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SYSTEMATIC REVIEW

Assessment of ambulation functions through kinematic analysis in individuals with stroke: a systematic review

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ABSTRACT

INTRODUCTION: Although kinematic assessments for stroke-induced lower limb impairments offer a promising alternative to conventional scale evaluations, interpreting high-dimensional kinematic data remains challenging due to numerous metrics reported in past studies. This study aimed to provide an exhaustive overview of existing studies using kinematics data to assess the gait impairments in individuals with stroke, along with examining their clinimetric properties for future clinical applications.

EVIDENCE ACQUISITION: A systematic search was conducted across PubMed (08/2024), Scopus (08/2024), Web of Science (08/2024), CINAHL (08/2024), EMBASE (08/2024), and IEEE (08/2024). We included articles that recruited individuals over 18 years old with stroke and utilized motion capture technologies to evaluate lower limb kinematics. Similar metrics were consolidated in the analysis, and the COSMIN Risk of Bias Checklist was used to evaluate the methodological quality of studies investigating the clinimetric properties of kinematic metrics. Convergent validity of metrics was evaluated by examining their association with the Fugl-Meyer scale of lower limbs and walking speed. Moreover, the GRADE approach was used to rate the quality of evidence.

EVIDENCE SYNTHESIS: A total of 383 studies were classified into 10 categories. Seven studies on metric reliability were rated high for methodological quality. Metrics with satisfactory reliability included spatiotemporal, spatial metrics, and a data-driven score. Six studies with high methodological quality assessed convergent validity. The dynamic gait index, angular component of the coefficient of correspondence (ACC), change in cadence, stride length, and hip range of motion showed satisfactory validity. Among the 13 studies, 12 studies were rated as moderate quality of evidence using the GRADE approach.

CONCLUSIONS: There are significant variations in measurements across studies, and high-quality studies evaluating clinimetric properties are scarce. For a more standardized evidence-based approach to kinematic lower limb assessment, further high-quality research validating these assessments' clinimetric properties is essential.

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KEY WORDS: Biomechanical phenomena; Stroke; Movement; Systematic reviews; Lower extremities.

Introduction

Stroke is a leading cause of long-term disability globally, with lower limb sensorimotor deficits accounting for a substantial portion of mobility limitations faced by stroke survivors.[1] These deficits often manifest as muscle weakness,[2] abnormalities in gait,[3] balance problems,[4] and difficulties in coordinating movements between joints.[5]

Gait impairments such as slower walking speed, irregular and unstable steps have all been identified as contributing to post-stroke disability,[6] which significantly hamper their community ambulation performance. Despite the availability of advanced acute medical treatments and specialized rehabilitation programs, a substantial number of people continue to experience lasting lower limb impairments. These impairments not only severely restrict their mobility but also considerably affect their ability to independently perform activities of daily living. Given the high prevalence and persistent nature of these impairments, understanding the complexities of lower limb sensorimotor recovery following stroke is imperative to improve rehabilitation outcomes.

Traditional clinical assessments, such as the Wisconsin Gait Scale[7] and the Gait Assessment and Intervention Tool,[8] and mobility assessments, such as the Timed Up and Go Test (TUG),[9] have been widely used to evaluate lower limb function. However, these ordinal scales often do not capture the nuanced aspects of sensorimotor performance and gait characteristics after stroke. To gain a comprehensive understanding of lower limb recovery and its impact on overall mobility, sensitive and responsive methodologies for evaluating lower limb sensorimotor deficits and tracking their progression over time are essential.

In recent years, technology-based kinematic assessments have emerged as a promising solution to overcome the limitations of ordinal scales. Three-dimensional gait analysis provides a comprehensive set of objective metrics that enable a more sensitive and refined assessment of movement quality. By monitoring the use of compensatory strategies by people, it provides insights into how they adapt to their impairments. Kinematic results aid in making clinical decisions regarding necessary interventions and enhancing treatment efficiency in participants' poststroke recovery. Moreover, as per the latest consensus on lower limb assessment, the use of composite kinematic metrics, such as the gait deviation index, is recommended for a more comprehensive and meaningful interpretation of gait analysis in stroke.[10]

However, interpreting high-dimensional kinematic data poses significant challenges as there are numerous metrics reported in past studies. A systematic review published in 2019 focused on the kinematic assessment of upper limb movements post stroke,[11] and the review identified 151 kinematic metrics that have been used to study these movements. This review provided a summary of assessment tasks and measurement systems and evaluated their performance metrics, and it also provided evidence-based recommendations for further research on upper limb movement after stroke. On the other hand, comprehensive reviews offering an overview of the metrics currently employed in lower limb assessment are lacking. Additionally, the clinimetric properties of these kinematic metrics, such as reliability and convergent validity, must be thoroughly examined, as more advanced analytical techniques and measurements have been developed in the field. Understanding these properties is essential to confirm the clinical relevance and utility of kinematic assessments, providing a definite foundation for their broader adoption in both clinical and research settings.

To bridge these gaps and address these limitations, our review delves into the literature concerning kinematic metrics for lower extremities in stroke survivors, offering insight into how kinematic data are utilized in evaluating their ambulation functions. We also scrutinize the clinimetric properties of these metrics, such as their reliability and validity. We hypothesize that widely used spatiotemporal parameters, such as walking speed, stride length, and joint angle spatial parameters, will exhibit high reliability and validity. Furthermore, other kinematic metrics derived from high-dimensional kinematic data are also expected to demonstrate satisfactory clinimetric properties, which are essential for their effective integration into future clinical practices.

Evidence acquisition

Identification and selection of studies

Two reviewers performed a systematic search of articles published before July 2023 in six electronic databases, namely PubMed (08/2024), Scopus (08/2024), Web of Science (08/2024), CINAHL (08/2024), EMBASE (08/2024), and IEEE (08/2024). No restriction on the earliest publication date was implemented. This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines[12] and the COSMIN-SR guidelines.[13] The search strategy involves combining key words related to stroke (*e.g.*, "stroke" OR "hemiplegic"), motion capture technologies (*e.g.*, "motion capture" OR "wearable sensor" OR "inertial measurement units"), and kinematics-related outcomes (*e.g.*, "kinematics" OR "mobility"). Detailed search terms for each database are provided in Supplementary Digital Material 1 (Supplementary Text File 1). In addition, the reference lists of the included studies (backward tracking) and literature citing the included studies (forward tracking) were reviewed to obtain additional information. The

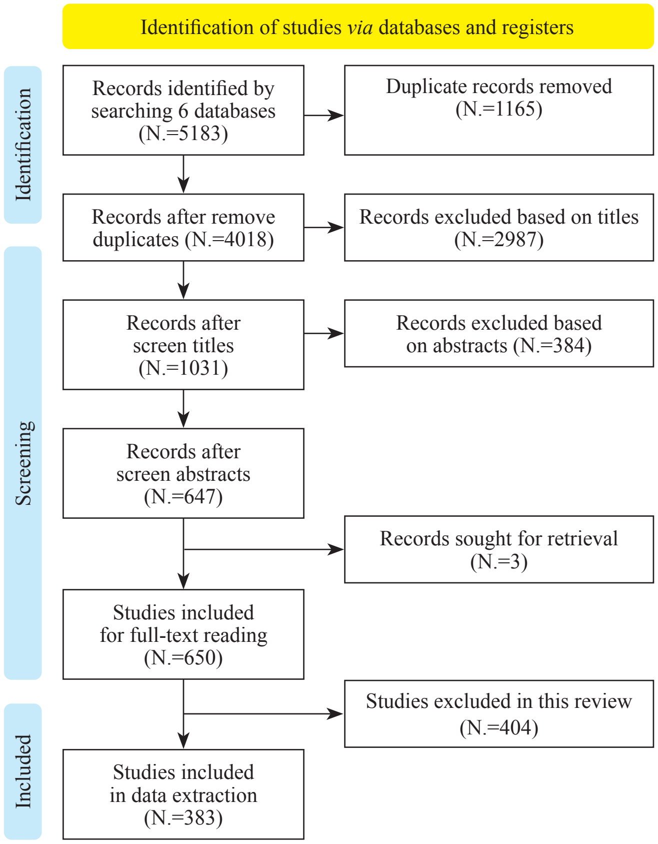

Figure 1.—Flow chart of the study selection process.

systematic review protocol is available on the International Prospective Register of Systematic Reviews (registration no.: CRD42020155403).

After removing duplicates, two reviewers independently screened for potentially eligible studies. In case of disagreement, a third reviewer was consulted. The PRISMA flow chart is presented in Figure 1.

Selection of articles

Studies were included if they 1) recruited participants who were >18 years and had a stroke regardless of stroke severity and timing; and 2) conducted an objective assessment of lower limb kinematic metrics, such as using 3D motion capture systems.

We excluded studies that 1) included participants aged <18 years; 2) only examined healthy individuals for testing newly developed equipment or algorithms; 3) only used GAITRite or pressure sensor equipment for measurement; 4) were commentary article or review articles; 5) had no full text available; and 6) were animal studies.

Data extraction and definitions

After screening the title and abstract, we performed a full-text review of the selected articles. Data were recorded on a Microsoft Excel sheet by two independent reviewers (JQL and WPW). We extracted the following information: 1) publication year; 2) first author; 3) number of participants; 4) clinimetric properties measured; 5) tasks; 6) measurement instrument used; and 7) kinematic outcomes.

On the basis of the nature of lower limb performance, measurement tasks were categorized into five primary groups, namely 1) walking, in which measurement was conducted during walking tasks, regardless of speed, including overground or treadmill walking with or without orthosis as well as with or without bodyweight support; 2) turning, in which tasks involving turning around while walking or in multiple tasks were considered; 3) sit-to-stand, in which tasks involving transitional movements to the upright posture as well as the "stand-to-sit" movement were considered; 4) step over, in which tasks involving stepping up stairs or blocks and crossing obstacles were considered; and 5) other tasks, which included tasks that could not be categorized into the aforementioned classifications, including running, dancing, and balance tests.

Kinematic metrics from these five functional tasks were extracted for further evaluation. We used a previous systematic review's classification of upper limb metrics as a reference[11] while considering the specific characteristics of lower limb function. The extracted metrics were classified into 10 categories based on their physiological interpretation: spatiotemporal parameters, spatial posture, temporal posture, speed, symmetry, coordination, data-driven scores, smoothness, efficacy, and anticipation. The detailed definitions of these categories and related articles are listed in Supplementary Digital Material 2 (Supplementary Table I). Furthermore, the measurement instrument used in each study was summarized as well.

Study quality assessment

The COSMIN Risk of Bias Checklist[14] is widely used to evaluate the methodological quality of patient-reported outcome measures (PROMs). This checklist contains 10 domains, in this study, we used reliability (domain 6) and criterion validity (domain 8) for assessment. Each evaluation item in boxes can be rated on a 5-level scale (very good, adequate, doubtful, inadequate, and not applicable). The overall assessment against the criteria of good measurement properties is rated as either sufficient (+) or insufficient (–). According to these ratings, the quality of methodology can be graded as high, moderate, low, or very low.

We initiated our analysis by assessing the risk of bias in the studies under consideration. For this evaluation, studies were deemed to be of high quality if only one item was rated as 'doubtful'. Subsequently, we evaluated the reliability of the metrics used in these studies. This was done by analyzing the reported interclass correlation coefficients (ICCs), which are crucial indicators of measurement consistency.

As walking speed and the Fugl-Meyer Assessment (FMA) are widely endorsed as standard clinical tools for assessing limb functions in individuals with stroke,[15, 16] our evaluation of metric validity focused on analyzing the reported correlations between these metrics and both walking speed and FMA scores for the lower extremity (FMA-LE). Additionally, to enhance the comprehensiveness of our analysis, we aggregated the reported interclass correlation coefficients (ICCs) and correlation coefficients for similar metrics into intervals. For example, ICC values for the hip angle, encompassing measurements of both hip flexion/extension and abduction/adduction, were combined to provide a more holistic view of their reliability.

The ICC values for reliability and the correlation coefficients (r) between the metrics and walking speed or FMA-LE scores for high quality studies were extracted. An ICC of $\geq$0.7 was deemed sufficient for reliability.[17] A moderate-to-very-high correlation ($|r| \geq 0.5$ with $P \leq 0.05$) was considered sufficient for validity.[18] Metrics with this level of evidence support were recommended for future use.

The quality of evidence was assessed using the GRADE system, as recommended by the COSMIN guideline for systematic reviews. Evidence was evaluated across four domains: 1) risk of bias, 2) inconsistency, 3) imprecision, and 4) indirectness, which also evaluate the consistency of conclusions between studies, sample size, and whether the studies were conducted in the target population. The quality of evidence was then categorized into four levels: high, moderate, low, and very low.

Evidence synthesis

Flow of studies through the review

The initial search identified 5183 records. After the removal of duplicates, 4533 articles were screened for the titles and abstracts. With 650 records being full-text read, finally, this systematic review included 383 studies involving 8109 individuals with stroke (Figure 1) (Supplementary Digital Material 3: Supplementary Table II).

Kinematic lower limb assessments

We categorized the studies into five groups based on the type of lower-limb tasks they investigated: 335 studies were grouped under the walking task, 17 under the turning task, 18 under the sit-to-stand task, 12 under the step-over task, and eight under other tasks (including nine articles that overlapped across categories). Overall, 205 metrics were extracted directly from the articles. After the combination of metrics with similar characteristics, 91 metrics remained for further analysis and were classified into 10 categories (Supplementary Table I). An online dashboard was also developed to visualize the frequency of metrics across various tasks and categories. (https://kwongwh.shinyapps.io/Stroke_kinematics/).

More than 78% (N.=301) of the studies used marker-based optical motion capture as their measurement tool. This tool has been widely used since its introduction in the 1990s. IMUs were used in 15% (56) of the included studies and have gained popularity since the 2010s. Video-based methods were used in 5% (N.=21) studies, with their usage spanning from before the 1990s to the recent 10 years, ranging from simple video analysis to artificial intelligence (AI)-based analysis. In addition, two studies used sensors embedded in training robots, two studies utilized goniometers to measure joint angles, and one study used an optoelectronic sensor.

Walking task

Most studies focused on spatiotemporal parameters in gait cycle measurement. We observed that 183 studies measured the walking speed, 172 studies measured the step or stride length, and 120 studies measured the single/double support time. In addition, 95 studies examined the cadence, which is expressed as step count per minute (Supplementary Digital Material 4: Supplementary Figure 1).

Both the spatial posture and temporal posture included 13 metrics each. Joint angle was the most frequently measured metric. Furthermore, 116 studies measured the knee angle (including the maximum and minimum values of the range of motion), 17 studies measured the knee angle at a specific time point during walking (initial contact and toe off), and 59 studies measured the knee trajectory in the normalized gait cycle (%). Ankle angle measurements, both at specific time points and within the gait cycle (%), were slightly more than knee angle measurements, with 24 and 66 studies, respectively. In addition, other joint angles, such as pelvic, hip, foot, and leg/shank angles, and the location of the center of mass (COM) in the spatial posture were examined in more than 10 studies. In addition to the joint angles, temporal parameters were measured in the temporal posture category. For example, four studies defined the gait phase, and six studies measured the timing of specific motions, such as peak joint angle, toe off, and heel strike.

In the walking task, symmetry and coordination are crucial performance metrics for individuals with stroke. More than 32 studies examined symmetry based on the step length and step time, whereas 10 studies focused on joint symmetry, symmetry index, and gait asymmetry metric. Metrics related to coordination included the angular component of the coefficient of correspondence (ACC) in 5 studies and inter-limb or intra-limb continuous relative phase in 12 studies. A study published in 2014 measured the center of oscillation, a type of spatial coordination.[19]

Other metric categories included speed, with 30 studies measuring the joint angular speed, one study examining COM velocity, and one study evaluating segment angular velocity. Data-driven scores were also considered, with seven studies employing principal component analysis (PCA), seven studies using the gait deviation index, six studies using the gait variability index, four studies using the gait profile score (GPS), one study using the gait cycle index, and one study using the dynamic gait index. Regarding efficacy metrics, 10 studies measured toe clearance, three measured the margin of stability, and two examined step precision. One study defined the coefficient of variation of the stride time, and one study examined the synergy index.

Turning task

Previous studies have examined the turning task during the TUG, modified dynamic gait index, and tasks involving changing direction while walking or performing only a turn motion.

In the spatiotemporal parameter category, 8 studies examined the turning phase (including TUG time). Moreover, 14 studies measured the joint angle and COM location in the spatial posture. One study measured PCA in the data-driven score category, and 4 studies measured the step length or time symmetry.

The turning task differs from the walking task in that it involves segment reorientation, which was categorized in anticipation category, such as the head anticipation distance (two studies); yaw rotation onset times for the head, trunk, and pelvis (one study); and step initiation (one study) (Figure 2).

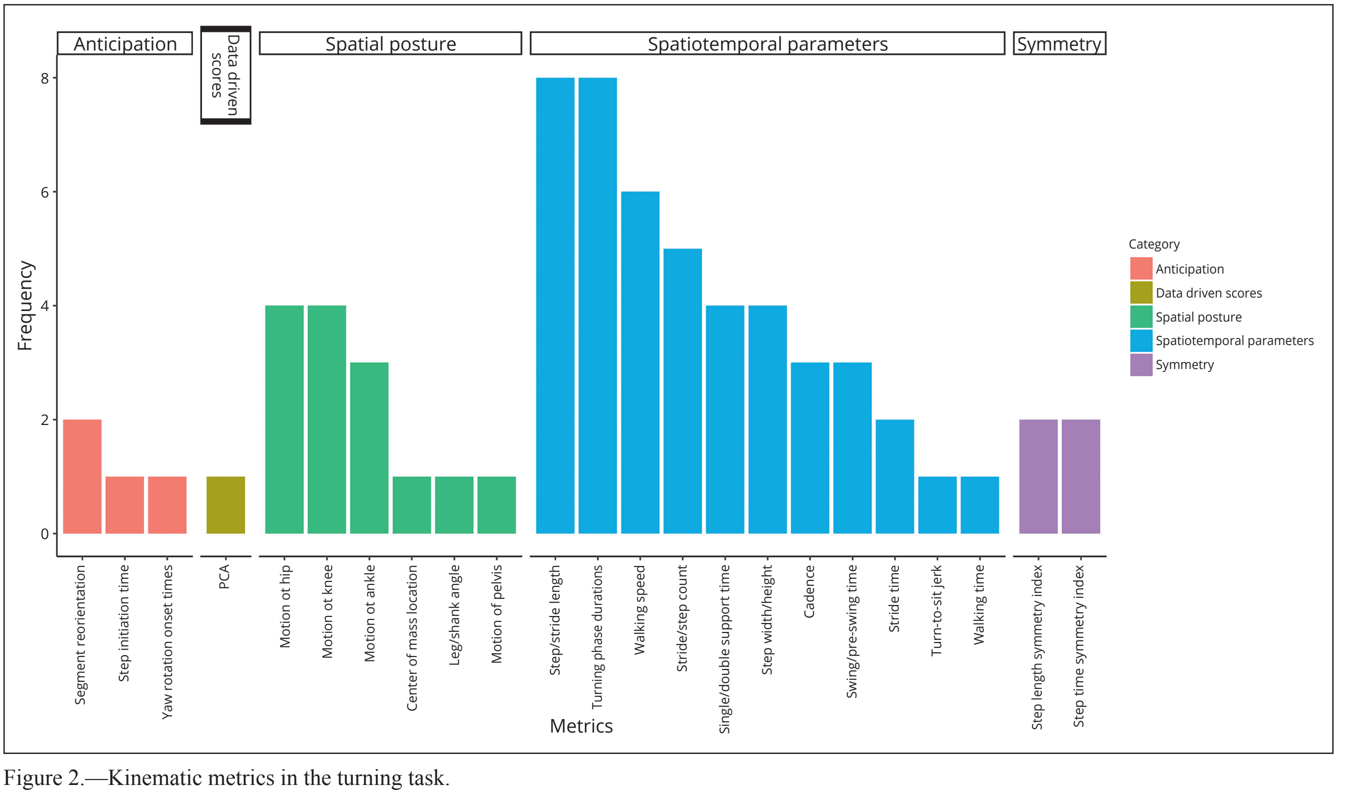

Figure 2.—Kinematic metrics in the turning task.

Sit-to-stand task

Because the sit-to-stand task is often measured as a part of a continuous task in clinical assessments, such as the TUG, which involves walking or turning, several spatiotemporal parameters were measured. The parameters included walking speed (three studies), step or stride length (seven studies), single or double support time (seven studies), time of the rise phase (four studies), and postural phase (from seat-off to first foot-off, one study). In addition, 11 studies measured the motion of pelvis, COM location, and other relevant joint angles of lower limbs.

Two studies measured step time/length symmetry characteristics. One study focused on weight-bearing symmetry, which is an exclusive metric in the sit-to-stand task. Other studies explored joint angular velocity (two studies), ACC (one study), start to end of the downward pelvic movement (one study), and fluidity index (which corresponds to the percentage of change in COM forward velocity, two studies) (Figure 3).

Step-over task

Three studies overlapped in terms of both turning and sit-to-stand tasks. In the analysis, metrics unrelated to step-up or stepover were excluded. In the spatiotemporal parameter category, the crossing obstacle speed was measured in one study, the joint angle in four studies, and measurements within the gait cycle or at specific time points in five studies. Joint angular velocity was measured in two studies. In addition, one study performed PCA.

Distinct parameters were noted in the efficacy category. One study measured the toe clearance efficacy during the crossing of obstacles separately. In addition, another study measured step precision and the success rate (Figure 4).

Other tasks

In the systematic review, the "other tasks" category included assessments related to balance control, running, and dancing. Six studies measured spatiotemporal parameters, and four studies determined the joint angle or COM location. Metrics related to the step length/time symmetry, velocity of COM, PCA, inter/intra-limb phase coordination, step initiation time (in the anticipation category), and step precision and step execution time (in the efficacy category) were sporadically measured according to the specific task (Figure 5).

Risk of bias assessment

Eighteen studies examined test–retest reliability. According to the COSMIN checklist,[14] seven studies were evalu-

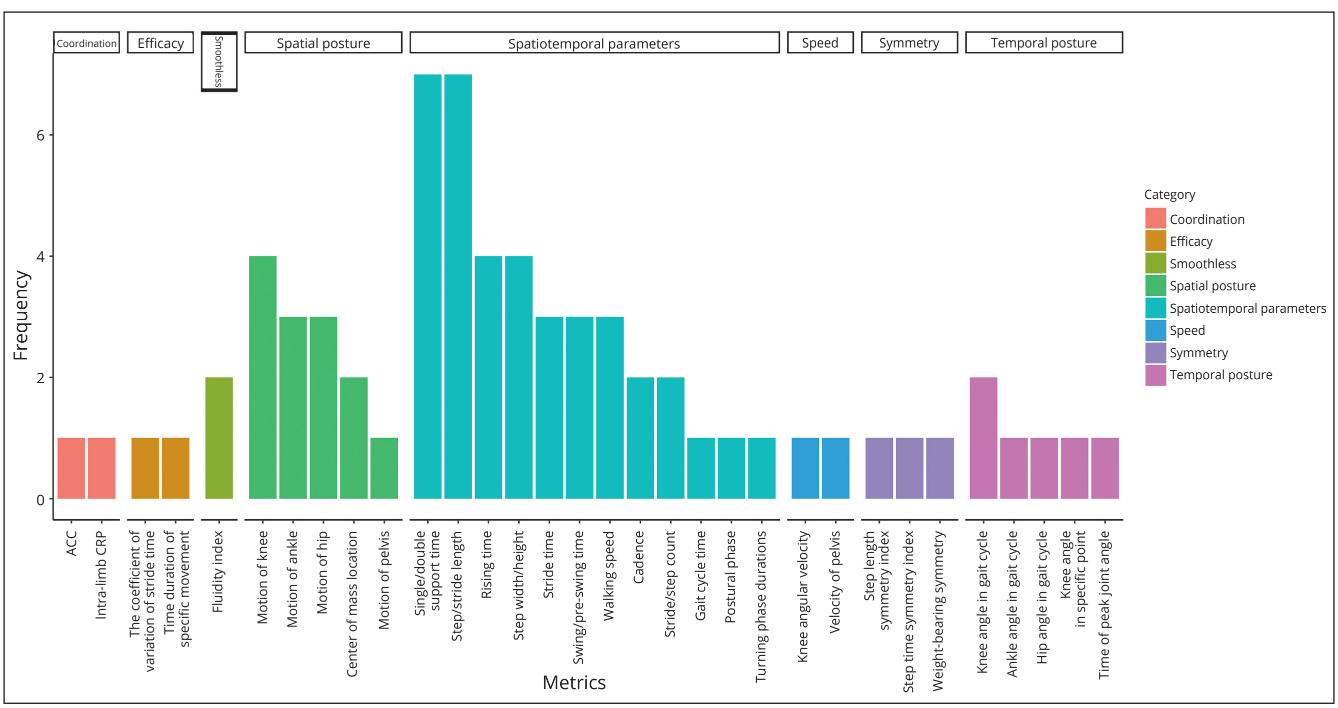

Figure 3.—Kinematic metrics in the sit-to-stand task.

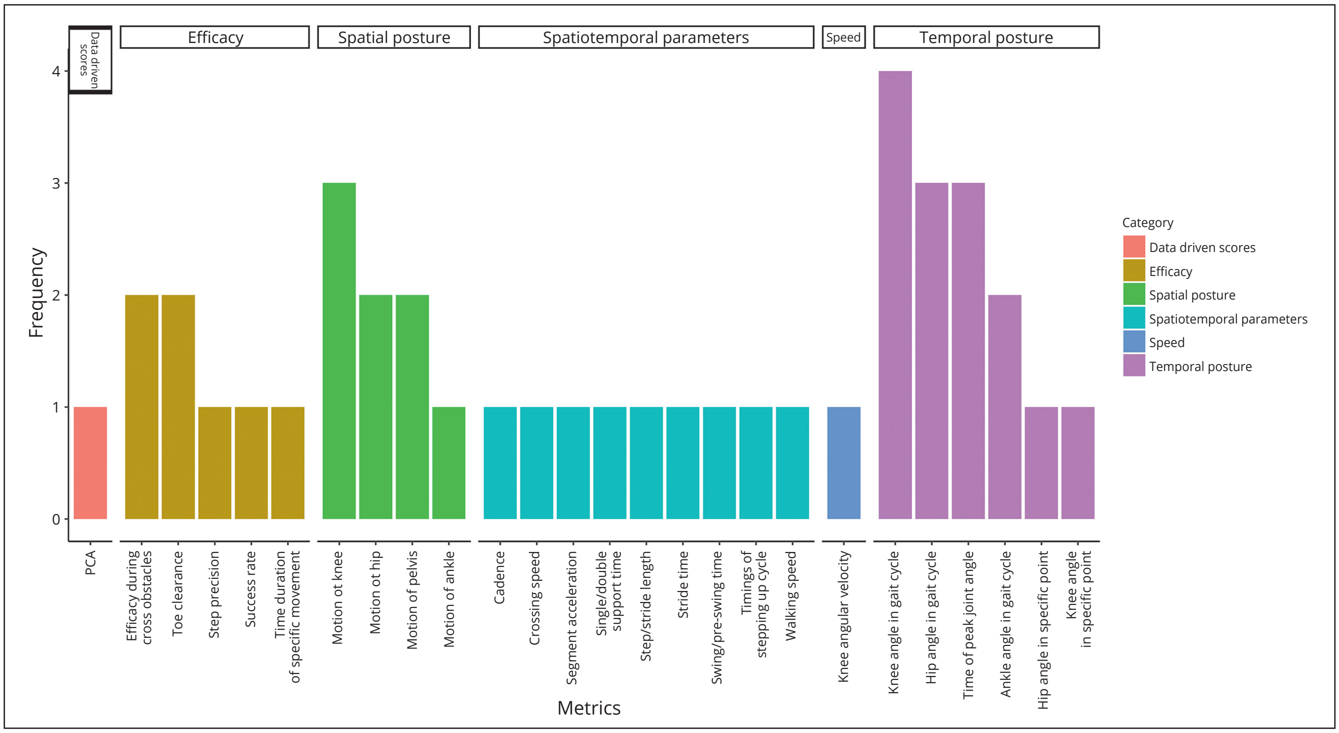

Figure 4.—Kinematic metrics in the step-over task.

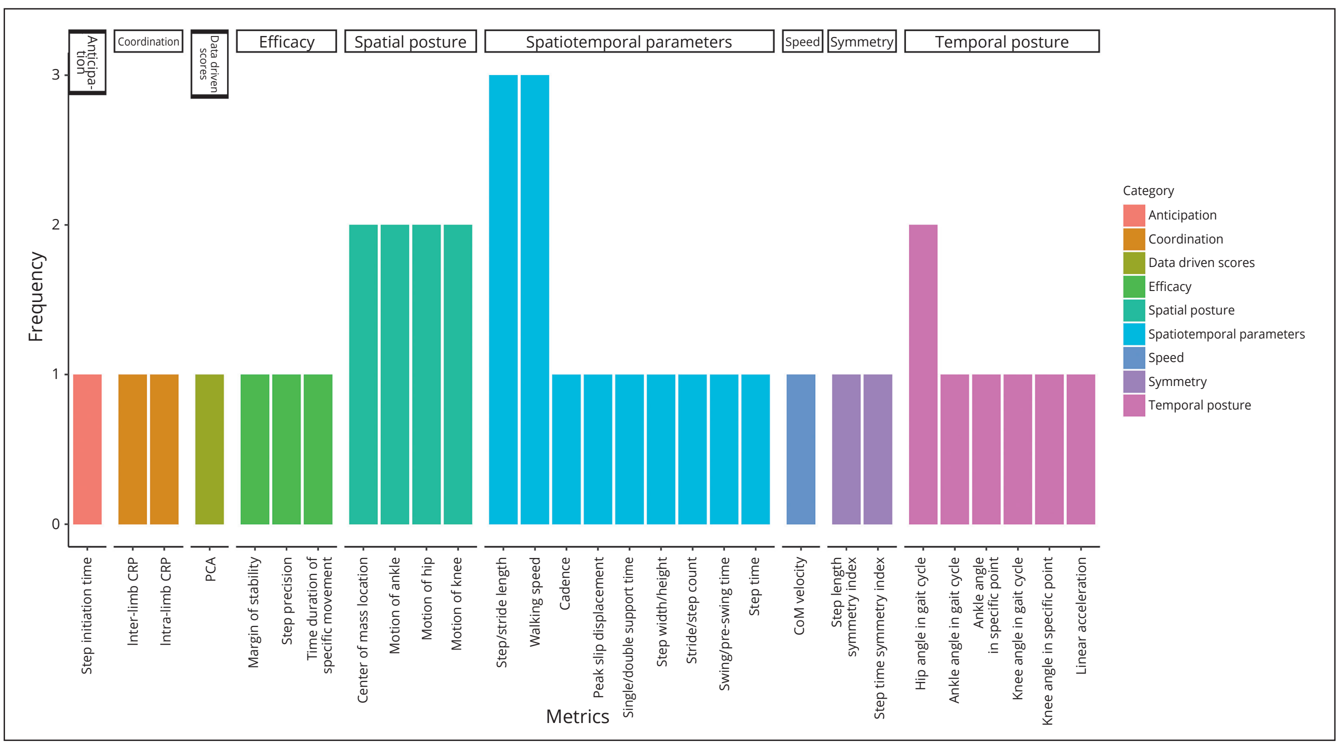

Figure 5.—Kinematic metrics in other tasks.

ated as having high methodological quality, with only one item assessed as “doubtful.” Five studies were evaluated to have moderate quality, with two items rated as “doubtful”. The remaining six studies were evaluated as having low quality, with two items rated as “doubtful” and one as “inadequate.” In total, 23 metrics with sufficient reliability were extracted, including spatiotemporal parameters such as cadence,[20] step length,[21, 22] support time,[20, 21] swing time;[20] the spatial posture of joint angles measured;[21-23] and data-driven score[23] exhibited high inter-rater reliability (Supplementary Digital Material 5: Supplementary Table III).[20-26]

Moreover, 12 studies evaluated the convergent validity, and six studies were evaluated as having methodological quality, with only one rated as “doubtful.” The remaining studies were evaluated as having moderate quality because they had two “doubtful” items. Finally, six metrics of the dynamic gait index,[27] hip/knee ACC,[28] change in cadence,[29] stride length,[29] and hip range of motion[29] displayed high validity in this review (Supplementary Digital Material 6: Supplementary Table IV).[27-32]

The 13 studies exhibited high methodological quality was further evaluated using the GRADE approach, the quality of evidence of 12 studies[20-25, 27-32] were rated as moderate quality, and only one study[26] was rated as low quality.

The primary reason for the downgrade was imprecision, as almost all studies had fewer than 50 participants. Additionally, joint range of motion showed inconsistent reliability.

Discussion

This study provides a comprehensive summary of instrumented lower limb kinematic measurements in individuals with stroke, given the variability and complexity of lower limb functions often observed in clinical practice. A total of 91 metrics were extracted from 383 articles, which enables the assessment of various aspects of lower limb functions.

The largest proportion (88%) of the identified studies focused on the walking task, and its popularity did not decrease with time. This focus on walking is attributed to its fundamental role in assessing individuals with stroke because it serves as a direct observation and is highly correlated with functional capacity, endurance, and quality of life.[33, 34] The assessment of walking ability is crucial for making clinical decisions regarding exercise prescriptions. Apart from walking, various other tasks are used to assess various dimensions of mobility function, including turning (including the TUG test), sit-to-stand, going up and down stairs, and crossing obstacles. However, most of the included studies primarily focus on walking tasks. While walking is fundamental, this narrower focus limits the exploration of other critical mobility tasks, potentially restricting the application of findings to real-world rehabilitation settings where multiple mobility functions are required, which are more advanced and provide insights into the daily ambulation ability.[35-37]

Instruments for measurement

In this study, we identified various tools used for gait evaluation. The most commonly employed measurement system was the marker-based optical motion capture system, which has been used in 301 studies over the last two decades. This technology, which uses multiple cameras to capture and reconstruct the 3D positions of passive reflective markers at key anatomical landmarks, is considered the gold standard because of its accuracy.[38]

IMUs were the second most used system. They were employed in 56 studies. This technology integrates accelerometers, gyroscopes, and magnetometers within a single unit,[39] making them portable and suitable for use in various settings without the need for a sophisticated laboratory environment. Since the 2010s, IMUs have been used in clinical studies, and studies have focused on validating their use in poststroke assessment[40] and assessing their reliability against optical motion analysis systems. Numerous studies involving participants with stroke have demonstrated their favorable consistency for measuring spatiotemporal parameters, joint angles during tasks such as walking,[41] and balance tests.[42] Given the increasing complexity of movements assessed in stroke rehabilitation, validating the metrics derived from IMUs is necessary for their future applications.

Video recording was widely used before the 1990s; however, with the emergence of more accurate motion capture systems, the limitations of traditional video-based systems became evident.[43] With the development of AI, motion capture with AI assistance can produce images with higher resolution and accuracy for three-dimensional post estimation.[44] Thus, video-based, markerless motion capture, such as Kinect v2 that uses a markerless depth camera and AI techniques to extract gait patterns, has gained popularity.[27] In addition, sensors embedded in training robots (such as Walkbot)[45, 46] are anticipated to be a powerful technology for discriminating kinematic metrics, although more studies are warranted to validate their use.

Conventional kinematic metrics

Spatiotemporal parameters are the most commonly used variables for stroke survivors. The self-selected walking speed, cadence, step/stride length, and swing/support time parameters are fundamental in evaluating participants' locomotor ability. Variations in these parameters, including crossing speed, turning phase durations, and the time spent transitioning from sitting to standing in the step-over task, turning task, and sit-to-stand task, directly reflect deficits in lower limb performance.

Joint kinematics is another parameter that can distinguish between adaptation and maintaining normal movement patterns.[47] Deviations in magnitudes (peaks and means) or joint angle trajectories from the normal gait cycle can serve as guidelines for training paradigms.[48] Specifically, joint angles at specific time points, such as heel strike and toe off, are instrumental for designing exercises to normalize these differences and improve locomotion and balance abilities. For example, Bae *et al.* developed real-time feedback functional electrical stimulation targeted at reducing ankle joint angle deviations and enhancing balance ability and gait patterns.[49] Moreover, joint kinematics data are used to evaluate and improve the fitting of advanced articulated orthosis tailored to individuals with stroke.[50] According to this review, the knee and ankle have received the most research attention. In the category of spatial posture and temporal posture, the COM location was frequently measured because it reflects dynamic stability,[51] and it serves as an effective predictor of falls. Studies focusing on overall posture stability used COM-related calculations.

Some spatial or temporal parameters are designed to capture the features of a specific task. Examples include the time to peak joint angle,[52] limb segment locations,[53] and indices such as the stride direction angle[54] in the turning task and trailing limb angle in walking tasks conducted on the treadmill.[55] These variations are measured to quantify specific functional aspects.

Joint angular speed/velocity is mainly measured in the walking task, with 29 studies addressing this parameter. In addition, two studies focused on COM velocity and segment angular velocity. A previous study[56] described that the clinical implications of a spasticity assessment may be better understood if the speed of movement during a lower limb assessment of muscle spasticity is matched to the relevant joint angular velocities during walking. This can provide insights into conditions such as hamstring spasticity, which affects the angular velocity of the knee during the terminal swing.

Derived kinematic metrics

In addition to directly observed variables, some synthetic parameters are derived from these basic metrics. These synthetic parameters can indicate the abnormal pattern comprehensively after calculations.

Symmetry is a critical parameter that measures the parallelism of lower limbs.[57] Increased gait asymmetry would lead to the reduction of dynamic balance and increases in energy expenditure.[58] A study reported that spatiotemporal asymmetry lengthens the hospital stay despite improvements in physical function during stroke rehabilitation.[59] Symmetry can be calculated based on the duration of the gait phases of two lower limbs, interlimb joint angles, or travelled distances. In this review, symmetry was measured in the walking task, turning task, sit-to-stand task, and other tasks. The symmetry index defined in one study[60] provides an alternative method to evaluate participants' walking capacity. Another term for gait asymmetry metric combines different asymmetry parameters using the Mahalanobis distance (a distance measure in multidimensional data space).[61]

Krasovsky and Levin[62] defined coordination as "the ability to maintain a context-dependent and phase-dependent cyclical relationship between different body segments or joints in both spatial and temporal domains." To adjust the walking pattern in response to environmental demands, the relationship between body segments must be flexible.[63] A study identified that poor coordination would contribute to slow walking even in individuals with stroke with good strength.[64] Coordination is mainly measured in the walking task, turning task, and other tasks. Phase coordination can be quantified in the intralimb or interlimb continuous relative phase. In addition, the ACC demonstrates the consistency of intralimb coordination between two joints. The "center of oscillation"[65] measures spatial coordination by quantifying whether the leg is oscillating about a flexed, extended, or neutral (vertical) axis.

Data-driven scores refer to the application of computational techniques for a more efficient analysis of quantitative data. They can reduce the dimensionality of complex data. PCA is a widely used method in this category, and it is known for its ease of use; it is particularly useful for reducing the dimensionality of a large number of variables into a smaller number of components,[66] although only nine studies used PCA, and its usage has increased over time. Other summary measures, such as the gait cycle index for normalizing the gait cycle;[67] the gait deviation index in which joint angles are examined through PCA;[68] dynamic gait index consisting of eight assessment items covering walking, walking while changing speed, walking while turning the head horizontally and vertically, walking with a pivot turn, walking over and around obstacles, and stair climbing;[69] the gait variability index computed from nine spatiotemporal parameters, such as step/stride length, step/stride time, support time and velocity;[70] and the gait profile score indicating differences in joint angle data (pelvis, hip, knee, ankle and foot) from individuals without gait pathology,[71] are gaining acceptance in clinical settings. These metrics offer a single index for evaluating deviations in gait patterns. However, it is crucial to exercise caution in their interpretation, as they may oversimplify the multifaceted nature of gait assessment.[72]

Efficacy metrics are used to measure whether a task can be completed successfully or to quantify the quality of task completion. In the studies included in this review, these metrics mainly involved the margin of stability, toe clearance in walking, effectiveness during crossing obstacles, and step precision in the step-over task, along with sporadic variables related to a specific task. A study[73] introduced the concept of the synergy index, which ranges from -1 to +1 and corresponds to the loss of COM trajectory stability.

Smoothness can provide valuable information on sensorimotor control, and it can be used to assess participants during neurorehabilitation.[74] It is widely regarded as an invariant in human movement.[75] The inability to synchronize motor units or regulate agonists and antagonists in appropriate amounts may result in smoothness deficits.[76, 77] Alternatively, changes in corticospinal tract excitability after stroke might cause these deficits. In the studies included in this review, smoothness was measured using the fluidity index and gait smoothness[78] (angular velocity axes of yaw, pitch, and roll). The fluidity index[31] reflects the degree of fluidity in the sit-to-stand task, and it is related to the percentage of change in COM forward velocity.

In the turning task, we identified an additional category known as anticipation. This can be interpreted as "motor planning." Given that stroke can disrupt the sequence of movements within segments, particularly during high-demand activities such as dual tasks, addressing this disarray is essential in stroke rehabilitation.[79] Anticipation was mainly measured in the turning task by using metrics such as yaw rotation onset times for the head, trunk, and pelvis,[79] segment reorientation,[79, 80] and step initiation time[81] (the reaction time phase when rapidly changing direction).

Evaluation of clinimetric properties

We systematically reviewed and assessed the quality of studies investigating the reliability and validity of the extracted metrics. Consistent with the approach of a previous study,[11] we used the COSMIN checklist to evaluate the risk of bias and methodological quality of the included studies. Furthermore, the quality of evidence was rated with the GRADE approach. However, many reviewed studies have small sample sizes (fewer than 50 participants), undermining the statistical power and precision of the findings. This reduces the statistical power and precision of the findings and contributes to the GRADE rating of evidence quality being assessed as moderate to low. Moreover, the challenge exists in the convergent validity test due to the unclear relationship between the representative clinical scale and kinematic metrics.

Some spatiotemporal parameters, such as "Trail pre-obstacle distance" and "Lead step time," demonstrate moderate reliability. While these metrics may lack precision for comprehensive mobility assessment, they can still offer valuable supportive information when used alongside more robust measures of lower limb function, emphasizing the need for ongoing refinement of assessment tools. Similarly, metrics such as GPS and Fluidity Index, which exhibit poor correlations with speed or FMA-LE, likely capture different aspects of mobility, such as specific gait characteristics (*e.g.*, asymmetry or irregularities) that speed alone cannot reflect. Therefore, clinicians should avoid relying solely on speed as the primary indicator of lower limb movement quality and instead consider incorporating complementary metrics to achieve a more holistic evaluation. Based on the results, high-quality studies with large sample size, sophisticated test conditions, and clearer descriptions of participants' status are warranted for further evaluation of clinimetric properties.

Limitations of the study

During the process of study identification, we used standard keywords in biomechanics, such as "kinematics," to identify potential studies. Nonetheless, some studies incorporate the names of metrics derived from kinematics data within their titles and abstracts. This divergence in nomenclature introduces a potential barrier, because it may result in the inadvertent exclusion of articles featuring these metrics from our comprehensive review. Another significant limitation of this review is the heterogeneity of the included studies. While the COSMIN framework was used to assess the quality of individual studies, the variability in methodologies — such as differing definitions of kinematic metrics and task performance — creates challenges in forming consistent and uniform conclusions. Furthermore, we only included studies written in English, which might have led to the exclusion of some related articles. In our assessment of clinimetric properties, FMA-LE and walking speed were employed as benchmark standards. Consequently, studies that focused on the correlation of these metrics with alternate clinical outcomes were not considered for inclusion in this review. Furthermore, we excluded studies that had a sample size of less than 30 participants. This decision was based on concerns about the robustness and reliability of the findings from smaller-scale studies, which could potentially compromise the evaluation process.

Conclusions

This systematic review comprehensively identified and detailed various measurement tasks and instruments, with a particular focus on the kinematic metrics used to assess lower limb function in individuals with stroke. By analyzing over 350 studies, we provided a more precise characterization of stroke-related gait abnormalities and categorized these variables based on their properties and the specific tasks they address, facilitating their clinical application. However, the current evidence base is limited by a lack of high-quality studies rigorously examining the clinimetric properties of these metrics, which impacts the generalizability of the findings. Further robust research is crucial to support clinical adoption and the development of standardized, evidence-based protocols for lower limb kinematic assessments.

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Conflicts of interest
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