%)
Ph2. Single support (%)
Ph3. Swing time (%)
Ph4. Double support (%): can be differentiated in initial and terminal double support

The stance phase includes the initial double support, single support, and terminal double support. It represents an overall component of the support of a foot on the ground. Its duration at spontaneous speed is about 60% of the gait cycle. It decreases with increasing speed, increasing the duration of the swing phase. Swing phase represents 40% of the gait cycle when the leg is no longer in contact with the ground and is brought forward.

The stance phase is often extended when the subject has a balance problem. When trouble in walking specifically affects one side (hemiplegia, prosthesis, pain), stance is shortened on the (most) affected foot and increased on the other limb. It should also be noted that the stance phase is shorter during walking with shoes compared to walking barefoot. Shoes create an area of support slightly larger and improve balance (Eisenhardt et al. 1996).

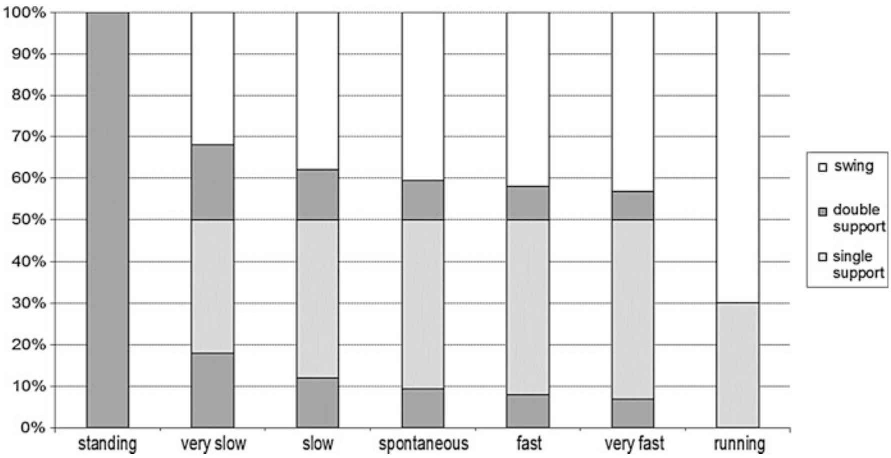

Fig. 2 Relative proportion of the gait phases depending on the walking pace. These data come from a single healthy adult (personal data) who walked at various paces on a gait mat and are given to illustrate the influence of the walking speed on the duration of the phases. In running, there are no periods when both feet are in contact with the ground. The time spent in stance depends on runner's level (for more details, see Novacheck 1998)

The most relevant information is given by the ratio between the single support phase (40%) and the two double support phases (twice 10%). First because these two parameters are sufficient to calculate all phases, single support phase of a limb being obviously equivalent to the swing phase of the contralateral limb. When walking is symmetrical, reducing the single support phase increases the proportion of double support. This is the case when a person has to walk more slowly than its spontaneous speed and/or when there is a problem with dynamic balance. Increased time spent on two limbs allows more time to control the center of mass. On the contrary, if asked to walk faster, the double support will be reduced in favor of the single support phase.

On the other hand, although the double support phase is often considered as a whole, distinguishing the initial double and terminal double support allows you to specify a problem during the transfer from one side to another.

Postural Control

This domain is mainly related to lateral movements.

Po1. Step width or base of support (cm): space between the feet during walking. (Note that calculation methods can differ).

Po2. Step width variability (cm or %): standard deviation or coefficient of variation of the base of support.

Po3. Step length asymmetry (cm): step length difference between the two lower limbs expressed in centimeters or under the form of a ratio. See also Asymmetry domain.
Po4. Foot angle (°): angle of rotation during stance.

The base of support is usually between 8 and 12 cm in children and adults and wider in the toddlers (when normalized by the pelvis width) and in the elderly. In the presence of problems of dynamic balance, expanding the base of support is a strategy to better control the walking and reduce the risk of falls. This can be effective, or not, but always indicates the presence of a balance disorder. A negative base of support can also be found in the presence of crossing steps as in cerebellar or ataxic gait, for example. On the other hand, in a healthy subject, the step width decreases when asked to walk faster than the spontaneous speed.

The variability of the base of support provides information about the dispersion of this parameter during walking. In other words, how the width between the feet varies from one step to another, which is measured through the standard deviation or the coefficient of variation. Extreme variability (i.e., too high or too low) was associated with history of falls in the elderly walking at a normal or near normal speed (>1 m/s) (Brach et al. 2005). Individuals unable to change their stride width (i.e., low variability) would experience more difficulties adapting to maintain balance, while excessive variability (often associated with crossing feet) could indicate a lack of compensation for instability. In the literature, most authors use the standard deviation to quantify the variability of the stride width, but we must be careful in reading the results when the coefficient of variation is preferred. Indeed, this relative parameter has mathematical disadvantage to tend toward infinity while, its mean is close to 0. In other words, with the same standard deviation variance, coefficient of variation will be greater if the base of support is narrow and smaller if the support base is wide (Fig. 3). Hence, it is recommended that coefficient of variation should only be calculated for ratio data. Since step width is interval data, standard deviation has to be used (Atkinson et al. 1998; Paterson et al. 2009).

The asymmetry of step length plays a role in postural balance since this difference causes an imbalance in the management of lateral imbalances, especially because the step length and stride width are geometrically linked. For example, Bril and Brénière (1992) have shown that two-thirds of the increase in step length, observed during the first months of walking of a child, could be explained by the decrease in the stride width.

The foot angle (about 0–15° in control adult) reflects the position of the foot (in abduction, adduction, or neutral position) during stance. This is a very personal characteristic, which is related primarily to the motor habits and to the bone architecture of the lower limb. Differences less than or equal to 5° between the two feet can be considered as normal. Excessive internal and external rotations are commonly seen in cerebral palsy subjects, where they derive from architectural defects that appear gradually during growth (rotational abnormalities of the femoral and tibialis segment, fixed deviations or irreducible foot in varus adductus or valgus abductus).

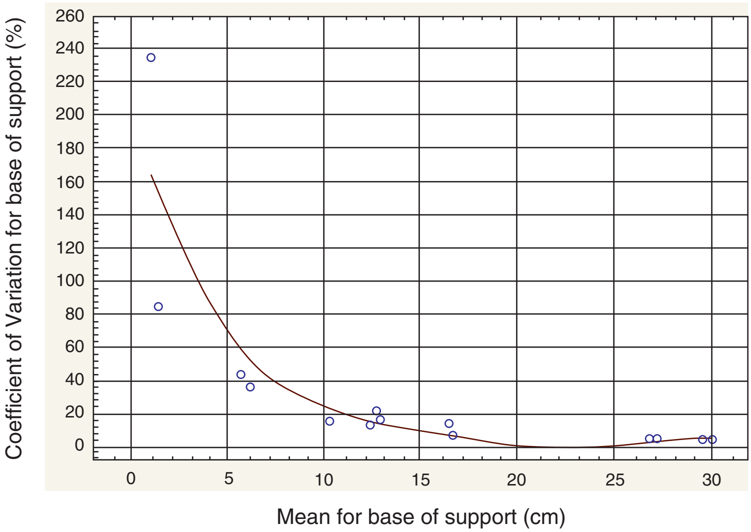

Fig. 3 Relationship between the mean and the coefficient of variation of the base of support for a healthy subject walking at the same speed through several trials, but modifying the space between his feet (personal data)

Beware, however, because the validity and reproducibility of this parameter is dependent on the full contact of the foot to the ground. For example, if walking in equinovarus, with exclusive forefoot pose, the angle given by a system based on pressure sensors will be incorrect, often with an overestimation of internal rotation. By indicating the measures of the foot (length and width), some software can give an indication of the effective area in contact with the ground, which then gives an idea of the validity of the measure of foot rotation.

Asymmetry: Differences Between Limbs

Asymmetry is the domain linked to differences between the right and left lower limbs parameters.

As1. Temporal asymmetry
As2. Spatial asymmetry

The spatiotemporal asymmetry is a measure of the quality of the walking pattern and can be seen as an important aspect in the gait analysis. Especially because it increases energy costs and is in line with the dynamic balance deficits. The asymmetry can affect gait in a spatial point of view (e.g., unequal step lengths between right and left) and temporally (e.g., difference in time spent in swing/stance phase between the two feet).

The main challenge is to choose the adequate calculation of asymmetry depending on what one wants to assess, which often depends on the type of disease. Generally, the easiest way is to use the difference between the two sides (e.g., left–right), either with raw or absolute values. In both cases, a difference of 0 represents a perfect symmetry. With raw difference, the value indicates the direction of the asymmetry, while the absolute difference gives only the magnitude of asymmetry. To compare successive evaluations or several subjects, it is better to use parameters already standardized.

The second possibility is to calculate a ratio (e.g., left/right). A ratio of 1 represents perfect symmetry. Different equations can be used in this case (symmetry ratio, symmetry index, logarithmic transformation of the ratio, angle of symmetry). Patterson et al. (2010) found strong correlations between these equations and concluded that none had more advantages over others. Thus, they proposed to use a symmetry ratio that is easier to interpret (no paretic limb/paretic limb, or the reverse).

Notice, if the symmetry is often observed in the asymptomatic population, it is possible to observe small asymmetries of parameters in controls. It is difficult to give a single asymmetry value beyond which it would exceed what can be observed naturally. Therefore, Patterson et al. (2010) proposed to consider asymmetric individuals whose asymmetry is beyond the 95% confidence interval in the healthy population. In other words, asymmetry thresholds for ratio (high value/small value) were determined for the step length (1.08), the duration of the stance phase (1.05), and the duration of the double support (1.04). Beyond, gait can be considered asymmetric for the considered parameter.

Most often, the subject seeks to reduce support on the most affected lower limb, and we observed:

– Increased swing time for the paretic side and/or decreased for the non-paretic
– Decreased stance time for the paretic side and/or increased for the non-paretic
– Shortened step length on non-paretic side

For more thinking about this, an excellent review of literature on the gait asymmetry in stroke patients has been published by Lauzière et al. (2014).

Variability: Fluctuations of Parameters

Va1. Temporal variability (standard deviation or coefficient of variation)
Va2. Spatial variability (standard deviation or coefficient of variation)
Va3. Gait variability Index (composite measure)

Gait variability, defined as the fluctuation in spatiotemporal characteristics between steps, is a sensitive indicator of mobility deficits. For example, variability in spatiotemporal parameters is reported to predict mobility deficits and future falls better than the mean of spatiotemporal parameters in older adult.

Fluctuation magnitude, as defined by Hausdorff (2005) in comparison to fluctuation dynamics, is computed through measure of dispersion, as standard deviation or coefficient of variation. With exception of only a few percent of healthy adults, variation increased with age, disabilities, and fall risk, as well as during walking in unstable condition or when subject has to perform a dual task.

One problem is that the gait variability measurement raises a question about methodological challenges. First, it is unclear which spatiotemporal measures are of greatest importance when assessing gait variability. Variability has been reported for at least 11 spatiotemporal parameters, but it is unclear which are most relevant to mobility function and the deficits that they reflect. How to deal with interdependence of the parameters? With spatial versus temporal variability? Has the variability to be considered as a global amount or should two limbs be considered separately? How to consider the step width variability? All these questions have to be considered as well as the way to quantify variability, but once again there is a lack of consensus regarding how best to do it. Standard deviation is sensitive to the scale and coefficient of variation goes toward high values when the mean is around 0.

Other questions involve how to consider levels of variability. It could be argued that variability represents noise and so just high levels of variability are needed to be observed. However, a minimum level is required to ensure ability to regulate step-to-step variations.

A composite score has been proposed to be used as a unique value, the gait variability index (Gouelle et al. 2013). Based on nine spatiotemporal parameters weighted by PCA, it quantifies the distance between the amount of variability observed for a reference group and the amount of variability observed for an individual. To enhance applicability, GVI is transformed into a score with 100 and 10 representing, respectively, the mean score and the standard deviation for a reference group. GVI above 100 indicates that the individual has a similar level of variability as the reference group. For GVI <100, each 10-point difference corresponds to a separation of 1 SD from the reference group score.

Variability is an area of importance for the assessment of walking because two walking pattern can be identical in terms of mean spatiotemporal parameters and asymmetry but present completely different levels of variability. In this case, the variability allows to decide, for example, on the interest of a strategy to minimize the risk of falls or interest for an assistive device.

Factors Influencing the Spatiotemporal Parameters

Natural Evolution During the Life

Before assessing the progress of a patient and the influence of pathology, it is necessary to know the standard values of spatiotemporal parameters and how they evolve naturally in life.

Several years are needed between the first steps of a child and the achievement of a fully mature gait. While in the first years of independent walking, a number of parameters related to the gait cycle progress toward adult profile (Sutherland 1997). The constraints for dynamic balance during walking will require a longer time before being fully controlled. The development of dynamic balance strategies involves the mastery of anticipation functions and coupling between the different mobilized joints. It, therefore, continues into relatively advanced ages of childhood. With practice and maturation of systems, a stable and efficient walking pattern will gradually emerge.

The first months are marked by a rapid evolution of spatiotemporal parameters, including gait speed which goes from 0.20 to 0.80 m/s, and step length that is growing while the base of support and relative double support decline. The range of speeds used during a recording session also expands significantly, indicating greater capacity for modulation of the movement. Subsequently, a period of refinement of gait control will last to about 5–6 years of independent walking, that is to say around 6–7 years of age (Bril and Brénière 1992). At this age, all kinematic, kinetic, and electromyographic characteristics of adult gait will be present in children. Changes in spatiotemporal parameters, subsequent to that age, would be due mainly to growth (Vaughan 2003), as these parameters do not evolve more once standardized by size or lower limb length.

However, the study of gait variability reveals significant changes, independent of growth, among children of 6–7 years and children aged of 11–14 (Hausdorff et al. 1999). For example, the coefficient of variation of the cycle time is halved between 4 and 7 years (8.4–4.3%); it remains significantly higher than in 11-year-old children (1.9%). It's the same for the composite score of variability, the gait variability index, which is not yet comparable for 7-year-old children to the adults as variability continues to decline after that age (Gouelle et al. 2016).

Note that normative data are available in the articles of Dusing and Thorpe (2007) and Gouelle et al. (2016), respectively, on 438 children aged 1–10 years (1-year interval groups) and 140 children aged 1–17 years (2-year interval groups).

Advanced age is associated with senescence, that is to say changes in anatomical, physiological, and cognitive systems, in absence of any pathology. Slow degradation of musculoskeletal and neurological systems that contribute to balance and postural control is progressive and can lead to vestibular deficit, decrease in visual acuity, worse sensitivity and proprioception, loss of muscle strength, or increased reaction time. This aging process is neither linear for an individual nor uniform through individuals, but the changes that take place can more or less affect the dynamic stability of subjects and ultimately increase the risk of falls.

It seems that the first signs can appear from the age of 50–55 years (Balasubramanian et al. 2015), and it accelerates after 60–65 years, but it is only in older subjects (75 years and more) that the changes are always visible. Thus, the first effects of aging on the gait stability are not always discernible in spontaneous walking conditions and are revealed only in the most destabilizing circumstances (e.g., uneven surface) or during dual task, the control of gait requiring increasingly cognitive control and attentional resources. In fact, all the characteristics of an unsteady walk are particularly exacerbated in the older subjects, in fallers and in people with a fear of falling (Maki 1997).

Studies which have focused on the identification of walking changes associated with age are numerous. Generally, it has been demonstrated that the organization of the walk is moving toward lower preferred and maximal gait speed, longer double support phase, shorter steps, a wider base of support, fewer vertical displacement of the center of mass, and poorer synchronization between the leg movement and swinging arms. These changes are often interpreted as the adoption of a steadier and more secure walking pattern to compensate for the reduced physical abilities. Moreover, the variability of the spatiotemporal parameters is increased with age, portraying more concrete dynamic instability.

Note that Hollman et al. (2011) published data on the walk of 294 healthy old persons, over 70 years, providing reference values for 23 spatiotemporal parameters.

Influence of the Pathology

Various pathologies affect walking and the resulting spatiotemporal parameters. These are not always the same parameters that are the most relevant to observe. Some walking patterns are obvious and easily identifiable (festination and freezing in Parkinsonian), while other diseases can affect different parameters depending on the type of injury and involved systems (balance control, muscle weakness, joint limitation, etc.), as possible compensations and strategies. We will give here two examples, one on the evolution of spatiotemporal parameters in patients with Friedreich ataxia, the other on the modifications due to the change of walking aids.

Friedreich ataxia is a neurodegenerative disease in which there is a combination of cerebellar, pyramidal syndromes, and axonal neuropathy causing coordination deficits, loss of proprioception, and balance difficulties in static conditions and during gait. The rapid degenerative nature causes instability and falls with increasing frequency over short periods. In this context, it is important to monitor progress over time or to gauge the effects of a therapeutic intervention.

The first signs of ataxia are balance difficulties with eyes closed or in low light condition. Spatiotemporal parameters are still not really altered if one considers only the mean values, while the variability is already increased. Almost all parameters are within the ranges of values observed in peer controls. Only the variability component (orange) shows coefficients of variation slightly increased at spontaneous gait speed, already portraying the presence of balance disorders (Fig. 4a).

Subsequently, parameters such as walking speed or step width highlight the disorder. In Fig. 4b, the gait speed is slightly decreased due to a reduction of the cadence and the base of support is slightly wider. The variability of the parameters is even greater.

With the progression of the disease, particularly marked by the worsening of ataxia and deep sensitivity disorders, it is common to see two types of evolution. One is based on the adoption of a safer walking pattern, less destabilizing, where the preservation of the balance is prioritized over the speed of progression: the speed and step length are reduced, the base of support is widened, and double support is very long (Fig. 4c). The other, in contrast, is based on an acceleration of the walking speed

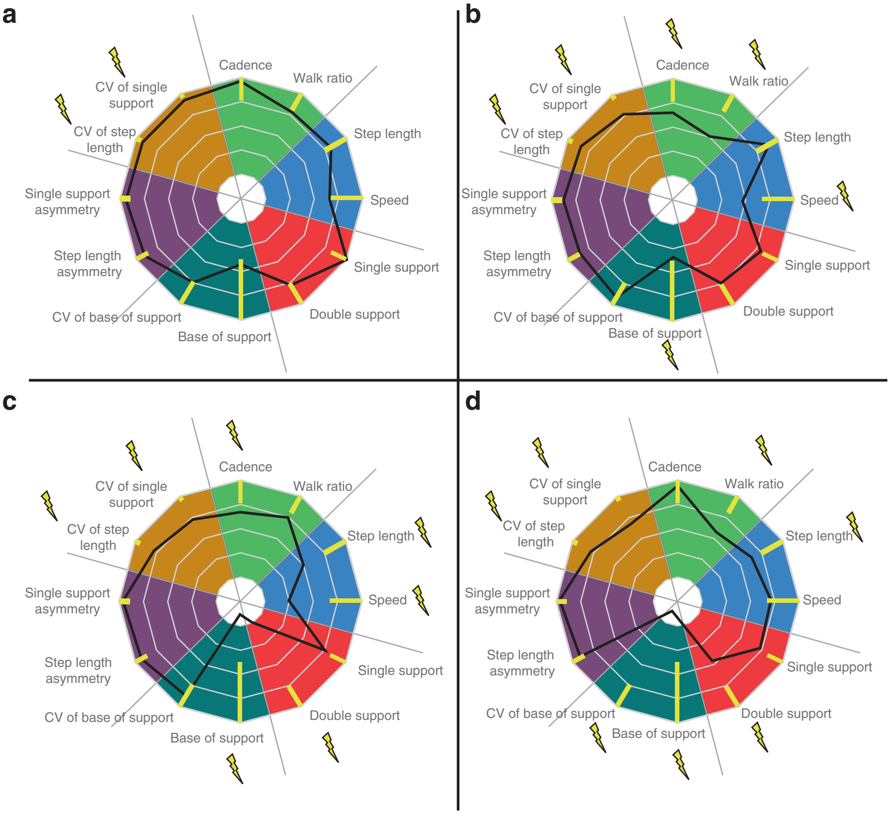

Fig. 4 Spatiotemporal parameters observed during disease progression in Friedreich ataxia. The *yellow* band represents the normal range for healthy controls at spontaneous walking speed. The more the patient parameter departs from this range, the more the value is close to the radar center. The lightning forms are added here to help the reader to identify where the main visible troubles are (Notice that this radar is a personal way of the author to present clinical data and is part of a current project by Gouelle and Poirier, not already published)

with a forward projection, but without efficient control. In Fig. 4d, the speed seems correct but is in fact the product of a high cadence and too short steps. The double support is far from the normative data, because it is highly reduced. It is the same for the base of support that is close to zero due to numerous crossing steps.

Finally, when the patient reached an advanced stage of disease and when disorders become major, it is impossible to walk without support (walk with assistive device) and all of these parameters are clearly affected (Fig. 5).

It is useful to use both analysis of the mean parameters and variability during rehabilitation. We will now try to illustrate this through the example of the most appropriate time for a patient to change from one assistive device to another. To simplify the connection, we will consider only two scores, one on the mean

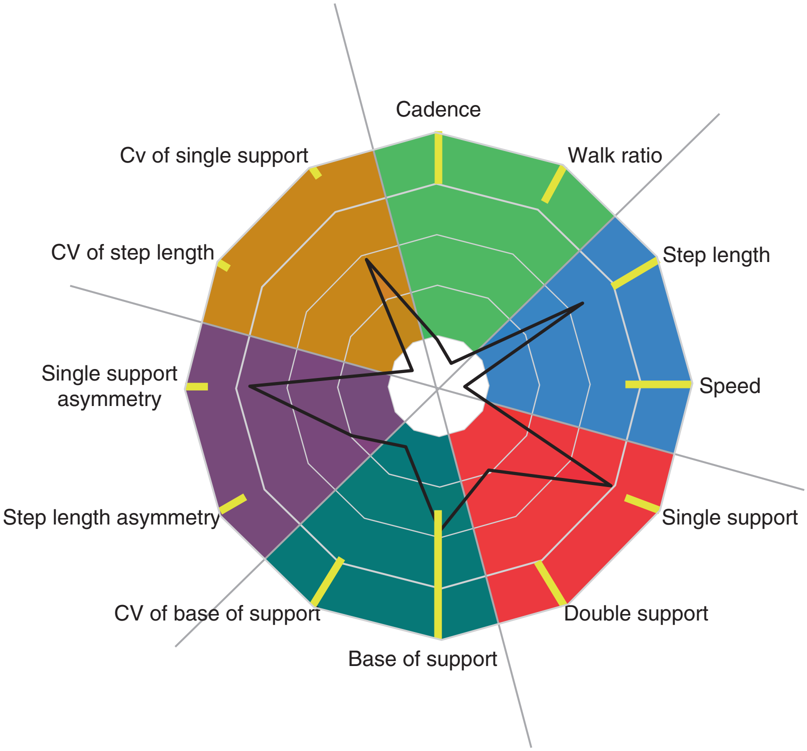

Fig. 5 Temporal and spatial parameters observed during the use of an assistive device in a patient with advanced stage of Friedreich ataxia

parameters (Functional Ambulation Performance Score), the other on the variability (gait variability index).

The Functional Ambulation Performance Score (FAPS) is a quantitative representation of the walk of a person based on a selection of spatiotemporal data obtained at spontaneous speed (Gretz et al. 1998). These parameters are speed normalized by the length of lower limb, normalized step length, step time, left–right asymmetry of the step length, and base of support. From a maximum score of 100, points are subtracted according to the deviation of the patient's parameters compared to a normative adult base. A normal walk is reflected by a score between 95 and 100 (Gouelle et al. 2011). The FAPS is commonly used for clinical evaluations and has been used in an increasing number of publications over the past few years. However, its use is sometimes distorted by misunderstandings of its composition and calculation, practical, and/or conceptual limits. We recommend you also read the review by Gouelle (2014) before using the FAPS. Regarding gait variability index (Gouelle et al. 2013), it has already been addressed in the definition of variability parameters (Va3). As a reminder, it is a score of 100 which decreases when the overall variability of the subject deviates from the variability observed in a control population. Thus, in both cases (FAPS and GVI), scores moving closer to 100 can be considered as an overall improvement in walking of the patient.

Along the natural evolution of an optimal rehabilitation for a patient using two crutches at the onset of rehabilitation and ending up not using technical assistance, we usually see that the functional improvement is continuous. As the FAPS is very sensitive to gait speed, it tends to increase gradually as the patient improve his/her step length and velocity, even if one can observe stabilization phases. The FAPS, by design, allows also to take into account in its calculation the use of assistive device; therefore, the score improves as assistive device become lighter. The GVI, meanwhile, reflects the quality of the control and stability. This is naturally degraded when there is a change of technical assistance, to the extent that each change frees a number of degrees of freedom that the patient has to master. While the patient progresses in the control of the assistive device, it becomes more reproducible and less variable from one cycle to another. In case the change of assistive device is premature, then the instability is such that it directly affects the functional parameters and FAPS then deteriorates. When changing from an assistive device to another (e.g., from two canes to only one), it is normal to observe a slight deterioration in gait variability, but this should not affect the functional aspect if the timing to switch walking aids is appropriate.

Conclusion

According to what has been mentioned above, it is complex to give a clinical interpretation to spatiotemporal parameters due to the large quantity and variety of information available. This includes the deviation from the mean normal parameters, which provides information about the functionality of the gait. We also discussed the notion of temporal and/or spatial asymmetry that shows mainly pathological dominance but also functional strategies to minimize the impact of the disease on the functional aspects of gait. Finally, taking into account the variability gives primarily information about quality of the motor control, reflecting the sustained disturbance and/or temporal and spatial regulation made by the patient.

This variety of information perfectly complements how we organize the reading of these parameters. Whatever the population is analyzed, regardless of pathology, the organization of the gait meets two key criteria: to minimize pain and to expend as little energy as possible. With these two criteria in mind, it becomes particularly interesting to analyze the set of spatiotemporal parameters. The patient adaptability, extended to respect these criteria, will be proportional to the degrees of freedom available. When we talk about the concept of degree of freedom, we are not only concerned with mechanical degrees of freedom (joint). The temporal and spatial regulation is also part of these degrees of freedom and, until all these degrees of freedom are mobilized, the patient can continue to walk. Walking is lost when no further adjustment is possible under the constraints posed by the disease and its consequences.

To follow these two immutable rules, minimize pain and reduce energy costs at the maximum possibilities in the moment, the patient will have only a short window of time to adapt: the swing phase. During this phase, the patient will be able to control the time and/or the space to minimize the single support on the side posing the most problems. Indeed, everyone will try to minimize the duration of the single support on the most problematic side. The mere mention of a pebble in a shoe allows us to understand that we will organize to minimize the support time of painful side (single support). At that time, on the contralateral side during the swing (swing phase), we will be able to choose between increasing the speed to land sooner the non-affected side without decreasing the step length, or else reduce the step length to land earlier without increasing the walking speed. Both solutions are possible and the choice depends largely on available adaptive capacity. For a patient who has knee extension limitations on one side, the minimization of the step length is de facto a strain. For this patient, the adaptive capacities are located mainly at the speed in order to minimize the duration spent on the affected side.

Interpreting variability is difficult, given that no single number or measure gives us its nature. Indeed, how does one differentiate variability due to pain during support and variability due to varying the temporal and/or spatial parameters from one cycle to another, to adapt to such pain. In fact, within a coefficient of variation hides the two aspects: perturbation and regulation. However, we can determine by deduction the disturbance and the control parts. Take the example of a right hemiparetic patient, in which we will observe a right single support deficit. In the specific case of the step length, it is possible to observe an increase in variability on the right and/or left. If it is on the right, I can hypothesize a painful gait on right side. If it is on the left, I can assume an anteroposterior regulation on healthy side, compensating for instabilities generated by the affected side. Of course, this reasoning is simplistic, and it can have meaning only by matching all of the clinical elements. However, it helps to understand the logic helping the interpretation of spatiotemporal parameters.

Cross-References

► Clinical Gait Assessment by Video Observation and 2D-Techniques
► Detecting and Measuring Ataxia in Gait
► Gait Parameters Estimated Using Inertial Measurement Units
► Gait scores – Interpretations and Limitations
► Interpreting Ground Reaction Forces in Gait
► Interpreting Joint Moments and Powers in Gait
► Measures to Determine Dynamic Balance
► Normalization Techniques
► Optimal Control Strategies for Human Movement
► Stance Phase Problems in Cerebral Palsy (Strength)
► Swing Phase Problems in Cerebral Palsy

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