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Three-Dimensional Motion Analysis for Occupational Therapy Upper Extremity Assessment and Rehabilitation: A Scoping Review

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Three-Dimensional Motion Analysis for Occupational Therapy Upper Extremity Assessment and Rehabilitation: A Scoping Review

Abstract

Background: Three-dimensional (3D) human motion analysis provides objective, quantitative, and reliable kinematic data that are valuable in rehabilitation. Clinicians, including occupational therapists and other specialists, can apply this technology to quantify patients' upper extremity (UE) motion during functional tasks. A better comprehension of altered body mechanics serves to guide clinical reasoning, develop evidence-based interventions, and monitor patients' progress through follow-up. However, the scientific literature has yet to emphasize the practicality of using 3D motion analysis as a clinical measurement tool.

Method: This scoping review appraised 20 articles that used 3D motion analysis to quantify UE movements for individuals with and without mechanical pathologies. The articles were evaluated based on their quality and clinically relevant applications of UE kinematics.

Results: This scoping review revealed that 3D motion analysis has already been implemented in rehabilitation but the variability across protocols and facilities can complicate the comparison of results.

Conclusion: To further expand clinical use of 3D motion analysis, an introduction of more accessible, inexpensive, and user-friendly kinematic systems is critical. Future research should also aim to establish a standardized protocol of 3D motion analysis in UE assessments to produce clinically relevant results and maximize patients' independence when engaging in daily activities.

Comments

The authors declare that they have no competing financial, professional, or personal interest that might have influenced the performance or presentation of the work described in this manuscript.

Keywords

activities of daily living, kinematics, motion analysis, occupational therapy, rehabilitation, upper extremity

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Three-dimensional (3D) human motion analysis uses a calibrated set of two or more digital cameras to calculate the spatial coordinates of markers placed on specific locations of the body, such as bony landmarks. The yielded kinematic data can be used to compare body segment angles and relative joint angles during functional tasks in individuals with normal physical function or with upper extremity (UE) impairments to understand further the efficacy of assessments and interventions in rehabilitation (Valevicius et al., 2018).

According to the *Occupational Therapy Practice Framework: Domain and Process* (American Occupational Therapy Association [AOTA], 2020), activities of daily living (ADLs) are basic activities necessary to care for oneself and survive, such as bathing, feeding, and dressing. Instrumental activities of daily living (IADLs) are activities that support daily functioning in the home and community, such as meal preparation, care of others, and home management. However, many individuals experience difficulties performing functional ADLs and IADLs tasks requiring them to reach, grasp, or manipulate objects as a result of UE neuromuscular disorders, musculoskeletal injuries, and other related disorders.

Three-dimensional motion analysis can be employed clinically to enhance the understanding of altered body movements and motor control mechanisms as a result of UE-related injuries to better inform and plan rehabilitation interventions (Jaspers et al., 2011; Klotz et al., 2014). Two-dimensional motion analysis using a single motion camera may be considered convenient with current smartphone and electronic tablet applications; however, it is susceptible to parallax error, especially in the multi-axial motion of many occupational tasks. Three-dimensional motion analysis enables clinicians and researchers to capture the complex motion of the upper limb with anatomically-defined axes of rotation and to quantify ongoing progress during functional tasks (Fritz et al., 2017). Performing 3D motion analysis in healthy individuals is also clinically important, as these detailed kinematic parameters of UE functions can be used to establish protocols and serve as a normative reference and a basis for subsequent comparison of participants from clinical populations (Gates et al., 2016; Jaspers et al., 2011; Valevicius et al., 2019; van Andel et al., 2008).

Various types of marker sets are widely used in 3D motion analysis. Active markers directly emit infrared light that allows motion capture cameras to identify and track anatomical locations during movement and locomotion. Passive, reflective, or retroreflective are covered in retroreflective materials, which reflect light from an array of infrared light-emitting diodes back to the camera lens it surrounds. Markers may also be classified according to how they are placed on the participants’ bodies: bony anatomical landmarks identified with individual markers or body segments tracked using rigid clusters of three or more markers (Caimmi et al., 2008; Engdahl & Gates, 2018; Janssen et al., 2017).

Three-dimensional motion analysis of the UE involves tracking anatomical landmarks and body segments to document the contributions of motion of the joints involved in performing a functional task, according to the structure of the clinical anatomy. The motion is resolved to anatomical axes of rotation; for example, trunk movements, including forward flexion/extension, lateral flexion/extension, and rotation, are often used to compensate for UE impairments during functional tasks (Alt Murphy et al., 2011; Fitoussi et al., 2011; Webber et al., 2018). Although motor controls of the forearm and hand may not elicit trunk movements, motions of the trunk may assist in postural stabilization in the transport of objects (Kaminski et al., 1995).

Various kinematic parameters can contribute to the analysis of UE movement characteristics. Execution of functional tasks can be divided into specific phases. Each phase and the entire movement can be quantified further with kinematic measures, including peak velocity, time to peak velocity, and mean velocity. Quality of control and smoothness of movement can be analyzed with various metrics, such as local minima and maxima of tangential velocities and average jerk (i.e., change in acceleration). Endpoint scores describe the quality of performance in terms of precision of target reaching. Index of curvature, the ratio of the length of the actual 3D trajectory of a marker during a reach to the straight line connecting the starting point and ending point, can be applied to hand motion (Artilheiro et al., 2014), or trunk compensation (Alt Murphy et al., 2011; de Sire et al., 2019). The functional range of motion (i.e., the difference between the maximum and the minimum angle of a particular joint during the whole movement) can be compared to clinical endpoint values for that joint.

Purpose of the Scoping Review

Three-dimensional motion analysis is already an established measurement clinical and research tool, particularly in gait; however, the current literature has yet to review the application of this technology in the context of occupational therapy. Although goniometers are inexpensive and convenient for measuring static joint angles, assessed changes may be inconsistent because of low repeatability and reliability (Reissner et al., 2019). Therefore, the purpose of this scoping review is to highlight the potential integration of 3D motion analysis for the clinical care of individual patients. This paper aims to summarize methodologies and overall findings of the included studies to illuminate the practicality and efficacy of using 3D motion analysis in occupational therapy using the following factors: (a) purposes of using motion analysis in rehabilitation, (b) identification of primary movement abnormalities and secondary compensations, (c) internal and external validity of studies, and (d) relationships of kinematic measures to standard clinical measures.

Method

Because of the highly variable descriptions of terminologies appearing in the articles included in this scoping review, the definitions are clarified in Table 1:

Table 1
Definitions or Alternate Terminology

Terminology	Definition or Alternate Terminology
(Absolute) body segment angle	The posture of a modeled portion of the body with respect to an external reference, such as the vertical axis of the laboratory coordinate system, e.g., trunk angle.
Functional tasks	Activities or actions that are specific, support, or related to occupations.
Linked body segments	Employed in motion analysis to model the human body, e.g., head, trunk, (upper) arm, forearm, and hand.
Participants	Individuals who have read and signed an informed consent form (approved by the institutional review board) to participate voluntarily in human subject research.
Patients/clients	Individuals who may be diagnosed with a medical condition and may be under the care of health care professionals.
Relative joint angle	The inclination of one body segment with respect to the adjacent proximal segment, e.g., the elbow angle is the angle of the forearm relative to the (upper) arm.
Upper extremity/upper limb	The body segments from the glenohumeral joint to the fingertips, including the shoulder, (upper) arm, forearm, and hand.

Search Strategy

Articles were acquired through database searches of CINAHL, PubMed, Archives of Physical Medicine and Rehabilitation, and EBSCOhost in June 2020. Search terms were used in the article selection process, including kinematic analysis, kinematic, motion analysis, motion capture, three-dimensional motion analysis, movement analysis, quantitative, clinical protocol, clinical diagnostic, diagnostic testing,

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diagnostic, testing, arm, upper limb, upper extremity, upper extremity rehabilitation, upper limb rehabilitation, rehab, occupational therapy, activities of daily living, cerebral palsy, weakness, abnormal movement, and healthy.

Eligibility Criteria

Articles were included based on all of the following criteria: (a) published in the English language, (b) tasks that primarily involved the use of at least one upper limb, and (c) used 3D motion analysis. Articles were excluded based on at least one of the following criteria: (a) published before the year 2000, (b) used only one motion capture camera for data collection, (c) employed either only one- or two-dimensional motion analysis because of the multi-axial movements in occupational tasks, (d) solely included a clinical protocol, and (e) recorded all kinematic data on the lower extremity.

Data Extraction and Quality Review

The quality of studies was determined by the Critical Appraisal of Study Design for Psychometric Articles Evaluation form (Law & MacDermid, 2008). Each article was scored for eight criteria on a scale from 0 to 2. A score of 0 indicates the article did not meet the criterion, a score of 1 suggests the paper partially met the criterion, and a score of 2 implies the research fully met the criterion. The total quality percentage for each criterion was calculated by dividing the number of articles that obtained a score of 2 by the total number of articles. The eight study characteristics were: (a) relevant literature (i.e., citations of pertinent and adequate background information to establish a foundation for the research question), (b) inclusion/exclusion criteria (i.e., key features of the target population studied or characteristics of disqualification for the studies), (c) retention (i.e., retesting or follow-up measures, if intended), (d) detailed measurement techniques (i.e., specific descriptions of techniques used for data collection), (e) standardized measurement procedures (i.e., use of standardized quantifying methods to minimize sources of error or misinterpretation of metrics), (f) analyses of data (i.e., administration of data analysis relating to research hypothesis or purpose), (g) use of statistical tests (i.e., appropriate statistical tests performed to attain metric properties), and (h) clinical recommendations or conclusions (i.e., specific conclusions and clinical recommendations clearly relate to the objective of research and are supported by data).

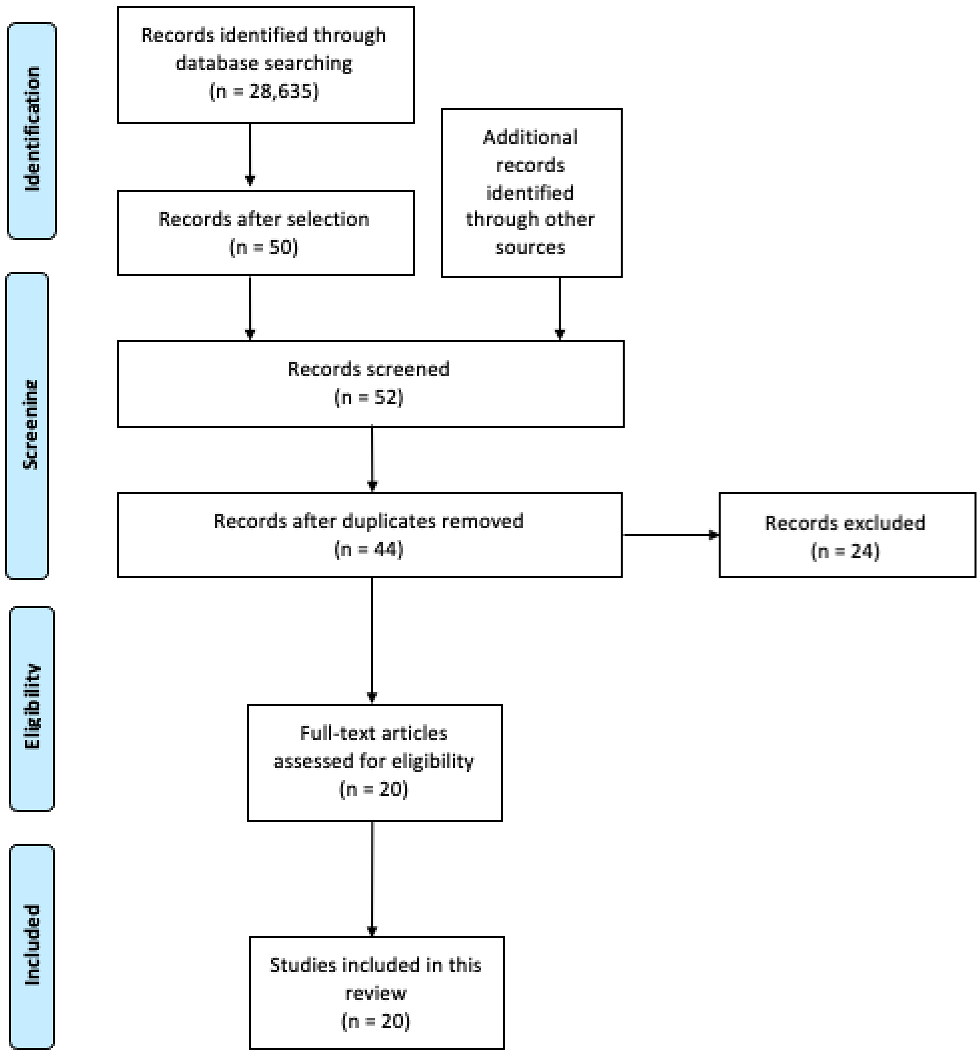
In addition, this scoping review extracted data based on the following: (a) health status of study participants, (b) functional tasks performed during studies, (c) information about motion capture systems, (d) body segments examined, (e) joint movements inspected, and (f) findings summary of each article.

Results

Study Selection and Characteristics

Using the keywords stated, 28,635 papers were identified through database searching. The search was further narrowed down using various combinations of keywords to increase the relevance of records, and 50 papers were selected for initial screening. Two papers were included through manual search, and eight duplicates were removed, yielding 44 full-text articles. Twenty-four articles were removed based on the exclusion criteria, resulting in 20 articles being included in this scoping review. A flow diagram of the study selection is presented in Figure 1.

Figure 1
Flow Diagram Illustrating the Process of Scientific Article Selection



Data Extraction and Quality Review

Quality review scores were given to each of the 20 articles using the Critical Appraisal of Study Design for Psychometric Articles Evaluation form (Law & MacDermid, 2008). All articles analyzed included relevant literature, such as citations and background information from credible literature sources. With regard to the methodology of each study, 65.0% of articles provided detailed information regarding the inclusion and/or exclusion criteria of their study, 55.0% delineated detailed measurement techniques, including specific information about anatomical landmark marker placements that allows precise reproducibility. Each article used standardized measurement techniques in the specific study. Out of 20 articles, nine that involved two or more visits discussed retention, but only 77.8% of those reported a reliable retention rate of participants. Meanwhile, the participants' retention criteria were irrelevant to the remaining 11 articles because they only involved a single visit for 3D motion analysis. Data analyses were conducted by all researchers, and 90% of articles provided appropriate statistical tests. All articles included specific clinical recommendations related to the objective of the research.

Types of Diagnoses, the Functional Tasks Studied, and Motion Capture System Used

Table 2 (see Appendix A) details the specific methodology executed by each of the 20 articles, including the health status of the population, tasks, motion capture systems, body segments, and joint movements examined.

Populations Examined Across Research

Six articles studied only healthy or typically developing individuals with no UE deficiencies (Engdahl & Gates, 2018; Gates et al., 2016; Jaspers et al., 2011; Petuskey et al., 2007; Valevicius et al., 2019; van Andel et al., 2008). Ten articles examined both healthy individuals and patients with one of the following diagnoses: CVA, cerebral palsy (CP), rotator cuff tear, Duchenne muscular dystrophy, or brachial plexus injury (e.g., Alt Murphy et al., 2011; Aprile et al., 2014; Artilheiro et al., 2014; see Table 2). Four articles investigated CVA, progressive MS, and CP individually in their studies (Alt Murphy et al., 2012; de Sire et al., 2019; Simon-Martinez et al., 2020; Wu et al., 2007).

Tasks Involved in Studies

Fifteen articles involved real or simulated ADLs or IADLs, such as drinking, combing hair, eating, and cleaning (e.g., Klotz et al., 2014; Petuskey et al., 2007; van Andel et al., 2008; see Table 2). The remaining five articles studied specific tasks, including reaching, grasping, and gross motor tasks (Caimmi et al., 2008; Jasper et al., 2011; Merdler et al., 2013; Simon-Martinez et al., 2020; Valevicius et al., 2019).

Motion Capture Systems Used

Several 3D motion capture systems were used in the examined studies. Out of the 20 articles, nine employed a Vicon system (e.g., Klotz et al., 2014; Valevicius et al., 2019, Wu et al., 2007; see Table 2), three articles used a ProReflex system (Alt Murphy et al., 2012; Alt Murphy et al., 2011; Merdler et al., 2013), and two articles used a Motion Analysis Corporation system (Engdahl & Gates, 2018; Petuskey et al., 2007). Meanwhile, each of the following motion capture systems was represented by only one article in this scoping review: SMART system (Aprile et al., 2014), Optotrak (van Andel et al., 2008), and Raptor (Webber et al., 2019). One article did not report the type of 3D motion capture system used (see Table 2). A variation of the type of markers employed was seen across 20 studies. One study used active LED markers (van Andel et al., 2008). Fourteen articles used passive, reflective, retroreflective, or passive reflective markers (Alt Murphy et al., 2011; de Sire et al., 2019, Webber et al., 2019; see Table 2), and five articles did not report the types of markers used (see Table 2).

Body Segments and Joint Movements Studied

The research questions of particular articles determined the body segment included in the UE motion analysis: head or neck, trunk, pelvis, arm, forearm, and hand. All articles provided information regarding the body segments investigated. Of the 20 articles examined, 90.0% reported detailed information on joint movements investigated. Table 3 (see Appendix B) highlights the overall findings of each paper included in the scoping review. Instead of including the vast number of individual numerical results from each study, overarching meaningful principles established by each paper are delineated.

Discussion

This paper aimed to summarize methodologies and overall findings of several high-quality studies to illuminate the practicality and efficacy of using 3D motion analysis in occupational therapy using the following factors: (a) health status of study participants, (b) functional tasks performed during studies, (c) information about motion capture systems, (d) body segments examined, (e) joint movements inspected, and (f) findings summary of each article. Comparison of results across studies and groups, such as pathological and normal populations, is strengthened by consistent definitions of joint and body segment kinematics. Therefore, the purpose of this scoping review is to highlight the potential integration of objective 3D motion analysis for the clinical care of individual patients.

Purposes of Using Motion Analysis in Rehabilitation

This scoping review of literature has identified four emerging benefits of using 3D motion analysis in rehabilitation, which can be applied in occupational therapy. First, UE motion analysis of healthy individuals can allow clinicians to establish normative databases for UE movements based on standardized methodologies (Gates et al., 2016; Jaspers et al., 2011; Valevicius et al., 2019; van Andel et al., 2008). Understanding the typical motions required for ADL and IADL performance allows occupational therapists to develop personalized treatment goals for specific daily tasks. The movement patterns obtained through studying healthy individuals can also assist in identifying tasks that are more difficult for patients with a specific UE impairment, hence recommending compensatory strategies or modifications in the environment to facilitate patients' participation in ADLs (Gates et al., 2016).

Second, clinical researchers can identify motor control kinematic patterns exhibited in specific clinical populations (Alt Murphy et al., 2011; Aprile et al., 2014; Artilheiro et al., 2014; Janssen et al., 2017; Klotz et al., 2014; Merdler et al., 2013). Since UE muscle function usually deteriorates before occupational performance deficits are evident, early detection of functional decline is clinically important (Janssen et al., 2017). 3D motion analysis empowers occupational therapists to detect subtle abnormalities influencing performance of ADLs and IADLs, and then guide early intervention to prevent contractures, diminished muscle strength, undesirable movements, and ultimately functional decline in patients (Artilheiro et al., 2014; Janssen et al., 2017).

Third, clinicians can employ 3D motion analysis to investigate the effectiveness of current rehabilitation approaches for patients, including constraint-induced movement therapy (CIMT), action-observation training, and environmental modifications (Caimmi et al., 2008; de Sire et al., 2019; Simon-Martinez et al., 2020; Wu et al., 2007). Three-dimensional motion analysis provides objective, clinically relevant measures of occupational performance, which supports clinical decisions concerning the application of evidence-based and client-centered interventions.

Lastly, investigators can apply kinematic analysis to evaluate and compare other surgical and pharmacological interventions performed on patients with UE impairments, including botulinum toxin injection, rotator cuff repair, and burn scar contracture release, to enhance knowledge of the effect on patients' UE functions post-treatment (Fitoussi et al., 2011; Fritz et al., 2017; Webber et al., 2019). Occupational therapists can better understand and establish realistic expectations on the functional performance of patients who undergo other medical treatments, which may also guide the rehabilitation focus of the path of treatment sessions.

Clinical Application of Compensatory Movements

Patients with UE impairments often engage in secondary compensatory movements because of a limited range of motion or strength at specific joints, in contrast to healthy individuals (Fitoussi et al., 2011; Valevicius et al., 2019). Identification of these compensatory movements may assist clinicians in early detection of factors that impede patients' recovery process and prevent overuse injuries that could lead to additional disorders, injuries, or pain (Valevicius et al., 2019). For example, both Aprile et al. (2014) and Alt Murphy et al. (2011) analyzed and compared motor strategies exhibited in a drinking task by participants post-CVA and conclusively demonstrated that patients employed more trunk forward flexion to compensate for their motor deficits. Trunk displacement was also observed to be significantly correlated with the severity of stroke impairment (Alt Murphy et al., 2011). In addition, children with hemiplegia CP who received botulinum toxin exhibited less compensatory trunk flexion in a similar drinking task than those who did not receive the treatment (Fitoussi et al., 2011). Exploration of secondary movements may enhance clinicians' understanding of abnormal and perhaps nuanced movement patterns exhibited by particular patient populations, which help to guide individualized, evidence-based treatment plans. Real-time 3D kinematic feedback has the potential to facilitate the identification of compensatory movements exhibited by patients, allowing clinicians to customize treatment during rehabilitation and engage patients in the process.

Clinical Application of Kinematic Measures

Of all 20 articles examined in this scoping review, 10 articles compared kinematic parameters and analyzed task performance between participants, with and without a medical diagnosis that involved the upper limb, aiming to pinpoint the extent of functional deficiencies (Alt Murphy et al., 2011; Aprile et al., 2014; Artilheiro et al., 2014; see Table 2). Five studies used the number of movement units (NMUs) as the basis for evaluating the efficiency and quality of motor performance (Alt Murphy et al., 2011; Alt Murphy et al., 2012; Aprile et al., 2014; Artilheiro et al., 2014; de Sire et al., 2019). NMUs specifically examine the number of local minimum and the maximum values of the hand velocity between two phases, the smaller number indicating better quality of movement (Alt Murphy et al., 2012; Aprile et al., 2014; Artilheiro et al., 2014; de Sire et al., 2019). For example, Artilheiro et al. (2014) revealed that adults with dyskinetic cerebral palsy (DCP), in comparison to healthy adults, showed differences in peak velocities, mean velocities, and time to peak velocity in a drinking task, implying the patients required more time to perform the ADL. In addition, the quality of movement by patients with DCP was found to be less smooth, as indicated by the index of curvature, average jerk, and NMUs. Alt Murphy et al. (2011) found that participants with mild and moderate CVA required more time to complete a drinking task in comparison to healthy individuals. The same patient population demonstrated less elbow extension during the reaching phase and more shoulder abduction during the drinking phase. Clinicians can employ kinematic parameters to identify the hallmarks of abnormal movements of individuals with UE impairments in comparison to those with normal physiological functions, to plan interventions and provide quantitative documentation.

Internal and External Validity of Studies

All of the included studies employed reflective markers placed on participants' anatomical landmarks for a 3D camera system to track movement kinematics. Alternatively, there are motion systems that employ 3D accelerometers attached to body segments; however, this type is not yet widely utilized for UE motion analysis. The focus of a particular study likely dictated the kinematic measures of interest, requiring particular anatomical markers to define body segments and joint angles tracked during the performance of motor tasks. Accordingly, protocols and points of reference used by researchers varied, leading to studies that explored similar functional tasks with variations in kinematic measures.

Within-session motion analysis yields higher repeatability compared to between-session due to variations of individual experimental set-up and marker placements (Engdahl & Gates, 2018), which could influence internal validity and external validity: how well performance was quantified and how applicable the findings of a particular study are to the larger population. This statement emphasizes the importance of standardized placement of markers on anatomical landmarks for 3D motion analysis.

Analysis approaches varied from article to article, which impacts the external validity of the conclusions of individual studies. For instance, some researchers analyzed a drinking task in terms of five phases: reaching for the glass, bringing it to the mouth, drinking, putting it back on the table, and returning the hand to the starting position (Alt Murphy et al., 2011; Alt Murphy et al., 2012). They defined the start of the transporting and returning phases as the times when tangential velocities of the glass exceeded 15 mm/s or under 10 mm/s, respectively (Alt Murphy et al., 2011; Alt Murphy et al., 2012). Conversely, Artilheiro et al. (2014) broke the drinking task into three phases: the going phase (lifting the mug to the mouth), the adjusting phase (drinking), and the returning phase (returning the mug to its initial position). That study identified the starting and ending point of each phase when the velocity was more or less than 50 mm/s, respectively (Artilheiro et al., 2014). These differences in criteria and extracted discrete measures are likely to result in issues of external validity pertaining to findings applicable to the general population.

Many of the studies analyzed in the present scoping review contained sample sizes ranging from eight to 50 participants. Hence, their findings may not be fully representative of a larger population. This scoping review suggests that larger sample sizes and more thorough descriptions of task protocols and data collection methods will enable future studies to improve external validity and perform cross-validation. Therefore, it may seem more convenient to reconcile the results of this wide range of studies if they had all employed the same definitions and measures; however, specific research questions of individual studies may have inspired particular approaches that, otherwise, may not have been brought to light.

Practicality of Upper Extremity 3D Motion Analysis

Three-dimensional motion analysis has gained increased attention among researchers and clinicians as a valuable tool to improve understanding of normal and pathological body movement and enhance clinicians' ability to perform assessments, plan interventions, and monitor patients' progress. It should be pointed out that standard clinical tests such as manual muscle testing and joint range of motion measures (such as with a goniometer) are still important to understand why a particular client may perform a specific UE motor task in the manner observed, but are not sufficient to be able to predict their success in task performance.

Three-dimensional motion analysis set-up time depends on user expertise and instrumentation complexity, which may impose barriers to the clinical adoption of the technology, particularly in facilities stressing high productivity. Papers in this scoping review did not discuss the set-up time for their specific research; however, it may take as much as 30 min based on 30 years of professional experience of one of the authors of the present paper (Hill). Precise placement of markers on anatomical landmarks is important to ensure the fidelity of calculating participants' movements during task performance. For 3D motion analysis to be clinically practical, the therapist must be proficient at navigating the complex operating software while managing other aspects of rehabilitation sessions. The cost of 3D motion analysis systems is high relative to traditional measurement tools; for example, a (minimal) 2-camera Vicon system could cost $12,500, whereas a well-equipped lab with 10 more cameras could cost over $150,000, which creates an obstacle to access in clinical settings (Markets and Markets, 2020). Therefore, a user-friendly motion analysis system for trained clinicians should be easy to learn, use, and maintain. The introduction of a low-cost, turnkey, portable 3D upper extremity analysis system specifically for functional assessment could facilitate widespread clinical adoption of the technology in rehabilitation. These clinical motion analysis results can then be easily included in the electronic health records and reported to insurance companies or third-party payers. The emergence of wearable systems employing inertial monitoring units (IMUs) (e.g., Chen et al., 2016) is a promising alternative to expensive multicamera systems. In addition, three-dimensional motion analysis combined with other emerging technologies such as virtual reality, game-based functional activities (Chen et al., 2016), and augmented reality has the potential to provide biofeedback in an immersive experience to enhance patient engagement and treatment efficacy.

Limitations

One limitation of this scoping review is that it exclusively focuses on using 3D motion analysis of the UE during functional tasks in rehabilitation; therefore, the findings may not be directly applicable to clinicians treating patients with lower extremity impairments. Another limitation is that although the studies in this scoping review covered a wide spectrum of diagnoses, functional tasks, and conclusions, many other UE movement disorders and functional tasks are not represented. Further investigations are needed to examine the benefits of kinematic analysis on other clinical populations with different functional deficits. Lastly, it may appear biased to include two articles from the same group of researchers (Alt Murphy et al., 2011; Alt Murphy et al., 2012); however, both articles were included because each made a distinct contribution to the body of knowledge regarding upper limb rehabilitation for patients who are post-stroke, and their methodologies have been incorporated into studies by other research groups (e.g., Aprile et al., 2014).

Conclusion

The objective of this scoping review was to explore the practical clinical applications of 3D motion analysis for patients with UE impairments. Initially, the intent was to focus on illuminating the practicality and efficacy of 3D motion analysis in occupational therapy specifically; however, on examination of these articles, it became clear that this scoping review should be broader to include other healthcare professions. In summary, 3D motion analysis offers a quantitative method to assess upper limb motion during functional tasks and has been used by researchers and clinicians, yielding a variety of benefits. Therefore, clinicians must consider this phenomenon when recording task performance. This technology may improve the understanding of biomechanical and kinematic changes in patients related to diagnoses, surgeries, or other clinical interventions. However, the availability of motion analysis systems that are more economical, easier to operate, and portable will increase the feasibility of large-scale implementation of this technology across different rehabilitation disciplines. Further development should aim to establish standardized procedures for clinical UE 3D motion analysis collection and reporting, allowing for comparable results across patients and rehabilitation facilities. Clinical specialty programs, such as occupational therapy schools and continuing education courses, are encouraged to incorporate 3D motion analysis in the curricula, preparing clinicians to be life-long learners by adopting technological advancements to promote innovative and patient-centered care.

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Appendix A

Table 2

Description of Participants' Health Status, Tasks, Motion Capture Systems, Body Segments, and Joint Movements Included

Authors (year)	Health status	Tasks	Motion capture systems brand (marker type)	Body segments	Joint movements
Alt Murphy et al. (2011)	CVA, healthy	**ADL:** *drinking*.	ProReflex MCU240 (P)	Thorax, right arm, forearm, hand	**Shoulder:** *flex/ext, abd/add.* **Elbow**: *flex/ext*.
Alt Murphy et al. (2012)	CVA	**ADL:** *drinking*.	ProReflex (P)	Thorax, right arm, forearm, hand	**Shoulder:** *flex/ext, abd/add.* **Trunk:** *Forward flexion.* **Elbow:** *flex/ext*.
Aprile et al. (2014)	CVA, healthy	**ADLs:** *drinking*. **Reaching tasks**	SMART system (P)	Head, trunk, UA, forearm, hand	**Trunk:** *axial rotation, forward flex* **Elbow:** *flex/ext*.
Artilheiro et al. (2014)	CP, healthy	**ADL:** *drinking*.	Vicon MX 40 (P)	Head, trunk, UA, forearm	**Shoulder:** *flex/ext, abd/add, internal/external rotation.* **Elbow:** *flex/ext, pro/sup*.
Caimmi et al. (2008)	CVA, healthy	**Reaching tasks**	3D optoelectronic movement analysis system (P)	Arm, forearm	**Shoulder:** *flex/ext.* **Elbow:** *flex/ext*.
de Sire et al. (2019)	Progressive multiple sclerosis	**ADLs:** *brushing hair*. **Daily tasks:** *putting and removing a pen, turning over pages and cards, etc.*	Vicon 460 (P)	Head, trunk, arm, forearm, hand	Hand trajectory
Engdahl & Gates (2018)	Healthy	**ADLs:** *hygiene, drinking*. **Daily task:** *turning a doorknob*. **IADL:** *cleaning.* **Work-related tasks**	Motion analysis corporation system (P)	Trunk, arm, forearm, hand	**Shoulder:** *elevation, internal/external rotations.* **Trunk:** *forward and lateral flex, rotation.* **Forearm:** *pro/sup.* **Elbow:** *flex/ext.* **Wrist:** *flex/ext, radial/ulnar deviations*.
Fitoussi et al. (2011)	CP, healthy	**ADLs:** *drinking*. **Daily task:** *moving an object*.	Vicon (P)	Trunk, arm, forearm, hand	**Shoulder:** *flex/ext, abd/add, internal/external rotations.* **Trunk:** *axial rotation, bending, flex/ext.* **Elbow:** *pro/sup, flex/ext.* **Wrist:** *flex/ext, radial/ulnar deviations*.
Fritz et al. (2017)	Healthy, rotator cuff tear	**ADLs:** *combing hair, drinking*. **Daily task:** *pushing a door open/closed*. **Reaching tasks**. **Work-related tasks**	Vicon (P)	Thorax, UA, forearm, hand	**Thoracohumeral:** *flex/ext, abd/add, internal/external rotations.* **Thorax:** *flex/ext, lateral bending, axial rotation*.
Gates et al. (2016)	Healthy	**ADLs:** *toilet hygiene, dressing, drinking*. **Daily tasks:** *moving items, reaching for back pocket*	NR (P)	Trunk, pelvis, UA, forearm, hand	**Shoulder:** *elevation, plane of elevation, internal/external rotations.* **Elbow:** *flex.* **Forearm:** *pro/sup.* **Wrist:** *flex/ext, ulnar/radial deviations*.
Janssen et al. (2017)	Duchenne muscular dystrophy, healthy	**ADLs:** *drinking*. **Reaching task**	Vicon (P)	Shoulder, forearm	**Shoulder:** *flex, abd, horizontal add.* **Elbow:** *flex/ext*. **Forearm:** *pro/sup*. **Wrist:** *flex/ext, radial/ulnar deviations*.
Jaspers et al. (2011)	Healthy	**Reaching, grasping, gross motor tasks**	Vicon (P)	Trunk, scapula, humerus, forearm, hand	**Shoulder:** *elevation, plane of elevation, rotation*. **Trunk:** *flex, lateral flex, rotation*. **Elbow:** *flex, pro/sup*. **Scapula:** *tilting, lateral/medial rotations, protraction/retraction*. **Wrist:** *flex, radial/ulnar deviations*.

Authors (year)	Health status	Tasks	Motion capture systems brand (marker type)	Body segments	Joint movements
Klotz et al. (2014)	CP, healthy	**ADLs:** *drinking, eating.* **Daily tasks:** *unlocking a door, moving items.* **Reaching task**	Vicon-M-series (P)	Shoulder, forearm	**Shoulder:** *flex/ext, abd/add, internal/external rotations.* **Elbow:** *flex/ext.* **Forearm:** *pro/sup*.
Merdler et al. (2013)	CVA, healthy	**Reaching tasks**	ProReflex (P)	Trunk, shoulder, arm	**Shoulder:** *flex/ext, horizontal abd/add.* **Elbow:** *flex/ext.*
Petuskey et al. (2007)	Healthy	**Simulated ADLs:** *personal hygiene, grooming*. **Daily tasks:** *reaching for a shelf, receiving an object, waving, throwing*.	Motion analysis corporation system (P)	Head, trunk, upper extremity	**Neck:** *forward flex, lateral flex, rotation*. **Shoulder:** *flex, abd, external rotation*. **Trunk:** *forward flex, lateral flex, rotation*. **Elbow:** *flex*. **Forearm:** *pro*. **Wrist:** *flex, radial deviation*.
Simon-Martinez et al. (2020)	CP	**Play. IADL:** *cooking.* **Reaching, grasping tasks**	Vicon (P)	Trunk, acromion, UA, forearm, hand	**Scapula:** *tilting, protraction/retraction, medial/lateral rotation*. **Shoulder:** *elevation, elevation plane, internal/external rotation*. **Trunk:** *flex/ext, lateral flex, rotation*. **Elbow:** *flex/ext, pro/sup*. **Wrist:** *flex/ext*.
Valevicius et al. (2019)	Healthy	**Reaching, grasping, transporting tasks**	Vicon Bonita (P)	Trunk, thorax, UA, forearm, hand	**Shoulder:** *forward flex, ext, abd/add, internal/external rotations*. **Trunk:** *forward flex, ext, lateral flex, rotation*. **Elbow:** *flex/ext*. **Forearm:** *pro/sup*. **Wrist:** *flex/ext, radial/ulnar deviations*.
van Andel et al. (2008)	Healthy	**ADLs:** *drinking, hygiene*. **Range of motion, reaching tasks**	Optotrak (A)	Shoulder, scapula	**Humerus:** *elevation, internal/external rotations with 90° abd*. **Scapula:** *lateral rotation*. **Elbow:** *flex/ext*. **Forearm:** *pro/sup*. **Wrist:** *palmar/dorsal flex*.
Webber et al. (2019)	Brachial plexus injury, healthy	**Simulated ADLs:** *feeding, dressing*.	Raptor (P)	Head, shoulder, scapula, trunk, pelvis, humerus, forearm, hand	**Elbow:** *flex/ext*. **Humeral thoracic and glenohumeral:** *elevation, plane of elevation, internal/external rotations*. **Scapulothoracic:** *anterior/posterior tilt, internal/external rotations, up/down rotations*. **Trunk:** *lateral bending, flex/ext, rotation*.
Wu et al. (2007)	CVA	**ADLs:** *drinking, hygiene.* **IADLs:** *cleaning.* **Reaching, moving tasks**	Vicon 370 (P)	Distal end of forearm	NR

Note. A = active; abd = abduction; add = adduction; ADL = activity of daily living; CP = cerebral palsy; CVA = cerebrovascular accident; ext = extension; flex = flexion; IADL = instrumental activity of daily living; P = passive; pro = pronation; sup = supination; UA = upper arm; NR = not reported

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Appendix B

Table 3

Results Summary of Each Study

Authors (year)	Summary of Findings
Alt Murphy et al. (2011)	Specific UE kinematic variables (i.e., number of movement units, total movement time, and peak angular velocity of elbow) could distinctly differentiate between participants who were healthy, with mild stroke, or with moderate stroke. It is proposed that the identified kinematic variables could provide objective UE motor assessment for patients post-stroke.
Alt Murphy et al. (2012)	The relationship between the movement kinematics of a drinking task (i.e., movement time, smoothness, and angular velocity of elbow and trunk displacement) and impairment or activity capacity level were measured and assessed for patients post-stroke. Kinematic measures obtained during drinking a task are strongly associated with activity capacity level. Movement time and smoothness, in addition to compensatory movement of the trunk, are valid measures to assess activity capacity and UE function for patients post-stroke.
Aprile et al. (2014)	3D motion analysis was used to analyze the motor strategies executed by patients post-stroke and healthy individuals when reaching and drinking from a glass. The results indicated that patients post-stroke utilize more compensatory strategies (i.e., trunk forward displacement and head movements) due to reduced elongation of the arm and trunk axial rotation.
Artilheiro et al. (2014)	Kinematic variables (i.e., smoothness of movement and peak velocity time) were used to analyze the performance of raising mugs to mouths among patients with dyskinetic cerebral palsy (DCP). The results indicated that using kinematic variables could help determine the extent of impairment in movements due to DCP.
Caimmi et al. (2008)	Kinematic data were collected during a hand-to-mouth and reaching task before and after two weeks of constraint-induced movement therapy (CIMT) among patients with chronic stroke. The results demonstrated improvements in the use of the affected UE, hand dexterity, speed of movements, and coordination after CIMT. In addition, it is demonstrated that 3D motion analysis is a sensitive assessment tool to evaluate motor recovery.
de Sire et al. (2019)	Kinematic parameters (i.e., normalized jerk, number of movement units, going phase duration, mean velocity, and endpoint error) were analyzed. The results indicated that participants with multiple sclerosis who received constraint-induced movement therapy exhibited significant improvement in the kinematic variables compared to the control group.
Engdahl & Gates (2018)	Healthy participants performed six activities of daily living in two separate sessions, and the recorded UE joint angles were used to establish within- and between-session reliability of motion analysis. The results indicated there is higher reliability within-session compared to between-sessions.
Fitoussi et al. (2011)	Significant kinematic changes were suggested in participants with cerebral palsy after botulinum toxin (Botox®, Allergan) treatment or surgery. They displayed improvement in forearm supination, wrist extension, elbow range of motion, and glenohumeral joint internal rotation and a decrease in trunk flexion/extension range of motion.
Fritz et al. (2017)	Compared to healthy individuals, participants who had undergone post-operative repair of the rotator cuff were found to complete ADLs within the same timeframe. They were only significantly limited in one task that required glenohumeral joint abduction and used thoracohumeral joint motions as compensation strategies, which were suggested by motion analysis.
Gates et al. (2016)	Healthy participants performed eight ADLs, and the UE range of motion obtained through motion analysis was used to establish a normative dataset for future evaluation of patients with UE impairments.
Janssen et al. (2017)	Using kinematic analysis to evaluate UE performance of participants with Duchenne muscular dystrophy, it is suggested that the active maximal joint angles are highly related to functional scales. Therefore, accurate monitoring of patients' active joint angles during goal-oriented tasks may help clinicians to initiate treatments earlier and minimize functional UE decline.
Jaspers et al. (2011)	The UE kinematics of healthy children had been investigated and used to establish a normative movement protocol, aiming to use in future evaluations of children with hemiplegic cerebral palsy when performing reaching, reaching-to-grasp, and gross motor tasks.
Klotz et al. (2014)	The kinematic results indicated that the restrictions in range of motion were pronounced in the forearm, and there was an increased trunk movement in children with unilateral cerebral palsy compared to healthy children.
Merdler et al. (2013)	Using the arm-plane parameters to describe the temporal and spatial characteristics of kinematic analysis, it was proposed that arm-plane measures were more sensitive than clinical tools to detect mild motor deficits and correlated with UE impairment in participants with cerebrovascular accidents.
Petuskey et al. (2007)	A normative database of kinematic values for specific ADLs (i.e., grooming, hygiene, and reaching for a shelf) was established for a normal pediatric population, which may be used for future comparisons with individuals with pathologies.
Simon-Martinez et al. (2020)	With the use of 3D motion analysis to examine motor control and kinematic movement patterns, the results indicated that there were limited benefits of adding action-observation training to constraint-induced movement therapy in children with unilateral cerebral palsy.

Authors (year)	**Summary of Findings**
Valevicius et al. (2019)	Kinematic variables (i.e., angular joint trajectories, peak angle, range of motion, and peak angular velocity) were used to establish a normative database for Pasta Box Task and Cup Transfer Task, which can help quantify secondary movements for patients with UE pathologies.
van Andel et al. (2008)	This study established a normative kinematic database of four representative ADLs, which presents a standard protocol for future researchers to compare values obtained from patients with UE impairments.
Webber et al. (2019)	Compared to healthy participants, individuals with brachial plexus injuries were found to display significantly greater trunk range of motion during feeding and dressing, followed by a limited glenohumeral joint external rotation.
Wu et al. (2007)	Kinematic variables (i.e., movement time, peak velocity, total displacement) were used to compare the effectiveness of constraint-induced movement therapy (CIMT) on motor strategies during a reaching task among patients who received CIMT and those who received traditional therapy post-stroke. The results indicated that patients who received CIMT exhibited improved motor strategies during a reaching task compared to those who only received traditional therapy.

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