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Clinical Efficacy of Instrumented Gait Analysis: Systematic Review 2020 Update

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Highlights

- Literature on the clinical efficacy of gait analysis (3DGA) has greatly expanded
- There is strong evidence that 3DGA changes and reinforces treatment decisions
- 3DGA increases confidence in treatment planning and agreement among clinicians

- 3DGA can help define diagnostic groups and understand expected treatment outcomes
- 3DGA can improve patient outcomes if recommendations are followed

Abstract

BACKGROUND: This paper updates our 2011 systematic review on the clinical efficacy of three-dimensional instrumented gait analysis (3DGA).

RESEARCH QUESTION: What is the current evidence base pertaining to the clinical efficacy of 3DGA?

METHODS: We identified English language articles published from September 2009 to October 2019 reporting primary research that used typical motion analysis laboratory methods to study human walking. Five gait laboratory experts classified articles according to the highest type of efficacy they addressed: type 1 (technical), 2 (diagnostic accuracy), 2b (outcome prediction), 3-4 (diagnostic thinking and treatment), 5 (patient outcome), 6 (societal). Articles classified into type 3-4 and higher were rated for quality using LEGEND.

RESULTS: Of 2,712 articles related to the efficacy of 3DGA, over 99% addressed technical (n=313), diagnostic (n=1,466), or outcome prediction (n=927) efficacy. Six type 3-4 studies showed that 3DGA changes treatment plans, increases clinicians' confidence in their treatment decisions, and increases agreement among clinicians. Two type 5 articles based on a randomized controlled trial demonstrated that patient outcomes improved only when 3DGA data were available and its recommendations were followed. A population-based type 5 study found that the incidence of severe crouch gait dropped from 25% to 4% following practice changes including the addition of 3DGA. The strength of evidence was mainly 3b (lesser quality prospective cohort studies) but also included stronger studies (three level 2 controlled clinical trials).

SIGNIFICANCE: Literature related to the clinical efficacy of 3DGA has grown substantially over the last decade. Thousands of articles contribute to continued improvement of data collection and interpretation, as well as understanding of gait pathology and treatment. A smaller number of studies clearly demonstrate the efficacy of 3DGA in changing and reinforcing treatment decisions, increasing clinicians' confidence in treatment planning, and increasing agreement among clinicians, as well as the potential to improve patient outcomes.

Keywords: gait analysis, kinematics, evidence, decision making, outcomes

INTRODUCTION

In 2011, we published a systematic review evaluating the literature related to the clinical efficacy of three-dimensional instrumented gait analysis (3DGA) [1]. This topic remains important since debate persists regarding the use of instrumented gait analysis for clinical care [2, 3] and due to the increasing emphasis on evidence-based medicine [4, 5]. In the decade since our previous review, the field of gait analysis has continued to advance with expansion of services, development of new technology, accreditation of motion analysis laboratories that provide clinical services, and increasing volumes of research. Given these advances, there is a need to re-evaluate the literature on 3DGA.

The current study is an update to our previous review [1] covering the time period since that initial assessment. Our goal is to provide an updated understanding of the current evidence base related to the clinical efficacy of 3DGA. This evidence is needed to understand how gait analysis influences clinical decision making, treatment planning, and patient outcomes to better inform clinicians, patients, families, insurers, and policy makers regarding the appropriate use of 3DGA in the clinical care of patients with gait disorders.

MATERIAL AND METHODS

A literature review was conducted to identify references related to human gait analysis published between September 2009 and October 2019. We limited our search to PubMed due to the large number of references identified and because most papers on 3DGA appear in the PubMed database. The search criteria were (gait or locomotion or walking or kinematic or biomechanic or electromyography) and (analysis or evaluation or diagnosis). Only English language references were included.

Initial screening was performed to narrow the search results to articles meeting more detailed inclusion and exclusion criteria. Each article was screened by one of five investigators with a minimum of 17 years of experience in clinical gait analysis. Articles not meeting the inclusion/exclusion criteria were eliminated from further consideration; articles where qualification could not be determined were passed through to the next phase of review for additional evaluation. To be included, papers had to investigate human walking using 3D kinematics, kinetics, ground reaction force, plantar pressure, and/or electromyography (EMG) obtained using typical motion analysis laboratory methods (e.g., optoelectronic motion capture systems, force plates, pressure mats, surface and/or fine wire EMG). Studies evaluating only temporal-spatial parameters like velocity or stride length were excluded under the rationale that these measures can be obtained without 3DGA. Alternative technologies such as mobile sensors (accelerometers, inertial measurement units, wearables, etc.), 2D video-based systems, depth cameras (e.g., Kinect), global position system (GPS) tracking, and fluoroscopy were excluded to keep the scope of the review manageable. Variants of walking such as slope walking, perturbed walking, walking with curves or turns, dual-task walking, walking with loads or unloading, and walking with obstacles were included. Non-walking gait such as running, gait initiation/termination, and stair climbing/descent were excluded. The walking could be performed over ground, on a treadmill, or in a virtual reality environment. Review articles were excluded under the rationale that the original papers would already have been included. Commentaries or opinion pieces were also excluded, along with publications describing study protocols without results and short conference abstracts.

In the second level of screening, articles were classified according to the type of efficacy they addressed. Types of efficacy were defined similar to our previous publication [1] (Table 1) based on the Fryback and Thornbury framework for technology assessment [6, 7], except that a broader definition of diagnostic accuracy (type 2) was adopted compared with our previous review. In the current review, we included studies comparing groups, gait conditions, or relating gait measures to other participant characteristics in type 2 because the knowledge from such studies contributes to the ability to interpret gait data and discriminate between diagnostic groups. An additional type (2b) was also added to identify papers evaluating the effects of treatments at a group level (as distinguished from type 5 which addresses treatment outcomes for individual patients).

Papers were excluded during second-level screening if it was determined that they did not meet the original inclusion/exclusion criteria described above. Papers that met the initial inclusion criteria but did not pertain to a type of efficacy were also excluded during second-level screening. These studies were primarily descriptive (often case studies) or used traditional 3DGA as a reference criterion to validate other (usually mobile or low-cost) technologies. Each article was independently evaluated by at least two of the five reviewers. If the type of efficacy did not match between these reviewers, an additional review was sought to reconcile the discrepancy. In cases where more than one type of efficacy applied, the higher type was used.

Papers meeting the criteria for efficacy type 3-4 and above were rated for quality and strength of evidence using the LEGEND evidence appraisal tools developed at Cincinnati Children's Hospital Medical Center (https://www.cincinnatichildrens.org/research/divisions/j/anderson-center/evidence-based-care/legend). These tools assess the validity, reliability, and applicability of a paper and assign it a quality rating based on study design and controls for bias according to a hierarchical system based on the Oxford Center for Evidence-Based Medicine Levels of Evidence. Systematic reviews and meta-analyses are rated highest (level 1), and opinion papers the lowest (level 5), with levels a and b also assigned within each level to distinguish between higher and lower quality studies. Each of the papers at efficacy levels 3-4 and above in the current review was assessed for quality by at least two reviewers. In cases of disagreement between reviewers, a third reviewer reconciled the discrepancy.

RESULTS

Literature Review Overview

A flowchart of the literature review results is presented in Fig. 1. The literature search identified 10,168 articles which underwent first-level screening. 6,830 were excluded as not meeting the inclusion/exclusion criteria, leaving 3,338 for second-level review. During second-level review, an additional 626 articles were excluded. Most of these failed the inclusion criteria; 94 were excluded because they were only descriptive; 84 were excluded because they did not pertain to the efficacy of gait analysis. Of the remaining 2,712 studies, 313 were classified as type 1; 1,466 as type 2; 927 as type 2b; 6 as type 3-4, and 3 as type 5. No articles were classified as type 6. The type 1 studies primarily dealt with development of improved technology for data collection and modeling, including reliability and validity studies. The type 2 studies generally compared different diagnostic or demographic groups, related gait measures to other gait measures, participant characteristics, or testing conditions, or developed methods to advance data interpretation. The type 2b studies mainly evaluated the effects of treatments such as surgery, bracing, prosthetics, or rehabilitation programs or compared the outcomes of different treatments. The studies classified as type 3-4 or higher are described individually below (Table 2).

References Classified as Type 3-4 or Higher

Type 3-4

Six articles were rated as type 3-4. One randomized controlled trial (Wren et al. 2011) found that 3DGA significantly alters treatment plans and the treatment ultimately performed for children with cerebral palsy (CP); gait analysis also has a reinforcing effect when it agrees with the original treatment plan [8]. Another study (Ferrarin et al. 2015) reported similar findings among patients post-stroke, with treatment plans changing for 71% of patients and clinicians reporting greater confidence in their treatment decisions with use of 3DGA data [9]. Pathology identification and surgical plans also changed with 3DGA in children with spina bifida, particularly for rotational problems (Mueske et al. 2019) [10]. Gait analysis data significantly increased the identification of gait problems including excessive hip flexion, abduction, and internal rotation and altered recommendations for surgical treatment in 44% of cases. Femoral derotational osteotomy was added due to 3DGA data 89% of the time, while tibial derotational osteotomy was either added or removed from the surgical plan 30% of the time.

With respect to the adoption of gait analysis recommendations, a retrospective cohort study (Wren et al. 2013) showed a high level of adherence to 3DGA recommendations (77-97%) [11]. Adherence was highest for surgeons directly affiliated with the gait laboratory (97%), but was still high for surgeons from outside the institution (77%).

Finally, two studies examined agreement in problem identification, goal setting, or treatment recommendations using clinical examination versus 3DGA. Ferrari et al. 2015 [12] found little agreement in problem identification and surgical planning between the two methods, and showed that use of 3DGA allowed greater insight to the causes of gait problems, particularly for internal hip rotation and flexed knee gait. Without 3DGA these problems were attributed to muscle spasticity, but with 3DGA they were attributed to structural abnormalities such as femoral anteversion, knee flexion contractures, and patellar tendon laxity. Franki et al. [13] found that physical therapists had better agreement for problem identification and goal setting when 3DGA was used.

<u>Type 5</u>

Three articles were classified into type 5, including two that derived from the same study. The first (Wren et al. 2013a) [14] presented the results of a randomized controlled trial in which pediatric patients with CP were randomized to either receive or not receive a pre-operative 3DGA report including gait data and treatment recommendations. The only difference in 1-year outcomes between groups was greater improvement in health as reported on the Child Health Questionnaire in the patients who received the report. The lack of greater differences between groups was attributed to low compliance with the 3DGA recommendations since, on average, only 42% of the recommendations were followed for patient-limbs receiving the report compared with a baseline level of 35% in the control group which also underwent 3DGA but did not receive the report and underwent surgery based on the surgeon’s clinical evaluation. This is much lower than what is typical for clinical referrals to the same laboratory, where over 94% of recommendations are followed for patients referred by physicians within the institution and 77% for referrals from outside physicians [11]. Outcomes measured by the Gillette Functional Activity Questionnaire and Gillette Gait Index improved more when at least half of the 3DGA recommendations were followed [14].

The second type 5 paper examined a subset of patients from the previously described study for whom femoral derotational osteotomy (FDRO) was recommended to correct excessive hip internal rotation (Wren et al. 2013b) [15]. Changes in femoral anteversion, hip rotation while walking, and foot progression while walking were assessed in the patients whose surgeon received the 3DGA report and followed the recommendation for FDRO, patients whose surgeon received the gait report but did not follow the recommendation for FDRO, and patients receiving treatment without access to the gait report. The outcome measures improved more and reached the typically developing range only in the group that received the 3DGA report and followed the recommendation for FDRO. When the report was received but the recommendation for FDRO was not followed, outcomes were similar to the group not receiving the 3DGA report.

The final study classified as type 5 was a population-based retrospective cohort study examining the impact of changes in surgical practice patterns on surgical outcomes for children with CP (Vuillermin et al. 2011) [16]. Multiple changes in standard of care were implemented at a particular point in time, including addition of pre-operative 3DGA, introduction of single-event multilevel surgery, and a shift from tendo-Achilles and gastroc-soleus lengthenings to Strayer gastrocnemius recessions. In the years following these changes, the incidence of severe crouch gait dropped impressively, from 25% to 4%, suggesting that the changes in practice including addition of 3DGA were effective in improving surgical outcomes.

Quality and Strength of Evidence

The most common quality rating (4/9 articles) was evidence level 3b denoting a lesser quality prospective cohort study (Table 2). However, two studies had a high evidence level of 2a and one had an evidence level of 2b, indicating good and lesser quality controlled clinical trials, respectively. The remaining two studies had lower evidence levels of 4a (descriptive study) and 5b (decision analysis). The lowest rated study (Vuillermin et al. 2011) was conducted well and reported results with high clinical significance, but did not apply directly to our question of interest. It should be noted that the highest evidence levels of 1a and 1b were excluded from this study since we did not include systematic reviews or meta-analyses, which are the only study types included in evidence level 1.

DISCUSSION

In the decade since our last review, the volume of studies pertaining to human gait analysis has increased almost 10-fold. This illustrates the growing use of 3DGA as both a clinical and research tool. Previously, over 100 studies were identified that dealt with technical efficacy (type 1). Three times as many have been published in the last decade, reflecting continued and accelerating development and improvement of technology, data collection and analysis methodology. Research has also increased pertaining to the clinical aspects of gait analysis efficacy. The vast majority of studies in the current review used 3DGA to increase understanding of gait in different groups and/or the effects of treatments on gait (type 2 and 2b). This highlights an important role of 3DGA in defining diagnostic groups and understanding expected treatment outcomes for different types of patients.

The large number of studies of types 2 and 2b (total of 2,393) in the current review compared with our original review (total of 78) reflects our increasing understanding of the importance of these types of studies. Diagnostic accuracy is enhanced by knowledge of which gait characteristics differentiate between groups and how gait characteristics relate to each other and to other participant characteristics such as sex, age, diagnosis, or disease severity. Treatment outcomes can also be critically evaluated and improved over time through systematic and objective review of pre- versus post-treatment outcomes. Much of the literature has focused on post-operative status only, which does not provide the same depth of understanding into treatment effects. Type 2 and 2b studies help us understand the biomechanics contributing to treatment outcomes at the joint level. For example, in patients who toe-walk, the resulting tripping and falling may be caused by excessive plantarflexion of the ankle during the stance and swing phases of gait. This joint level understanding cannot be obtained from general measures of activity and participation; it is critical to help explain why patients may differ from typically developing peers or why more general outcomes like activity monitoring or walking speed change over time.

Nine new studies related to higher types of efficacy (3-4 and 5) have been published since our last review. Six addressed the effects of 3DGA on diagnostic thinking and treatment planning (type 3-4). These studies support the findings of 11 studies of this type from the previous review period. The evidence clearly demonstrates the efficacy of 3DGA in changing and reinforcing treatment decision-making in multiple patient populations. There is also strong evidence of efficacy of 3DGA for accurately defining gait problems and their causes (such as in-toeing and crouch) and prescribing appropriate treatments (e.g., surgery versus non-surgical treatment or type of surgery). The use of 3DGA data also increases clinicians' confidence in their treatment planning [8, 13] and improves agreement among different clinicians [13, 17]. The new studies on this topic include a randomized controlled trial, further elevating the level of evidence and quality of research supporting the efficacy of 3DGA in diagnostic thinking and treatment planning.

Three new papers addressed the impact of gait analysis on treatment outcomes for individual patients (type 5). Two derived from the same randomized controlled trial of children with CP who were being evaluated for lower extremity orthopaedic surgery. This analysis clearly showed superior outcomes when 3DGA recommendations for FDRO were both received and followed. Outcomes were inferior when the gait report was not received or was received but not followed. The low adherence to the 3DGA recommendations in this trial was atypical. For clinical referrals to the same gait laboratory, 77% of 3DGA recommendations were followed by physicians from outside the institution [11]. Possible reasons for not following gait analysis recommendations identified in previous research include independent clinical or radiographic evaluation, intraoperative assessment, changes in function between gait analysis and surgery, and patient/family request [18]. Implementation of 3DGA recommendations may also have been hindered by the challenge of understanding the difference between visual assessment of gait and 3DGA [19].

Transverse plane problems are particularly difficult to assess visually. Several studies indicated that 3DGA is particularly helpful in evaluating flexed knee gait and rotational problems [10, 12, 15, 20, 21]. Visual assessment of where the knees and feet are “pointing” can lead to erroneous conclusions about transverse plane function. Objective 3D kinematic data for the pelvis, hip, knee, and foot progression are needed to fully understand the complex interaction of joint and segment position and motion that contribute to rotational gait deviations. Overreliance on visual assessment can lead to suboptimal treatment decision-making and outcomes. The barriers to interpreting 3DGA data and implementing gait analysis recommendations should be further explored.

No new studies were found addressing the societal (cost-benefit) efficacy of gait analysis (type 6). This is not a common area of study since our previous review also identified only one paper on this topic [22]. The study found that patients with CP who had undergone 3DGA before their initial surgery required less subsequent surgery because more procedures were performed initially. Essentially, a similar total amount of surgery was done, but 3DGA enabled more procedures to be done initially avoiding additional disruption to patients’ lives due to subsequent surgeries.

The study by Vuillermin et al. was difficult to classify and generated considerable discussion among the reviewers. The study involved a population-based retrospective cohort of patients from the Australian Cerebral Palsy Register who underwent 3DGA between 1995-2009. 3DGA became standard of practice in Australia in 1995 and was used as an outcome assessment tool in this study. Those evaluated early in the study period had undergone treatment without pre-operative 3DGA, while those evaluated in later years received treatment informed by 3DGA. All reviewers agreed that the paper provides strong support for the clinical importance, and therefore efficacy, of 3DGA. The primary finding was that the prevalence of severe crouch gait declined dramatically, from 25% to 4%, over the 15-year study period, subsequent to the introduction of 3DGA. Severe crouch is one of the most common gait problems affecting the CP population and increases with age and growth [23, 24], likely leading to cessation of walking over time for many patients. Prevention of crouch gait would vastly improve quality of life for patients with CP and their caretakers.

The difficulty with the Vuillermin et al. study was that its design did not directly address the issues of interest to this systematic review. Seven patient management factors changed in 1995, of which the addition of 3DGA, single-event multi-level surgery (SEMLS), and replacing tendo-Achilles lengthenings with gastrocnemius recessions were identified by the authors as being the most impactful. The authors reasoned that the routine use of 3DGA enabled the changes in surgical practice patterns which dramatically improved long-term outcomes for many patients, as exemplified by the significant reduction in severe crouch gait. We agreed with this assessment, but noted that the improved outcomes could not be attributed specifically to 3DGA since multiple changes in practice patterns occurred simultaneously. In addition, outcomes were analyzed based on the time of outcome assessment and were not available based on whether 3DGA was used in treatment planning. It was therefore difficult to assess this study with respect to our types of efficacy. Nevertheless, it is clear that this paper supports, at least indirectly, the efficacy of 3DGA.

The strength of evidence for the studies in efficacy types 3-4 and 5 mainly fell into evidence level 3b (lesser quality prospective cohort studies), but also included stronger studies (two at level 2a and one at 2b). This reflects an increase in the quality of evidence produced since our previous review, in addition to the greatly increased quantity of evidence.

It should be noted that higher evidence levels were not possible in the current study since we excluded review articles which are the only study design capable of reaching evidence level 1. Our previous systematic review represents a study at evidence level 1b. It is possible that other systematic reviews or meta-analyses also provide level 1 evidence but were not captured by our methodology.

The current systematic review was limited to gait analysis during walking using traditional 3DGA techniques. This was necessitated by the large number of studies published and the need to define a reasonable scope for the review; it is also consistent with our previous review. Motion analysis is increasingly used to analyze movements beyond walking including other functional tasks (sit-to-stand, return to sport tasks such as drop vertical jump and hopping, etc.). These applications can provide useful clinical information not available through traditional assessments. The body of literature supporting the use of instrumented motion analysis in these applications is well underway, but was not systematically assessed in this paper. There is increasing interest in alternative technologies for quantifying movement, particularly lower cost and mobile technologies, which are often benchmarked against 3DGA for validation.

In summary, this update to our previous systematic review demonstrates increased utilization of 3DGA, new and higher quality studies supporting the efficacy of 3DGA in diagnostic thinking, treatment planning, and improving patient outcomes, and a continuing need for research examining cost-effectiveness at a societal level. Gait analysis clearly influences treatment planning in multiple patient populations and can lead to better outcomes when properly used. Recommendations for future research include large, high quality studies examining patient-level surgical outcomes from single-event multilevel surgery, controlling for use of and adherence to the recommendations of 3DGA, and additional cost-effectiveness studies evaluating whether 3DGA reduces health systems utilization, decreases cost, and improves quality of life. Future research should also include assessment of emerging technologies, examination of other patient populations, and broader application of motion analysis beyond gait.

Conflict of Interest Statement

The authors have no conflicts of interest to declare. No funding was received for this project.

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Table 1. Types of efficacy

Efficacy Type (Numeric)	Efficacy Type	Description	Examples
1	Technical	Physical process of obtaining data, including accuracy and reliability of equipment & procedures used in data collection	• Accuracy & reliability studies • Data collection methods development • Marker placement, anthropometric measurements, joint center location, models, processing methods
2	Diagnostic accuracy	Data interpretation, including performance in classifying patients & making diagnoses, interpreting data, identifying measures predictive of good or bad outcomes for specific treatments	• Comparing groups & identifying gait analysis parameters that distinguish between groups • Methods to improve interpretation of gait data • Evaluating relationships between gait measures and other gait measures or subject characteristics
2b	Outcome prediction	Gait analysis used to evaluate the efficacy of treatments at group level	• Identifying parameters that differentiate patients likely to have better or worse outcomes for a treatment • Effects of treatment • Comparing different treatments
3-4[a]	Diagnostic thinking & treatment	Impact of gait analysis on treatment decision-making and the treatment actually done for individual patients	• Change in treatment plan • Reinforcement of treatment plan • Difference between treatment done and original treatment plan • Confidence in treatment decisions • Agreement among different clinicians
5[a]	Patient outcome	Effect on outcomes for individual patients	• Outcome studies controlled for whether gait analysis data are used in treatment planning
6	Societal	Cost effectiveness or cost-benefit analysis from societal viewpoint	• Cost-benefit analysis

[a] These focus on efficacy in individual patients.

Table 2. Articles addressing higher types of efficacy

Efficacy Type (Numeric)	Efficacy Type	References	Evidence Level
3-4	Diagnostic thinking & treatment	Wren et al., Influence of gait analysis on decision-making for lower extremity orthopaedic surgery: baseline data from a randomized controlled trial. Gait Posture 34, 364-369, 2011.	2a
		Wren et al., Differences in implementation of gait analysis recommendations based on affiliation with a gait laboratory. Gait Posture 37, 206-209, 2013.	4a
		Franki et al., A clinical decision making framework for the identification of main problems and treatment goals for ambulant children with bilateral spastic cerebral palsy. Res. Dev. Disabil. 35, 1160-1176, 2014.	3b
		Ferrari et al., Gait analysis contribution to problems identification and surgical planning in CP patients: an agreement study. Eur. J. Phys. Rehabil. Med. 51, 39-48, 2015.	3b
		Ferrarin et al., Does gait analysis change clinical decision-making in poststroke patients? Results from a pragmatic prospective observational study. Eur. J. Phys. Rehabil. Med. 51, 171-184, 2015.	3b
		Mueske et al., Impact of gait analysis on pathology identification and surgical recommendations in children with spina bifida. Gait Posture 67, 128-132, 2019.	3b
5	Patient outcome	Wren et al., Outcomes of lower extremity orthopaedic surgery in ambulatory children with cerebral palsy with and without gait analysis: results of a randomized controlled trial. Gait Posture 38, 236-241, 2013.	2a
		Wren et al., Impact of gait analysis on correction of excessive hip internal rotation in ambulatory children with cerebral palsy: a randomized controlled trial. Dev. Med. Child Neurol. 55, 919-925, 2013.	2b
		Vuillermin et al., Severe crouch gait in spastic diplegia can be prevented: a population-based study. J. Bone Joint Surg. Br. 93, 1670-1675, 2011.	5b
6	Societal	None	

Figure 1. Review flowchart