

Research Article

Intra-limb Coordination and Control in Individuals with Stroke: Conceptual and Methodological Considerations

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Abstract

Background: A substantial amount of descriptive, rehabilitation and review research examined the behavioral (kinematic) nature of intra-limb organization in reaching and grasping actions in individuals who suffered a stroke. However, the majority of this work failed to explicitly address the level of movement organization affected, the conceptual relevance to existing theories of motor control, and the impact of different constraints on the emerging actions. Thus, the purpose was to examine whether the selected studies examined the issue in coordination and/or control, in the context of the existing conceptual frameworks. The second purpose was to delineate which individual and task constraints have been examined in previous work, and infer the degree to which these factors affected the nature of the emerging movement patterns.

Methods: The search of four databases (PubMed, Embase, Web of Science and CINAHL), including published work between January 2019 and March 2022, yielded twenty studies.

Results: Despite the fact that stroke substantially alters the emerging movement patterns majority of the studies examined issues in control, not coordination. In term of spatial and temporal control, the actions of individuals with stroke were slower and involved minimal use of the shoulder and elbow joints, as compared to their healthy counterparts. The analysis of emerging movement patterns, via inverse kinematics, showed that stroke resulted in segmented coordination between shoulder and elbow, while no studies examined the relations between distal anatomical structures (e.g., elbow and wrist). In terms of specific theories or models of motor control, most research was data-driven as only three studies made inferences to existing motor control theories (e.g., Equilibrium Point Hypothesis). In regards to the second purpose, time after stroke was the most impactful individual constraint which differentiated the nature of movement organization exhibited by those with and without stroke. The impact of variables such as gender and age, on performance of individuals with stroke, was not examined. From

the methodological standpoint, lack of measures of intra-individual variability represents an important limitation in rehabilitation research reviewed.

Conclusion: Collectively, the understanding of how individuals with stroke organize their actions remains equivocal. This is due to a variety of different methodological approaches used (e.g., forward vs. inverse kinematics), limited insight into critical aspects of movement organization (e.g., coordination) and the effects of key individual constraints (e.g., age/gender) on the nature of emerging movements. Also, the fact that data driven research still represents the primary impetus in this clinical field undermines the validity of the emerging inferences.

Keywords: Stroke; Coordination/Control; Intra-Limb Organization; Kinematics

Introduction

Stroke is the second leading cause of death among older adults, as well as the most prevalent neurological disability that negatively affects various aspects of daily-living, such as reaching and grasping [1]. From 1990 to 2019, the number of stroke

incidents increased by 70%, with most cases in males above 70 years of age [1,2]. Individuals with stroke exhibit a plethora of motor issues in upper and lower body parts which result in abnormal muscle tone, muscle weakness, and atypical postural adjustments. In addition, these motor impairments emerge in a proximal to distal gradient, meaning that muscles farther away from the trunk are more affected compared to those more proximally located [3]. One important side-effect of stroke, which is particularly debilitating during even seamlessly simple task such as reaching and grasping, is less than optimal intra-limb movement organization [4,5]. In line with the hierarchical model of organization, these issues may be attributed to less-than-optimal coordination or control [6]. In this context, the notion of coordination refers to the ability to produce functional patterning of the joints and segments that are both stable and functional, whereas control refers to the ability of the system to adapt to the changes in the emerging constraints. Thus, a person with stroke may exhibit more pronounced issues associated with less-than-optimal coordination, or he/she may retain the ability to produce the pattern but lose the ability to control it in face of changes to different constraints [7]. From the clinical stand-point, another important issue to be addressed is delineating the nature of the relationship between the different individual constraints such as time after stroke, age and gender in relation to the tasks being performed (e.g., reaching vs. pointing). To address these issues, research has used various kinematic approaches to behaviorally examine the nature of emerging actions. In the motor control literature, which focuses on intra-limb organization, these methodological kinematic approaches have been implemented in the context of well-established conceptual frameworks such as equilibrium point, uncontrolled manifold or the leading joint hypothesis [8-10].

Behavioral research involving kinematic analysis of intra-limb movement organization post-stroke gained impetus in the second half of the 1990s. To date, numerous descriptive and intervention-based research studies have been published. Also, numerous reviews have been published which provided a thoughtful and extensive overview of the nature of the emerging actions [11-13]. Nevertheless, some important issues still remain equivocal and require further overview. Thus, the purpose of this review was two-fold. The first purpose was to examine and systematically review the studies in relation to their conceptual scope, hence whether they examined the issue in coordination and/or control, and if that was accomplished via forward or inverse kinematics. The second purpose was to delineate which individual and task constraints have been examined, and their impact on the emerging intra-limb coordination/control.

Material and Methods

Search Strategy

A systematic literature search was performed to identify all relevant research articles. The primary search method involved electronic databases such as CINAHL PubMed, Medline, Web of Science and Google Scholar. To include literature since the last published systematic review each database was searched from January 1, 2019 until March 31, 2022 [13]. The search terms used included keywords such as “stroke”, “unimanual”, “coordination”, “upper limb”, “kinematics”, “reaching and grasping”, “pointing”. To be included in this review, each study had to focus on kinematic analysis of uni-manual reaching and grasping or pointing actions being performed by male and/or female participants who were at least 18 years of age, have been diagnosed with either hemorrhagic, ischemic, or Transient Ischemic Stroke (TIA), and include one or more of all five stages of stroke chronicity (hyper acute, acute, early subacute, late subacute, and chronic) [14]. From the design standpoint, the review included both rehabilitation and descriptive studies including Randomized Controlled Trials (RCTs), cohort, case-control and cross-sectional studies. The review excluded systematic reviews or meta-analyses, single-case reports with no empirical data, commentaries, articles published in languages other than English, studies with nonhuman subjects (i.e., monkeys), articles published in books, conference abstracts without full-text access, dissertations, or articles published before 2019. This data range was chosen to include the most recent literature since the last published systematic review [13].

Data Collection

All of the search results were initially screened by one researcher (MP) using the Rayyan mobile application [15]. The initial screening process involved identifying duplicates between search databases as well as reading the title and abstract of each article. Each study was marked as relevant, irrelevant, or possibly relevant in the Rayyan mobile application using the inclusion and exclusion criteria. Next, a second researcher (EP) performed the same process using Rayyan to minimize information and selection bias. The search strategy and results were recorded using the PRISMA guidelines to ensure clarity and reproducibility [16]. Also, the methodological quality of each study was evaluated using the Downs and Black checklist. Lastly, the AMSTAR-2 tool was used to assess the methodological quality of the current review [17,18].

Analysis

In line with the first purpose, each study was ranked and labelled based on its conceptual scope, framework, and motor control theories used. Conceptual scope labels included coordination, control, and both. For the conceptual framework, labels consisted of forward kinematics, inverse kinematics, and inverse dynamics. Lastly, motor control theory labels included the equilibrium point hypothesis, uncontrolled manifold hypothesis, or leading joint hypothesis. In the context of the constraints examined, each study was ranked and labelled based on the task performed and the associated individual constraints. Task constraint labels included categories such as movement (pointing, reaching, and reach to grasp), posture (standing or sitting), vision (eyes open or closed), and environment (real or virtual). In addition, a description of the task was recorded (e.g., reaching to a cup at waist height using virtual reality) for each study in the review. Individual constraint labels included categories such as age, gender, time since stroke, affected limb side, dominant hand side, and lesion location (right or left hemisphere). To delineate the methodological approaches implemented, each study was ranked and categorized based on whether it included coordination and/or control-based outcome measures. Coordination-based outcome measures labels included qualitative (e.g., angle-angle plots) and quantitative (e.g., correlations) variables. The outcome measure related to movement control included categories such as joint space in the spatial domain (e.g., joint angles, range of motion), joint space in the temporal domain (e.g., joint angular velocity), end effector space in the spatial domain (e.g., trajectory, displacement of the hand), and end effector space in the temporal domain (e.g., movement time of the hand; time to peak velocity, smoothness/jerk metrics).

Results

Initial Search

The initial search strategy yielded 5435 results, 1000 from PubMed, 2025 from Embase, 1978 from Web of Science, and 432 from CINAHL. The Rayyan web application was used to identify and remove 2445 articles as duplicates. One researcher (MP) then reviewed the remaining 2990 articles in Rayyan by screening the title and abstract. A total of 35 full-text articles were deemed relevant, and the full-text articles were retrieved. After reading each full-text article, 15 articles violated the inclusion criteria and were removed due to (1) lack of kinematic measures, (2) wrong sample demographics (i.e., only healthy individuals), or (3) wrong publication type (i.e., abstracts). As a result, 20 articles were deemed relevant and included in this review as each study (see PRISMA flowchart, Fig. 1). Nine of the studies were descriptive and 11 were interventions [19-38].

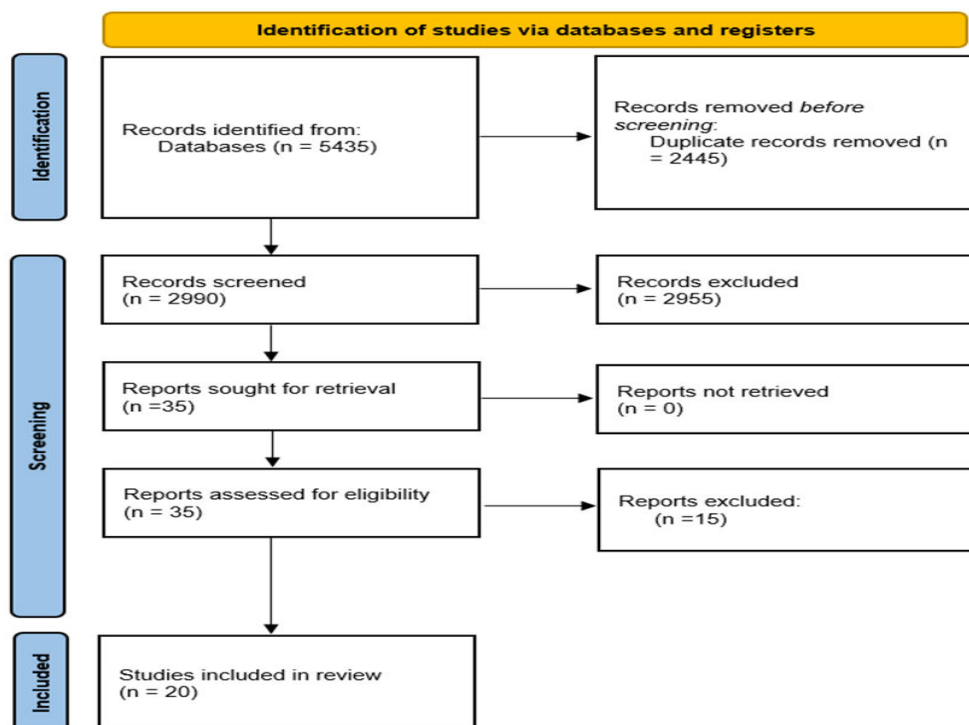


Figure 1: The PRISMA chart representing the flow of information through the different phases of a review. Adapted from “The PRISMA 2020 statement” [16].

Quality Assessment

The quality of each study was assessed using the Downs and Black checklist [17]. In line with criteria put forward by studies that received a quality index score of less than 60.0% were classified as low quality, those between 60.0% and 75.0% were considered as moderate, and those above 75.0% were considered as high quality (Table 1) [11]. Lastly, the quality of this review was assessed using the AMSTAR-2 checklist. The results indicated that the quality of this review was moderate. This indicates that this review has more than one weakness, but no critical flaws and may provide an accurate summary of the results of the available studies included.

Study	Quality Index Score (%)	Quality Rating
Carpinella, et al., 2020	96.8	High
Cho and Song, 2019	93.6	High
Feingold-Polak, et al., 2021	71.0	Moderate
Gomes, et al., 2021	67.7	Moderate
Hasanbarani, et al., 2021	83.9	High
Hejazi-Shirmard, et al., 2020	71.0	Moderate
Hussain, et al., 2021	80.7	High
Jayasinghe, et al., 2020	90.3	High
Lencioni, et al., 2021	83.9	High
Liao, et al., 2020	96.8	High
Mochizuki, et al., 2019	77.4	High
Montoya, et al., 2022	83.9	High
Mullick, et al., 2021	83.9	High
Nibras, et al., 2021	87.1	High
Park, et al, 2020	96.8	High
Raj, et al., 2020	71.0	Moderate
Teremetz, et al., 2022	96.8	High
Thrane, et al., 2020	80.7	High
Tomita, et al., 2020	74.2	Moderate
Tomita, et al., 2021	80.7	High

Table 1: The scoring results of the downs and black checklist for each study.

Sample Characteristics

In terms of the sampling implemented, majority used purposive sampling, while three implemented convenience sampling [22,31,37]. In regard to sample size, they ranged from relatively small-scale studies (9 participants) to larger studies involving 50 or more participants. Only one study explicitly stated that a power analysis was conducted [29]. In addition, each study was heterogeneous with respect to gender and age. Both male and female participants were included in approximately equal proportions, however, gender was not an independent variable. In terms of age, all participants were older adults between the ages of 54.9 and 70.3 years, but once again this variable was not considered a factor in the design or analysis.

Intra-Limb Movement Organization

Coordination vs. Control

In the current review, 14 articles examined issues in movement control. Six studies examined issues of both coordination and control [19-35].

With respect to movement coordination, inferences were made by examining the quantitative and qualitative aspects of the movement. In this review, the quantitative measures involved a correlational approach capturing the degree of spatial coupling between shoulder and elbow and synergy index. The qualitative measures consisted of angle-angle diagrams of the shoulder and elbow and angular velocity profiles of the shoulder and elbow [20,26-28,35]. The issues in movement control were examined

in spatial and temporal domains, in both joint and effector space. In joint space, measures of spatial control included maximum joint angles of the shoulder elbow and wrist forearm, as well as range of motion of the shoulder, elbow wrist and forearm [19,20,24,26,32-34,37]. The nature of temporal control was inferred from angular velocity of the elbow, shoulder, wrist and forearm as well as execution time [34,37].

In effector space, spatial measures consisted of an index of curvature trajectory length reaching trajectories spectral arch length, constant final position error, path length ratio normalized total displacement of the hand and variability of endpoint position [19,22-38]. In the temporal domain, the measures included movement duration of the hand peak velocity of the hand number of velocity peaks mean endpoint velocity time to peak velocity end effector velocity profiles, normalized jerk, percentage of movement time in which peak velocity occurred and reaction time of the hand [19-38].

Conceptual Relevance

In regards to the conceptual framework specifying how goal-directed actions are planned and executed, 11 studies implemented a forward kinematics approach [21-24,29-31,33,36-38]. Three studies based their inferences on inverse kinematics and five studies incorporated a more eclectic approach involving both forward and inverse kinematics [19,20,26-28,32,34,35]. Only one article examined the complex issues of torque modulation using inverse dynamics [25]. In terms of motor control theories, 14 studies failed to explicitly mention any known models related to intra-limb coordination/control [19,21-23,26,28-31,33,34,37,38]. Three studies mentioned motor control theories in the introduction or the rationale for the experiment, and those included the equilibrium point hypothesis, the uncontrolled manifold hypothesis and the leading joint hypothesis [20,25,27].

Constraints on Coordination and Control

Individual Constraints

A variety of individual constraints were identified including gender, time post-stroke, type of stroke, brain lesion location, hand dominance, and affected limb. In regards to gender all but one study specified that both male and female participants were recruited and equally represented in the sample [26]. In relation to time post-stroke, most studies examined participants who were in the chronic phase of stroke, ranging from 6.3 months to 5.9 years [20,21,23-25,27-30,32-34,36,38]. Two studies recruited participants in the subacute phase which ranged within three days post-stroke and three studies focused on individuals who exhibited subacute symptoms ranging from 33.9 to 56.0 days post-stroke [19,26,31,35,37]. Only one article failed to provide any details about time post-stroke [22]. In relation to type of stroke examined, all studies included participants who had both ischemic and hemorrhagic stroke, however only 14 studies included details about the specific type (ischemic vs hemorrhagic) [19-22,24,26-29,31-33,36]. In terms of the brain lesion location, 12 studies indicated if the lesion was in the right or left hemisphere [19-22,24-26,28,32,33,37,38]. In relation to the affected limb, all studies examined the more affected (paretic) arm. However, only 10 studies included details that specified if the affected side was right or left [19,21,23-25,28,29,31,32,38].

The other type of individual constraints that were sought were functional constraints. Only a few functional constraints were identified in this review including anxiety self-perceived ability to perform meaningful activities attentional focus and attention during dual tasking [21,24,26,30].

Tasks Constraints

Eight studies utilized a reaching task while five studies involved a reach to grasp task [19-29,33,36,38]. Furthermore, three studies implemented more complex tasks including reaching, grasping, and lifting an object reaching in an egocentric and exocentric frame of reference and maximum forward reaching [20,26,34]. Other tasks involved pointing a pronation task and a drinking task [31,32,35,37]. Regarding protocol associated with the task, two studies incorporated performing a reaching movement under a time limit and one study involved performing the reaching movement at a constant speed between trials [24,26,35]. In relation to the devices used to perform the task, two studies utilized robotic rehabilitation apparatus and three utilized robotic exoskeletons [23,28,29,35,36].

Discussion

Intra-Limb Organization: Movement Control

The majority of the reviewed research focused on the issues in movement control. This aspect of movement organization was primarily investigated via forward kinematics approach, which assumes that the CNS plans movement around the final position of the end effector (e.g., hand). With respect to spatial and temporal planning, this process can be described mathematically as a nonlinear coordinate transformation from intrinsic coordinates and angular velocities in joint space to extrinsic coordinates and velocities in hand space. The basis for this framework is embedded in Bernstein's (1967) work and in more modern times the work by Flash and Hogan (1985) involving reaching [39,40]. From the standpoint of spatial control, the expected differences between individuals who suffered a stroke and their typically functioning counterparts emerged in only two descriptive studies. One examined reaching tasks in individuals in the subacute phase and one involved participant who were classified as being in the chronic phase post-stroke [19,24]. The differences emerged across measures of the index of curvature, as well as its derivative the trajectory length. As compared to typically functioning adults, individuals with stroke exhibited more curved reaching trajectories that resulted in greater distance travelled. Thus, from the clinical perspective, the spatial adaptations of individuals post-stroke were jeopardized. These findings were also in line with earlier research, not included in this review, which examined reaching movements in a sample of participants in the subacute and chronic stages after stroke [41]. Aside from the descriptive research, rehabilitation studies included in this review also focused on spatial control. However, surprisingly, they failed to reveal the expected differences or changes in the end effector spatial trajectories as a result of the different rehabilitation approaches applied [26,33,36,38]. These findings were rather robust as they emerged across participants exhibiting different individual constraints (e.g., stage of stroke), who were involved in different types of rehabilitation treatment (e.g., robotic exoskeletons, transcranial direct current stimulation, interactive video game bases, and conventional rehabilitation), and across different tasks (e.g., both reaching, and reaching and grasping tasks).

Another important aspect of movement control, as related to the performance of self-paced goal-directed actions, is the issue of timing. This aspect of organization can be inferred from different kinematic measures derived from movement time or velocity (e.g., time to peak velocity; peak velocity; percentage of acceleration and deceleration phase). In this review, six descriptive and two rehabilitation studies examined the nature of temporal control [19,21-24,30,31,37]. Overall, the inferences that emerged showed a robust pattern of results indicating that the temporal adaptations exhibited by individuals with stroke were less than optimal. These inferences were confirmed by differences between individuals with and without stroke in measures of movement time, mean velocity, peak velocity, and the number of velocity peaks of the hand. Those with stroke, regardless of the post-stroke phase they were in, showed consistently longer movement times, lower peak velocity, and a larger number of velocity peaks as compared to healthy individuals. Thus, from the clinical perspective, these behaviors would be characterized as slow, jittery, and lacking smoothness. Functionally, the differences in movement time or velocity may not be as critical given the self-paced nature of the action. However, several "stops and goes", as evident from multiple velocity peaks and "zero-crossing" in the acceleration profiles, may limit the spatial accuracy of the emerging action as the individual has to reposition the end effector several times between the beginning and end of the action. Despite the strong evidence from the literature in regards to a general temporal deficit in individuals with stroke, there were few studies which failed to support this conclusion [20,26,38]. The results from these investigations did not reveal differences between the groups in comparative studies and failed to show changes among individuals with stroke as a result of rehabilitation [20,26,38]. For example, one study Hasanbarani, et al., found no statistical difference in movement time and mean velocity, while both Termetz, et al., and Tomita, et al., found no difference in peak velocity of the hand after training [20,26,38]. As it was the case with the previously discussed research, the samples in these studies were also composed of individuals with stroke who were in the chronic stage, thus individual constraints were similar between studies. However, this was not the case in terms of task constraints and the respective protocols. Hasanbarani, et al., examined a distinctly different reaching tasks that consisted of reaching in two frames of reference, egocentric and exocentric, under two conditions with and without a trunk restraint [20]. Also, Termeetz, et al., utilized a relatively low training dose consisting of three one-hour sessions per week for four weeks, while all the other intervention studies utilized at least five training sessions per week for four weeks [38]. Lastly, as previously discussed, Tomita, et al., examined a reach-to-grasp-to-reach but required the participants to reach with the same speed before and after the intervention [26]. Thus, it is plausible that the inconsistencies emerging from the studies reviewed here may be attributed to the differences in the relevant task constraints.

Intra-Limb Organization: Movement Coordination

In contrast to forward kinematics, which examines control of the end effector, the inverse kinematics approach assumes that the CNS pre-plans movements around the complex interaction between joints. An important conceptual and methodological distinction between the two approaches is that forward kinematics deals primarily with issues of control, at the intra-limb level of organization, whereas inverse kinematics also allows inferring the nature of emerging coordination [42]. In the motor control literature, dealing with degrees of freedom problem at intra-limb level of organization, this process has been accomplished at both the qualitative (angle-angle plots) and quantitative (correlations) levels of measurement.

It is surprisingly, given that movement patterns exhibited by individuals with stroke are often qualitatively different than those without stroke, that only few studies examined the issue of coordination explicitly. At the qualitative level only one descriptive and one intervention study examined the nature of the emerging coupling between the shoulder and elbow [20,26]. Hasanbrani, et al., showed that regardless of the condition, individuals with stroke exhibited a segmented type of movement where shoulder and elbow extension were decoupled [20]. In comparison, the angle-angle plots of the healthy individuals revealed smooth coupling between the two joints. Tomita, et al., also compared the angle-angle diagrams of elbow and shoulder flexion of individuals in the subacute stage of stroke, before and after four weeks of rehabilitation [26]. The findings indicated that with training the degree of spatial coupling between the joints changed to resemble patterns that are expected to emerge in typically functioning individuals, where shoulder and elbow are actively involved as the movement is unfolding.

Although angle-angle plots provided insight into the qualitative nature of the action, another reliable and valid way of capturing the nature of emerging coordination is via correlations. This approach is particularly useful as it allows statistical analysis for the purpose of comparisons. In this review, only one study utilized this methodological approach [28]. The degree to which the shoulder and elbow joints were spatially coupled in individuals in the subacute and chronic stages of stroke was examined before and after receiving robotic-based rehabilitation. In line with qualitative inferences, the results from the baseline condition indicated that the elbow and shoulder were decoupled in those with stroke as evident from low correlation ($r=-0.32$). This was in contrast to the actions exhibited by healthy individuals where the changes in both joints were smooth, as evident from high value ($r=-0.92$). After training, individuals in the chronic stage experienced a tighter coupling of the shoulder and elbow ($r=-0.54$), which indicates that the nature of their intra-limb coordination changed substantially. These results, although limited, suggested that rehabilitation can have a positive effect on the ability of the person with stroke to regain their intra-limb coordination, as captured by quantitative and qualitative measures.

In the studies reviewed here, none addressed the nature of coordination between shoulder / elbow joints and the wrist actions, in qualitative or quantitative domain. This is surprising due to the fact that coordination / control of the wrist, in relation to the other joints, represents an important functional component of the “homing” phase of reaching and grasping. Also, since stroke affects proximal versus distal muscles groups differently, the nature of synergistic relations between them constitutes an important clinical and conceptual issue. Hence, less than optimal spatial control of the shoulder can be compensated by the adaptations to the wrist, by either releasing or freezing the respective degrees of freedom. In addition, another important shortcoming of studies examined here is the fact that they failed to address the issue of variability at either the intra- or inter-group level. Thus, it remains unclear if the emerging actions are different, but stable, which from the clinical perspective would render them as compensatory. Also, from the rehabilitation standpoint, changes in variability represent an important indices of (re)learning as it is expected that with training the emerging movement patterns will become more stable. Issues in stability of the emerging actions represents an important pillar of motor redundancy models, which requires further investigation.

Constraints on Intra-Limb Coordination

Individual Constraints: Karl Newell's (1985) model of constraints asserts that a coalition of different individual, task and environmental factors “channels” the CNS to coordinate and control actions in a particular way, even when an infinite number of possible outcomes are available [7]. Individual constraints represent characteristics of an individual which can be broadly classified as structural and functional [7]. Structural constraints refer to the status of different subsystems within the central and peripheral nervous systems. In the case of individuals with stroke these constraints may impose the most significant restrictions as they relate to the role of the location of the brain lesion (right or left hemisphere), and the relevance of time which elapsed from the time the stroke occurred. Also, in the context of the morphological characteristics of the body, they are related to the

affected side of the body as a result of the stroke (left or right).

One of the most important considerations in relation to the ability to perform or regain the actions lost due to stroke-related impairment is the duration of time which passed from the stroke. Most studies reviewed here involved individuals who were in the chronic stage, whereas only three studies recruited participants in the subacute stage [19,26,35]. In addition, two longitudinal studies involved participants who were in the subacute stage when the study started (less than three days since the stroke) and followed their progress through rehabilitation one year later until they were in the chronic phase [31,37]. The inferences from these two longitudinal studies suggested that those in the subacute phase exhibit different deficits in control mechanisms than those in the chronic phase. These issues were imbedded in different aspects of more rudimentary spatial organization, as well as in the temporal domain. The reason for such functional discrepancies may be attributed to the fact that in the acute phase, motor performance is more variable as the CNS is still relearning the lost movement pattern, while those in the chronic phase have already recovered and their performance is more stable [6,14]. Thus, in line with the hierarchical model of organization, it appears that individuals in subacute stage may have deficits in both spatial and temporal coordination, whereas those who were able to recover for longer period of time exhibit predominantly issues in movement control.

In addition to the time elapsed since the stroke, the location of the lesion within the brain can also be considered as an important individual constraint. Injury to the left hemisphere results in paralysis on the right side of the body, while injury to the right hemisphere results in paralysis on the left side [43]. Based on a model put forward by Mani, et al., the left hemisphere is responsible for predicting and adjusting for limb dynamics, while the right hemisphere stabilizes limb positions [44]. Thus, those who exhibit lesions on the left side would be expected to have problems coordinating joints and performing goal-directed actions, while those who exhibit lesions on the right would be expected to have problems associated with control of the end effector. Despite this neurological dichotomy, most of the studies reviewed here included heterogeneous groups of participants which included individuals with right and left hemisphere damage. This type of sampling likely leads to enhanced within-group variability, which may result in the presence of “person x interaction” effect. This is a critical issue in rehabilitation studies as the effect, of the treatment, maybe seen in some individuals but not others. The presence of such effect is difficult to detect statistically, unless the analysis is carried out at the individual rather than group level. The presence of such effect may impact the nature of the emerging inferences and further down the line the nature of clinical programs implemented. Only one descriptive study included the side of the lesion as an independent variable [22]. The results showed that both groups of individuals, with left and right hemisphere damage, had higher variability at the end of the movement compared to the variability at peak velocity. However, the two groups differed as the individuals with right hemisphere damage had higher variability at the end of the movement. Due to lack of research involving a suitable design, the impact of side of the lesion on intra-limb movement organization in people with stroke remains equivocal.

Task Constraints

Task constraints are factors related to the goals, protocol, rules and equipment involved in the performance of motor skills [7]. These factors represent important constraints as the degree of similarity or difficulty between the tasks will have an impact on the degree to which certain behaviors are invariant across participants from the same or different samples. In this review, five interventions and three descriptive studies examined a reaching task, while one intervention and four descriptive studies examined a reach to grasp task. Also, two descriptive studies examined three unique variations of reaching [20,37]. Thrane, et al., examined a drinking task which although seemingly simple from the control standpoint, it involves a rather complex series of actions as the performer needs to organize multiple joints in various planes of motion during reaching, grasping, transporting, and manipulating the object [37]. From the degrees of freedom problem standpoint, such discrepancies in task demands although subtle, represent an important factor to consider. Generally, when performing un-manual discrete tasks, the arm has 7 degrees of freedom that need to be coordinated and controlled in a suitable synergistic spatial and temporal relation. In a simple reaching task, the degrees of freedom at the wrist, which afford it to flex, extend, adduct and abduct, do not need to be controlled to the degree required when the arm is reaching with the goal of grasping or rotating the object (e.g., pouring water into the glass). Thus, the kinematic synergies that are planned and executed in one context will be different than those evident in a task that is even seemingly similar. Thus, at the behavioral level of analysis the differences that may emerge in one context may not emerge under different context, therefore the inferences regarding the nature of intra-limb organization in uni-manual tasks always have to be considered in the context of the task goal.

The other type of constraint that is expected to impact the nature of coordination and control in relation to the kinematics of intra-limb actions is the height and weight of an object to be manipulated. In this review, only one study examined the nature of reaching actions at three different heights (50 cm, 75 cm, and 92.3 cm above the ground) and two weights (273 g and 443 g) [19]. It was found that the trajectory of the end effector was less smooth when reaching for objects located at higher heights, while no differences emerged when the conditions, including different weights were examined. This finding indicates, once again, that the nature of intra-limb coordination and control is affected by many different task constraints, when individuals with stroke are examined. From the measurement standpoint, it is imperative that the protocols and variables being implemented are reliable and sensitive to even subtle differences in coordination and/or control.

General Implications and Future Directions

The majority of research reviewed here focused primarily on issues of control, either via forward kinematics. The issues in temporal but not spatial organization were evident, but more research is still warranted. Also, although forward kinematics represents an essential tool in examining the nature of trajectory formation via analysis of the end effector, its application is limited as it does not address the issue of coordination explicitly. In line with hierarchical organizational model introduced by Burton (1990) the ability to produce stable synergies (coordination) must be mastered before achieving control of the movement [6]. Thus, from clinical standpoint, both levels of organization in spatial and temporal domains, should be systematically examined.

Another important aspect of movement organization that gained little attention in the reviewed literature was the issue of stability. At the intra-individual level, documenting changes in variability allows making inferences about the degree of dysfunction present, as the trajectory of recovery. In the context of rehabilitation, movements that are different, but stable, maybe viewed as adaptive and functional. Thus, changes/differences in emerging behavior have to be considered in the context of coinciding variability. From the conceptual standpoint, regardless if the research implemented forward or inverse kinematic approach, surprisingly only three studies included in this review explicitly referred to either the Uncontrolled Manifold, Equilibrium Point Hypothesis, or the Leading Joint Hypothesis [20,25,27]. These theories are vital as they help to translate conceptual constructs into rehabilitative practices [45,46]. Also, they allow to predict changes in behavior as manipulation of relevant constraints may evoke desired changes in movement patterns, from less to more stable and more importantly from those which are ineffective to those which are more functional. Thus, a critical shortcoming in this field of study is a primary focus on data-driven investigations, and relative neglect of more deductive research designs.

From the standpoint of different constraints, the issue of heterogeneity of the population has been scarcely addressed. It appears that time after stroke had the most impact on the nature of coordination and control. Individuals in the subacute stage exhibited issues related to movement control, while those in the chronic stage were more stable as their patterns resembled those exhibited by their typically functioning counterparts. Also, it was surprising that gender and age were not incorporated in any of the reviewed studies as the independent variable. Intuitively, and based on the existing literature, both impact the degree to which stroke affects performance. This is particularly true in the context of motor learning, as the changes in behavior are often non-linear and confounded by both variables. In terms of task constraints, the issue of complexity (difficulty) also represents an important methodological consideration. Often the performance of relatively simple tasks may not reveal the underlying deficits in the spatial and/or temporal domains, especially in self-paced tasks such as reaching and grasping. The manipulation of such constraints can also provide insight into the flexibility of the system as the performer has to be able to adapt their trajectory, in time and space, to the different complexities of each task. From the clinical standpoint, regaining the ability to perform stable (consistent) movement patterns or trajectories represents only one indicator of recovery, while the ability to adapt the actions or generalize them across different contexts (e.g., via transfer tests) is the ultimate goal of the rehabilitation process.

In terms of limitations to the present work, the inferences from the present review should be considered in face of a few limitations. This review represented a combination of both a systematic and scoping review, as both intervention and descriptive studies were investigated. Systematic reviews typically only include intervention or descriptive studies, while scoping reviews encompass a wide range of research. Thus, the inclusion of both types of studies may have impacted the generalizability of the results of this review, and thus the scoring of the AMSTAR-2 checklist. Furthermore, the down and black checklist was used to assess the quality of the included studies. It should be acknowledged that more comprehensive assessment tools could have been

used, however current protocol was in line with previous work [11,47]. Also, the number of chosen investigations was relatively low. This is due to the fact that the time set up in the inclusion criteria, since the last review of this nature, was relatively short. Despite these limitations, and while considering them in the context of the emerging inferences, the present work represents a valuable and novel insight into the issues of intra-limb coordination as well as control, exhibited by those affected by stroke.

Conflict of Interest

The authors have no conflict of interest to declare.

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