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Spatiotemporal gait analysis of older persons in clinical practice and research

Which parameters are relevant?

This narrative review aims to provide a framework of quality aspects of spatiotemporal gait analysis in older persons with corresponding parameters. This may be relevant for selection of outcome parameters in clinical practice and research.

Walking performance

Walking is a basic activity and one aspect of mobility in younger and older persons. Although for a healthy person it is not necessary to consciously focus on alternate stepping during habitual walking, it is a complex and challenging movement. While two thirds of the body mass is located two thirds of the body height above the ground, the center of gravity is accelerated ahead of the base of support in order to move forward with every step laterally oscillating around the line of progression along the medial border of the feet (as described by Winter [1]).

The aging process often results in an altered walking pattern [2, 3], sometimes enhanced by a trauma or by progressive neurologic and/or musculoskeletal disorders. Here, different aspects of walking performance can be affected, related to the trauma or disorder. As an example, gait symmetry can be negatively affected by e.g. stroke or hip fracture. As a consequence of a trauma or of an age-related decrease in physical performance, the improvement of walking performance during geriatric rehabilitation is one of the most relevant clinical outcomes and serves as a marker of functional independency.

Gait analysis

In clinical practice, visual inspection is always necessary to get a first impression of a person's walking performance and is the basis for further analysis. Quantitative gait analysis can help to identify any pathology, provide information about disease progression and measure the efficacy of interventions. High-tech gait analysis, such as 3-D motion capture systems, electronic walkways or body-fixed sensors, provide a long list of gait parameters of which some show high intercorrelation. Different parameters can be investigated for special interest with respect to left and right steps and their (left/right) relation or with respect to trunk or arm movement. It is not helpful to provide a long list of all possible (related to the measurement system) parameters but to focus on relevant gait parameters. Relevancy depends on the clinical or research question as well as on the investigated patient/participant/cohort and the clinical/research context. The kinetics of walking can also be measured by force plates embedded in the walking track. Since aiming at an embedded target on the floor may mask other gait parameters, this kind of gait analysis is limited to special interests and is not described here.

In order to bring gait analysis into clinical settings and to use it in clinical research providing valid and reliable data, the organizational conditions (test protocol) must be appropriate [4]. Guidelines and recommendations for gait analysis in the laboratory have been published with respect to e.g. the shoes of the test person (closed around heel), the location (well-lit and without distraction) or the test track (20 gait cycles with additional 2.5 m for acceleration/deceleration) [5–7].

Although a frail person in the clinical setting sometimes has the functional capacity to perform only 1 trial, it must be kept in mind that several gait parameters, such as step-length and step-frequency, are speed-dependent. Therefore, when rating the walking quality of a frail person by analyzing only 1 trial in the clinical setting for pre-post comparison, gait speed has to be additionally considered. For normalizing the parameter results to gait speed a minimum of 3 trials at different speeds (e.g. slow, normal, fast) is necessary [8, 9]. Especially when healthy older persons are investigated, the test protocol should be challenging and should be related to the research question, e.g. fast walking, stepping over obstacles and narrow walking [10]. Furthermore, a cognitive and/or motor dual tasking, such as counting backwards, enumerating animal names or carrying a glass of water, can be integrated into the test protocol if the motor-cognitive interference is investigated [11, 12].

With respect to ecological validity, daily life gait speed is relevant. Body-fixed sensors are used for the analysis of indoor and outdoor daily activities [13]. With such systems the basic activities of older persons, such as walking, sitting, standing and lying can be detected and their duration can be calculated [14, 15]. From detected phases of walking, spatiotemporal gait parameters can be estimated [16–18]. A comparison between spatiotemporal gait parameters measured in the laboratory and under normal living conditions is difficult because walking tracks in the normal living conditions are unclear with respect to possible curves, inclines, obstacles, lighting or distractions. Furthermore, the gait speed can be low or high with respect to the intention and motivation for walking, which is also unclear. Therefore, extreme values of a data set from a period of 1 or several days may overestimate or underestimate daily life gait speed. Here, the gait speed most often used might give an estimate of daily life gait speed. In addition, the range of gait speed during short, middle and long walks may be of interest, since gait speed seems to decrease with increasing walking distance [19]. Furthermore, long walks better discriminate between groups with respect to gait speed and variability parameters [20]. Lastly, other gait parameters, e. g. complexity of walking sessions during the day or duration of walking sessions, may be relevant for questions related to walking performance under free-living conditions and can be measured by body-fixed sensors [21]. Thus, if spatiotemporal gait parameters during daily activities are relevant for clinical practice or research, these can be estimated by use of body-fixed sensors and respective calculations.

In this article all gait parameters are described in the context of a laboratory assessment. The aim is to provide a framework of different aspects of walking performance based on the literature and with evidence for different health-related pathologies. Different spatiotemporal gait parameters are described, which are appropriate for older persons to be tested for special interests in clinical practice and/or research. With respect to special persons or groups of persons, the clinicians and researchers have to decide which aspect of walking performance is relevant, and therefore, which parameters are appropriate to be assessed.

Aspects of walking performance and representative parameters

Gait speed as a parameter of walking capacity

Most forms of walking impairment are associated with a reduction of gait speed, which can simply be measured by a stop watch. During the aging process slow gait speed is associated with mortality [22], hospitalization [23], frailty [24] and risk of falling [25, 26]. Therefore, gait speed measurements can be used to describe a person's or a cohort's physical health or to provide a general description of physical performance, especially in older persons. Furthermore, slow gait speed is associated with cognitive decline [27–29] with dual-task assessments increasing the discriminative power by higher challenging [27]. When assessing gait speed of a particular person or cohort, normative values of a healthy population [5, 30–32] or values of another cohort can be used for comparison. With respect to health problems and/or therapeutic interventions, a change of 0.1 m/s in habitual gait speed can be rated as clinically meaningful [33, 34].

The difference between habitual and maximum gait speed provides information about a person's reserve capacity, which is necessary to adapt to special situations. Furthermore, slow gait speed while walking backwards is associated with poor balance performance [35, 36].

Quality of walking performance

Different aspects of walking quality can be assessed during steady state (constant speed) straight walking. Symmetry describes the left-right comparison of walking. The regularity of walking describes the smoothness of a walking pattern and is assessed by calculating the variability of parameters. Coordination of step-length and step-frequency is expressed by the walk-ratio [37, 38]. Dynamic balance is a synonym for the regularity of moving along the line of progression [39]. Foot movement describes the 3-dimensional trajectories of the foot during the swing phase. This framework of quality aspects is based on similar frameworks in the literature [31, 40, 41] but may have some overlaps. The corresponding spatiotemporal parameters were selected based on their evidence. Besides steady state straight walking, acceleration during walk initiation, deceleration, stopping or walking along a curve may be of special interest (e. g. in Parkinson's disease [42]) but are not described here.

Symmetry of gait

Human walking is characterized by an anti-phased but symmetrical left-right stepping pattern. Asymmetry describes functional differences between lower limbs [43]. In pathologies, such as hemiplegia, unilateral limb loss, osteoarthritis or after a hip replacement, the symmetry of gait is often obviously impaired [44–47]. After visual inspection and the decision to further investigation, high-tech gait analysis provides quantitative parameters of walking symmetry. Here, the single support difference (% of gait cycle) and the step-length difference provide information about weight-bearing distribution and spatial differences, respectively [46, 48, 49], both possibly associated with limitations in pain, flexibility and/or strength. Besides habitual walking speed, the left/right coordination is further challenged by slow walking speed, which can therefore enhance possible asymmetries [50]. Furthermore, measures of trunk movement, such as the mediolateral trunk acceleration, which can be assessed by body-fixed sensors measuring vertical, anteroposterior and lateral acceleration, are able to assess gait asymmetry [51].

Regularity and adaptability of gait

Regularity describes the uniformity of walking which is associated with low energy costs [52]. It can be assessed by measuring the variability of gait, which is the stride to stride fluctuation of quantity and timing of any parameter. Usually, the variability of a parameter is expressed as the coefficient of variation, as (standard deviation/mean) × 100 = %. The variability of several gait parameters, such as stride-length, stride-width or step-time, is associated with future falls in older persons [53–55]. Furthermore, high stride-length variability is associated with cognitive decline [29].

Since curves and obstacles will change stepping in a special way based on situational factors, regularity should be assessed during straight walking. Here, a minimum of 20 gait cycles is recommended [7] because the accuracy of calculation is proportional to the distance walked. Only steady state walking should be used to investigate regularity because the initiation of gait with acceleration and the deceleration at the end of the test track affect gait regularity.

Different aspects are comprised in the concept of regularity/variability of walking [56]. With respect to steady state straight walking, a low variability of e. g. stride-length indicates a correct performance. Higher values of variability are obvious when a person has to adapt to a specific walking track (e. g. single obstacles). Here, a low variability of step-frequency during straight walking with obstacle crossing may also reflect a correct performance when foot clearance height and step-length have to be adjusted but the values are higher compared to steady state straight walking. The two-sided aspect of regularity/variability is corroborated by a study showing the association between fall history and high step-width variability as well as low step-width variability [57]. Here, high variability may indicate a problem when regularity is required and low variability may indicate a problem when adaptability is required. Other measures of adaptability of walking performance are the exactness of stepping on a target, which can be assessed by an electronic walkway [58] or by a treadmill [59] or foot clearance of an obstacle, which can be assessed by 3-D motion capture systems [60] or inertial sensors fixed to the foot [61].

Abstract · Zusammenfassung

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Spatiotemporal gait analysis of older persons in clinical practice and research. Which parameters are relevant?

Abstract

For older persons walking is a basic activity of daily life which characterizes the person's functional mobility. Therefore, the improvement of walking performance is a major clinical outcome during geriatric rehabilitation. Furthermore, walking performance is relevant for several geriatric research issues. Quantitative gait analysis can describe walking performance in detail. Besides gait speed, various qualitative parameters related to different aspects of walking performance, such as symmetry, regularity, coordination, dynamic balance and foot movement during the swing phase, can serve as outcome parameters in geriatric research and in clinical practice. Clinicians and researchers have to decide which parameters are appropriate to be used as relevant outcome parameters in the investigated person or group of persons.

Keywords

Gait speed · Symmetry · Regularity · Coordination · Dynamic balance

Spatiotemporale Ganganalyse älterer Menschen in der klinischen Praxis und Forschung. Welche Parameter sind relevant?

Zusammenfassung

Gehen ist eine Basisaktivität älterer Menschen, die auch den funktionalen Status der Mobilität beschreibt. Daher ist die Verbesserung der Gehfähigkeit ein wichtiges Ziel während der geriatrischen Rehabilitation. Darüber hinaus ist die Gehfähigkeit ein wichtiger Endpunkt für verschiedene geriatrische Forschungsprojekte. Durch quantitative Analysen kann das Gehen sehr detailliert beschrieben werden. Neben der Gehgeschwindigkeit können verschiedene qualitative Aspekte durch quantitative Parameter beschrieben und als Endpunkt für klinische Fragen oder Forschungsfragen genutzt werden. Diese Aspekte sind z. B. die Symmetrie, die Gleichmäßigkeit, die Koordination, die dynamische Balance und die Fußbewegung während der Schwungphase. In der klinischen Praxis und in der Forschung muss entschieden werden, welcher Parameter bei den untersuchten Patienten oder der untersuchten Studienpopulation für die jeweilige Fragestellung der richtige ist.

Schlüsselwörter

Gehgeschwindigkeit · Symmetrie · Gleichmäßigkeit · Koordination · Dynamische Balance

Coordination

The step-length/step-frequency ratio is referred to as the walk-ratio and describes the spatiotemporal coordination of walking representing the control of amplitude and frequency of rhythmic leg movement [37, 38, 62]. In order to walk faster or slower, the amplitude and frequency are increased or decreased harmonically during habitual walking. Therefore, the walk-ratio is stable across the range of habitual walking speed [38, 62] but decreases at very high (>150 steps/min) stepping frequencies [62]. A low walk-ratio during habitual walking is associated with a higher falls risk [53, 63]. A reduced walk-ratio (i. e. short steps, high step-frequency) is known as cautious gait [64] and is associated with rheumatoid arthritis [65], Parkinson's disease [66], normal pressure hydrocephalus [67], Huntington's disease [68], progressive supranuclear palsy [69] and multiple sclerosis [70]. Therefore, the walk-ratio can be used as an outcome parameter when gait analysis is applied, e. g. to support a diagnosis of Parkinson's disease, normal pressure hydrocephalus, rheumatoid arthritis, Huntington's disease, progressive supranuclear palsy or multiple sclerosis pre-post medication, puncture or other interventions. Furthermore, normative values are available for comparison [38] when visual inspection suggests a cautious (i. e. short steps, high step-frequency) or ataxic (i. e. long steps, low step-frequency) walking pattern. In contrast, changes in the walk-ratio (reduction) can be related to an adaptive walking pattern, such as walking on ice, when the step-length is reduced and the step-frequency is increased in order to shorten unstable single support phases and so avoiding possible falling.

Table 1 Different aspects of older persons' walking performance in the context of clinical practice and research

Aspect	Parameter	Evidence
Walking capacity	Gait speed	Mortality, hospitalization, falls, frailty, cognition, balance
Symmetry	Step-length difference, single-support difference, mediolateral trunk acceleration	Hemiplegia, osteoarthritis, hip replacement
Regularity	Stride-length variability, step-width variability, step-time variability	Falls, cognitive decline
Coordination	Walk-ratio	Falls, rheumatoid arthritis, Parkinson's disease, normal-pressure hydrocephalus, Huntington's disease, progressive supranuclear palsy, multiple sclerosis
Dynamic balance	Step-width variability, mediolateral trunk acceleration	Balance
Foot movement	Foot clearance height, foot distance of deviation	Energy costs, falls

Table 2 Pearson's coefficients of correlation of gait speed, step-length difference, stride-length variability, walk-ratio and step-width variability in a cohort of 88 community-dwelling older women [88]

	Gait speed	Step-length difference	Stride-length variability	Walk-ratio
Step-length difference	−0.18	–	–	–
Stride-length variability	−0.43	0.27	–	–
Walk-ratio	0.32	−0.13	−0.27	–
Step-width variability	0.36	−0.02	−0.10	0.22

This aspect can be neglected during assessments in a laboratory.

Dynamic balance

Equilibrium during gait is maintained by compensatory trunk movement and compensatory stepping [42]. Moving forward along the line of progression, the center of mass is shifted outside the base of support during single support. In order to regain balance the next step can be adjusted laterally and in the forward direction. Dynamic balance requires step by step integrative control for balance, mainly in the lateral direction [71, 72]. Thus, changes in step-width can be seen as a protective strategy to avoid falling [73]. Since the forward adjustment is highly correlated to variations of gait speed, the step-width variability is recommended as a marker of dynamic balance [39, 57, 71, 74]. The step-width variability of healthy older adults increases with advancing age [8, 75] and decreases with increasing gait speed [76]. Furthermore, step-width can be seen as a global marker of balance control [77, 78], which increases with advancing age [31]. Step-width can be measured by 3-D motion capture systems or by electronic walkways.

The aspect of dynamic balance can also be described by the mediolateral trunk acceleration amplitude [79], which is measured by body-fixed sensors at the lower back [80]. The mediolateral trunk acceleration is associated with gait speed [8]. If dynamic balance is a parameter of interest, it can be additionally assessed by very slow walking [81] because during the long single support phase with the center of mass moving forward, balance is challenged by a minimal base of support.

Foot movement

During the swing phase the foot is lifted (toe off) and transferred to the next step (heel strike). This transfer requires low energy costs if it is straightforward and slightly curved in vertical height [82]. With respect to fall-related tripping, the foot clearance (vertical height) during the swing phase is an important measure [83, 84]. Foot clearance can be assessed by 3-D motion capture systems [60] or inertial sensors fixed to the foot [61]. Reference values are available for foot clearance [85].

Neurologic and orthopedic problems, such as e. g. hemiplegia or hip arthrosis, can result in a drop-foot or weakness of the pelvic muscles. Consequently, the foot is transferred in a circumduction which can be measured by 3-D motion capture systems [86] or by inertial sensors fixed to the shank or foot [87] with thigh angle or the foot's distance of deviation as outcome variables.

Independence of parameters

Table 1 summarizes different aspects of walking performance in the context of clinical practice and research. In a subsequent analysis of a data set of 88 community-dwelling older women (mean age 78.0 years, SD 5.69 years; mean gait speed 1.10 m/s, SD 0.23 m/s) the independence of representative parameters, which were assessed by an 8 m-long electronic walkway (GAITRite, CIR Systems, Franklin NJ, USA), was shown. Parameters describing foot movement could not be assessed by the electronic walkway. In **Table 2** the results are presented, which were not presented in the original study [88]. Here, the association of gait speed with 4 parameters representing symmetry, regularity, coordination and dynamic balance was poor with Pearson's coefficients of correlation below 0.5. The intercorrelation of step-length difference, stride-length variability, walk-ratio and step-width variability was also poor with Pearson's coefficients of correlation below 0.3. The general model of gait determinants (capacity: gait speed; quality: symmetry, regularity, coordination, dynamic balance and foot movement) is corroborated by studies investigating 189 [40] and 294 [31] community-dwelling older adults and 249 hip fracture patients [41] identifying independent domains of gait, such as pace, rhythm, variability, asymmetry and base of support/postural control.

Conclusion

Quantitative gait analysis can be used in the laboratory to document walking performance and the progress of impairment or improvement. Gait speed describes the general physical performance of a person or cohort. In addition, different gait parameters describe qualitative and quantitative aspects of walking performance, such as symmetry (e. g. by step-length difference), regularity (e. g. by stride-length variability), coordination (e. g. by walk-ratio), dynamic balance (e. g. by step-width variability) or foot movement (e. g. by foot distance of deviation or by foot clearance height). Clinicians and researchers must decide which parameters are appropriate to be used as relevant outcome parameters in the investigated person or group of persons.

Conclusion for the practice

- **Different aspects of the spatiotemporal gait pattern, such as gait speed, symmetry, regularity, coordination, dynamic balance and foot movement, can be relevant in clinical practice and research.**
- **It depends on the pathology of the patient or the research question, which aspect of the spatiotemporal gait pattern is relevant and which parameter should consequently be used as an endpoint.**

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Compliance with ethical guidelines

Conflict of interest U. Lindemann declares that he has no competing interests.

The underlying study showing the independence of parameters was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the ethics committee of the University of Tübingen (578/2011/BO2).

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