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

A Thesis Presented to the
School of Kinesiology
Lakehead University
Thunder Bay, Ontario, Canada

In Partial Fulfillment of the Requirements
for the Degree of Master of Science in Kinesiology
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Abstract

Stroke results in substantial difficulties in reaching and grasping actions, which may emerge at different levels of coordination and control, in both the spatial and temporal domains. In the context of motor control, these issues relate broadly to the Degrees of Freedom Problem (Bernstein, 1967), as well as to many other theoretical models (e.g., Models of Constraints) that fall under this conceptual umbrella. Over the last few decades, a substantial amount of studies have been published to examine these issues, including various systematic reviews. However, the majority of this work failed to explicitly address the level at which these issues occur, the impact of different constraints on the emerging patterns, and the conceptual relevance of the emerging inferences. As such, the purpose of this study was threefold. The first purpose was to examine whether the selected studies examined the issue in coordination and/or control, and to determine the conceptual framework underpinning these investigations. The second purpose was to delineate which individual, task, and environmental constraints have been examined in previous work, and infer the degree to which these factors affected the nature of the emerging movement trajectories. Lastly, the third purpose was to address the methodological aspects of the existing studies, by identifying the prevalence of different measures of coordination (angle-angle plots; correlations) and control.

The search of four databases (PubMed, Embase, Web of Science and CINAHL), for research published between January 2019 and March 2022, yielded twenty studies that were identified based on the inclusion criteria. In relation to the first purpose, the results showed that most of the studies examined issues in control, while 7 examined both coordination as well as control aspects of organization. Among those, the forward kinematics approach was most prevalent, while only four studies implemented inverse kinematics, and another four incorporated both forward and inverse kinematics. Only one study examined the issues of coordination and

control via inverse dynamics. Research implementing forward kinematics revealed that individuals with stroke exhibited issues in spatial and temporal control where the actions appeared to be slow and involved minimal use of the shoulder and elbow joints as inferred from angular velocity and displacement respectively. Also, the trajectories of the hand were curvilinear, which is an indicator of less than optimal spatial control. However, these results should be considered with caution as some studies rendered support to this hypothesis, whereas others did not. The analysis of emerging movement patterns, via inverse kinematics, revealed that individuals with stroke exhibited segmented coordinative tendencies, and tended to release the respective degrees of freedom with practice, as inferred from both angle-angle diagrams and correlational coefficients. The lack of analysis of coordination between more distal anatomical structures (e.g., elbow and wrist) represents an important limitation of the existing work. In terms of implementation of specific theories or models of motor control, related to how the CNS plans and executes intra-limb action, only three studies attempted to make inferences to models which included the Equilibrium Point (Hasanbarani et al., 2021), Uncontrolled Manifold (Tomita et al., 2020), or the Leading Joint Hypothesis (Raj et al., 2020). In regards to the second purpose, time after stroke appeared to be the most impactful individual constraint which differentiated the nature of coordination and control exhibited by those with and without stroke. The impact of variables such as gender and age, on the nature of movement organization post stroke, were not examined in the reviewed research. With respect to task constraints, their complexity may result in the floor or ceiling effect, thus systematic manipulation of task demands is warranted, in the context of the issues being examined and sample characteristics. The impact of environmental constraints, which were operationalized here in terms of restraints on posture, remained equivocal. The third purpose aimed at examining the methodological approaches involved in the kinematic analysis of emerging movement trajectories. The most notable issue was the lack of measures of variability and stability, at both the intra-individual as well as intra-group level. From the motor control as well as a clinical standpoint, this significantly undermines the internal validity of the emerging inferences. The expected changes in stability, at the individual level, represent an important indicator of learning. Also, given that the sampling approaches implemented resulted in rather heterogeneous samples, the lack of insight into the potential existence of person by treatment interaction effect warrants caution.

Collectively, the reviewed research showed that the degrees of freedom problem and understanding how individuals with stroke organize their actions remains equivocal due to a variety of different methodological approaches. The fact that inverse dynamics has been rarely examined in research examined for this review, as well as in other investigations not considered here, indicates that our understanding of how trajectories are formed and change due to retraining after a stroke is still in its infancy. Conceptually, little effort has been made to connect the inferences that emerge from the data to established theories or models, within the motor control field. Unfortunately, data driven research still represents the primary impetus in this clinical field clinical. This is worrisome as there is a lack of deductive research attempting to test the robustness of the existing theories, and inductive frameworks aiming at theory "building". Methodologically, the nature of sampling methods implemented and heterogeneity of the samples represent important issues which require further consideration, particularly in clinical (rehabilitation) studies. From the standpoint of design and coinciding measures, the issue of stability needs to be addressed as movement patterns that are different, but stable, may represent the adaptive expression of CNS functioning after stroke. Lastly, an important limitation of this work was a relatively small number of research studies reviewed. Also, although this research replicated the protocols used in previous systematic reviews (e.g., Mesquita, Fonseca et al. 2019), it should be acknowledged that more suitable assessment tools of the quality of the included studies could be implemented in future work.

Acknowledgments

I am extremely grateful to have had the opportunity to be a graduate student. Throughout the years I have been able to refine my interests and uncover what I am truly passionate about. None of my accomplishments would have been possible if it were not for countless individuals who have helped and supported me throughout the process. In the fall of 2019, just before the COVID-19 pandemic struck, Dr. Eryk Przysucha agreed to be my supervisor. Since then, he has been an unbelievable mentor as helped me navigate the sophisticated world of academia. Words cannot describe how grateful I am for his support and guidance. Eryk has left a positive impact on my life, both personally and professionally. It is my hope that I will one day be able to guide others with the same level of kind-heartedness as Eryk.

I would also like to thank Dr. Taryn Klarner and Dr. Carlos Zerpa. I both admire and respect their desire to provide and foster high-quality education. Lastly, I would like to thank my family, especially my parents (David and Diana), siblings (Stefanie and Christopher), and dogs (Ginger, Casper, and Penny). They supported me throughout the years with unconditional love and care.

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Key Terms

Angular Motion: Motion that occurs around an axis of rotation, such as the rotations of body segments around joints (Winter, 2009)

Biarticular Muscles: Muscles that spans two or more joint (Schmidt et al., 2019)

Compensation: The substitution of different degrees of freedom to achieve the same motor task (Latash, 2009)

Constraint: A characteristic of the individual environment, or task that encourages movements while discouraging others (Schmidt et al., 2019)

Coupling: The process of joining two individual components together to form a system (Schmidt et al., 2019)

Coordination: The process of establishing stable relationships (spatial or temporal between joints, muscles, or body segments during voluntary goal-directed actions (Schmidt et al., 2019)

Coordinative Structures: A group of muscles spanning multiple joints that function as a functional unit (Latash, 2008)

Control: The process of changing/adapting an individual's components of actions

Control Parameters: Naturally occurring intrinsic, endogenous factors, or environmental conditions that move a system through its repertoire of patterns and causes them to change (Schmidt et al., 2019)

Degrees of Freedom: A set of independent displacement and/or rotations that specify the position and orientation of the body (Schmidt et al., 2019)

Flexibility: The ability of joints to adapt the relationship between the elements to maintain relations across various task demands (Latash, 2008)

Forward kinematics: The process of computing extrinsic (end-effector coordinates) variables from intrinsic (joint) variables (Winter, 2009)

Intra-limb: The interaction of components within one limb (Schmidt et al., 2019)

Inter-limb: The interaction of components between two limbs (Schmidt et al., 2019)

Invariant: A fixed relation among parameters that remains constant (Latash, 2008)

Inverse kinematics: The process of computing intrinsic (joint) variables from extrinsic (end effector) variables (Winter, 2009)

Inverse dynamics: The process of deriving joint torques and forces from endpoint kinematics and forces (Winter, 2009)

Redundancy problem: Represents the multiple ways of mapping neural impulses and the merging trajectories for a given motor task (Latash, 2008)

Relative Phase: The nature of temporal relations between two components within a cycle (Winter, 2009)

Spasticity: Inhibition loss due to damage to the dorsi and reticular spinal tract, which lead to hyperactivity to stretch reflexes and lack of activation of voluntary muscle control (Latash, 2008)

Stability: The ability to maintain a stable relationship between the elements of the coordinative structures under the same or similar task demands (Latash, 2008)

Synergies: Classes of movement patterns involving connecting collections of muscles or joint variables (Latash, 2009)

Review of Literature

Stroke

Prevalence

Stroke is a major health concern around the globe. This condition is the second leading cause of death (Feigin et al., 2021), and a leading cause of neurological disability that negatively affects various aspects of life. These include communication, cognition, motor control and coordination, and as a result the ability to perform Activities of Daily Living (ADL)'s. From 1990 to 2019, the number of stroke incidents increased by 70%, with most cases in individuals older than 70 years old and most cases in the male gender (Appelros et al., 2009; Feigin et al., 2021). In Canada, approximately 405 000 individuals experience a stroke each year (Kreuger et al., 2015). This number is estimated to increase to between 654 000 and 726 000 in 2038 (Kreuger et al., 2015). There are different types and etiology definitions regarding stroke.

Types and Etiology

Classically, stroke is defined as the sudden loss of neurological function due to a hemorrhage or infarct within the brain (Hankey, 2017). More recently, this definition has been revised to incorporate the notion of an acute episode of focal dysfunction of the brain, spinal cord or retina that persists longer than 24 hours (Hankey, 2017; Sacco et al., 2013). In the brain when blood flow stops brain tissue begins to die. If this event lasts long enough, a significant amount of brain tissue is damaged, leading to neurological impairment. Stroke can also be classified based on the time since injury. The chronicity of stroke is used to classify the time since injury and includes five separate categories: hyper acute, acute, early subacute, late subacute, or chronic. Hyper acute is classified as less than 24 hours, acute as one to seven days, early subacute as seven days to three months, late subacute as three to six months, and choric as greater that six months since the event (Bernhardt et al., 2017).

Stroke is distinctly grouped into three main types: ischemic, hemorrhagic, and transient ischemic attack (TIA). Ischemic stroke occurs when a blood clot in a blood vessel breaks off and obstructs blood flow to the brain (Adams et al., 1993). The most common cause is plaque accumulation within the lining of the blood vessels (atherosclerosis) (Hankey, 2017). The specific type of ischemic stroke is also classified based on the anatomical injury location (i.e. lobar, deep, cerebellar, and other) (Rannikmäe et al., 2016).

Hemorrhagic stroke occurs when a fragile blood vessel ruptures and bleeds into the surrounding tissue of the brain (Cordonnier et al., 2018). The accumulation of blood compresses the surrounding brain tissues, disrupts the flow, and may cause irreversible damage. Two types of hemorrhagic stroke include subarachnoid and intracerebral hemorrhages. Subarachnoid hemorrhages occur when a vessel on the brain's surface ruptures and bleeds into the space between the brain and the skull. Intracerebral hemorrhage happens when a blood vessel deep within the brain ruptures and bleeds into the surrounding area.

Transient Ischemic Attack (TIA), also referred to as a mini-stroke, occurs when blood flow to the brain is temporarily blocked (Adams et al., 1993). This type of stroke is distinguishable from the other types, as the blockage is temporary and typically lasts less than 24 hours. Most often, permanent brain injury does not arise as a result of this event but is still classified as a medical emergency and warrants urgent medical care, as there is an increased future risk of more severe complications (Whiteley et al., 2011).

Standard methods for classifying ischemic stroke include the Trial of Org10172 Acute Stroke Treatment (TOAST) classification system, Atherosclerosis Small vessel disease, Cardiac source and Other (ASCO), Causative Classification System (CCS), and the Chinese Ischemic Stroke Sub classification (CISS) systems (Chen et al., 2012). TOAST is a simple system used for over two decades to classify stroke based on five sub-types: large artery atherosclerosis, cardio embolism, small-artery occlusion, a stroke of other determined causes, and stroke of undetermined cause. Limitations to this approach, however, include misdiagnosis of small artery stroke, over-classification in the "undetermined stroke" category, and variable definitions influenced by user opinions and interpretations (Chen et al., 2012). The ASCO classifies stroke based on atherosclerosis, small-vessel disease, cardiac source and other causes. One advantage of ASCO is the incorporation of patient demographics, which are typically important when conducting epidemiological studies (Chen et al., 2012). The CCS system incorporates current advances in CT and MRI medical imaging techniques to classify stroke for a more accurate diagnosis (Chen et al., 2012). Lastly, the CISS system uses a two-step classification that integrates etiological and pathophysiological causes (Chen et al., 2012).

Signs and Symptoms

Signs and symptoms of ischemic and hemorrhagic stroke typically occur rapidly and persist. They include loss of vision, balance, slurred speech, imbalance, headache, confusion, and numbness of one side of the body or face (Hankey & Blacker, 2015; Hankey, 2017). In comparison, signs and symptoms associated with TIA may take hours or even days to develop and usually subside eventually. Additionally, the anatomical location of the bleed or blood vessel rupture may increase or decrease the severity of signs and symptoms. For example, a larger bleed deep in the brain may present more noticeable signs and symptoms than a minor superficial bleed (Hankey & Blacker, 2015). In addition, left and right hemisphere strokes display different symptoms. For right hemisphere stroke, common signs and symptoms include impaired vision, curious behaviour, memory loss, and paralysis on the left side. For left hemisphere stroke, common signs and symptoms include memory loss, cautiousness, slow behaviour, paralysis of the right side and dysphasia (Campbell & Khatri, 2020). Prior research has indicated that left hemisphere stroke may be more common in stroke patients. For example, Hedna et al. 2013 found that left-brain stroke is more common, severe, and associated with worse outcomes than right-brain stroke. After analyzing data for 476 stroke patients, in terms of age, TOAST classification, event frequency, and National Institute of Health Stroke Score, they concluded that 54% of the patients had left hemisphere stroke while 46% had right hemisphere stroke (Hedna et al., 2013).

Stroke is often mistaken for other metabolic and neurological conditions such as hyperglycemia, hyponatremia, hypercalcemia, encephalopathy, and brain tumors (Vilela, 2017). For example, Hosseininezhad and Sohrabnejad (2017) found that from a sample of 1985 patients diagnosed with brain stroke, 14.9% were misdiagnosed. This misdiagnosis may prevent patients from receiving potentially life-saving treatment drugs. If administered correctly, a lifesaving drug such as Alteplase works to break up the clot, restore blood flow, and minimizes permanent brain damage. However, if the window of time is missed, permanent brain injury may occur and lead to permanent disability and impairment. The most commonly used drug, Alteplase, is widely studied and accepted due to its efficacious effects (Micieli, 2009).

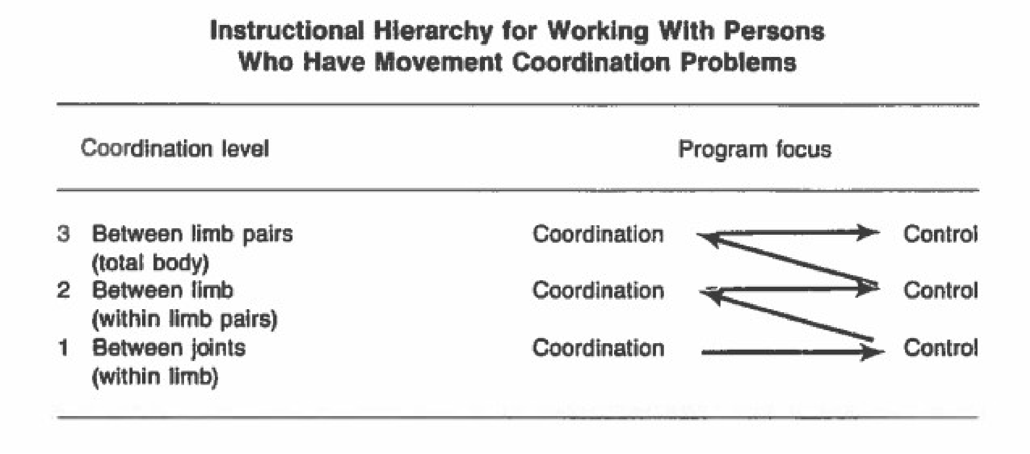
Further Classification based on Causes, Subtypes and Mechanism

Stroke can be further sub-classified based on the mechanism of action using medical imaging such as Magnetic Resonance Imaging and Computed Tomography. For example, common sub-classifications include thrombotic, embolic, venous, intracerebral, and silent (Hankey & Blacker, 2015). A thrombotic stroke is the result of blockage of blood in the brain due to a blood clot. This blood clot typically develops within the brain and blocks brain blood flow (Knight-Greenfield et al., 2019). The clot is typically a composition of atherosclerotic plaque, which is a buildup of lipids and fat on the walls of blood vessels (Adams et al., 1993). An embolic stroke results from a blood clot that forms elsewhere in the body and travels to the brain. This type of stroke is usually the result of heart surgery and is common in atrial fibrillation

(Adams et al., 1993). A venous stroke, also referred to as a Cerebral Venous Sinus Thrombosis (CVST), arises from a short chain of events. First, a blood clot forms in the brain's venous sinuses (Knight-Greenfield et al., 2019). Next, the clot prevents blood drainage from the brain and causes blood cells to build up, break apart, leak into the brain, and result in a hemorrhage (Knight-Greenfield et al., 2019). An intracerebral hemorrhagic stroke occurs when blood vessels in the brain rupture, causing a bleed in the brain (Cordonnier et al., 2018). Lastly, silent stroke differs as it occurs without easily recognizable symptoms and is a warning sign to a more severe stroke (Cordonnier et al., 2018).

Motor Consequences of Stroke on Coordination and Control

As indicated from Figure 1, issues in coordination and control can emerge at different levels of organization. This is also true in regards to the problems that result from having a stroke. As evident, the issues can emerge in most complex actions involving total body actions. Due to the nature of the cerebral vasculature, stroke is localized in one hemisphere of the brain and individuals develop a distinct asymmetrical motor impairment between the right and left sides. These motor impairments on the affected side of the body are characterized by abnormal muscle tone, muscle weakness, abnormal postural adjustments, abnormal movement synergies, lack of mobility between structures at the shoulder and pelvic girdle, incorrect timing of movement pattern components, and loss of inter-joint coordination (Bobath, 1999; Bourbonnais & Vanden Noven, 1989; Burke, 1988; Cailliet, 1980; Carr & Shepherd, 1989; Di Fabio et al., 1986; Lance, 1980; Levin, 1996; Twitchell, 1951). In addition, motor impairment presents on a proximal to distal gradient, meaning that muscles farther away from the trunk are more affected compared to those more proximately located (Brunnstrom, 1970).



Instructional Hierarchy for Working With Persons Who Have Movement Coordination Problems

Coordination level	Program focus	
3 Between limb pairs (total body)	Coordination	Control
2 Between limb (within limb pairs)	Coordination	Control
1 Between joints (within limb)	Coordination	Control

Figure 1. The hierarchical model of organization. This figure illustrates the perquisite level of focus (coordination or control) that must first be mastered when performing a task involving a given coordination level (total body, within limb pairs, or within limb). Reprinted with permission from "Applying principle of coordination in adapted physical activity" by A. W. Burton (1990). *Adapted Physical Activity Quarterly*, *7*(2), p. 136 (https://doi.org/10.1123/apaq.7.2.126). Copyright 2003 Human Kinetics. Reprinted with permission.

As a result, when individuals with stroke attempt to move an arm, they employ compensatory strategies in order to accomplish the motor task. One strategy involves abnormal movement patterns, which are categorized into two types, extensor or flexor synergies. Where, synergies are a complex dynamic relationship between two joints (Latash, 2008). Extensor synergies consist of shoulder extension and adduction combined with elbow extension, forearm pronation, and wrist flexion (Brunnstrom, 1970). Flexor synergies consist of shoulder flexion and abduction, elbow flexion, forearm supination, and wrist extension (Brunnstrom, 1970). In addition, the abnormal movement patterns in the upper limb result in abnormal coordination in the shoulder and elbow. (Levin et al., 2000). Another compensatory strategy is the fixation of body segments. For example, individuals with stroke tend to fix the pelvis on the lumbar spine or the scapula on the thorax. These fixation patterns permit the individual to complete the task in a postural threatening situation (Brunnstrom, 1970). In line with this hierarchical model and levels of organization from Figure 1, the intra-limb level of organization represents the rudimentary aspect of action production. Hence, these are the actions that have to be acquired before higher levels of organization are achieved. In this context, the notion of coordination refers to the ability to produce stable pattering of the joints and segments that are both stable and functional. On the other hand, control refers to the ability of the system to adapt to the changes in the emerging constraints, while maintaining the same movement patterns or altering them when the task demands change substantially (Burton, 1990). In a sense, "control" assures the flexibility of the emerging movement pattern, in the face of changing task, or other constraints. In addition, as evident from Figure 1, the ability to acquire proper coordination has to be mastered before achieving control of the movement. This means that if a particular condition (e.g., stroke) negatively affects the overall pattering of the actions, it has to be methodically described and understood before the issues in control can be delineated.

Coordination

In this section, coordination of interlimb movements will be reviewed. This will begin with the presentation and solution to the degrees of freedom problem, followed by a discussion of constraints involving of task, individual, structural and other factors affecting torque modulation. This will be followed by a review of intralimb coordination and how it changes after stroke. It will include a discussion on three frameworks, forward, inverse, and dynamics, their associated conceptual and methodological considerations and relevant motor control theories. Finally, this literature review will culminate with a discussion on the existing review on stroke and intra-limb coordination.

Degree of Freedom Problem and Synergies

In an attempt to better understand the complex interaction between joints, Bernstein (1967) formulated the degrees of freedom problem. This problem states that there is a surplus of degrees of freedom in the body necessary to perform a given motor task. The main dilemma is how the CNS can select a particular solution out of an infinite number of possible combinations (Schmidt et al., 2019). For example, in the upper arm, there are seven degrees of freedom. Three are within the shoulder, one in the elbow, and three in the wrist. However, only three degrees of freedom are required for most goal-directed actions to achieve the intended goal (Soechting, 1989). When reaching for a cup, for example, only three extrinsic Cartesian coordinates, x, y, and z are needed to specify the end position of the hand. Additionally, the cup could be orientated with three degrees of freedom about the axis of rotation (i.e., sagittal, horizontal, or frontal plane). Since the arm contains more degrees of freedom than are required, there are excess possibilities around which joints can be configured when an action is performed (Soechting, 1989). These redundant degrees of freedom make it complicated for the CNS to organize a consistent movement pattern given a particular task goal. Often this issue in the field of motor control has been referred to as "motor equivalence" which acknowledges that there are multiple acceptable ways to perform a given movement and accomplish the same goal. For example, the additional degrees of freedom leave a null space that can be configured in an infinite number of ways. Initially referred to as the problem of redundancy an updated version replaces the term with abundance (Latash et al., 2007). In this perspective, the CNS is not a constraint but has at its disposal the ability to select the most appropriate combination of degrees of freedom for any given task and set of constraints.

To make it easier to perform a particular task, the CNS organizes the joints into functional units of action, known as synergies of coordinative structures, instead of controlling individual joints and their respective degrees of freedom individually. Bernstein's (1967) notion of synergy was further developed by Gelfand and Tsetlin (1966) and by Latash (2008) leading to a new concept of synergies. It is important to notice that Bernstein put forth the notion of synergies first, even though his work was not published until 1967 in English. Latash (2008) stated that a combination or group of elemental variables (i.e., joints, muscles) must meet three criteria to be coined a synergy. First, there must be a relationship among relevant variables in order to achieve the task effectively. For example, the angular displacement of the shoulder and elbow joints could form a relationship to transport the arm during a reaching task. Second, error compensation must be present between the elemental variables. This statement means that if there is an error due to stabilizing or rotary action, of the shoulder, the elbow joint will compensate to ensure the task is completed effectively. Third and probably the most important feature is task dependency. This concept infers that the same group of elemental variables can be organized into a different synergy if a novel task is present. For example, the elbow and wrist joint can be organized differently to point to a target as opposed to reaching and grasping an object.

Intra-limb Coordination: Constraints

Bernstein (1967) proposed that actions are likely organized at the kinematic level due to a lack of a one-to-one relationship between muscles and behaviour. Thus, to organize movement trajectories in uni-manual tasks, the CNS must complete an inverse kinematics calculation to determine the required joint angles, in space and time, to define the emerging actions (Soechting, 1989).

Although synergies, or coordinative structures (Kugler, Kelso, & Turvey, 1980), make movement organization easier for the CNS, they only partially solve Bernstein's degrees of freedom problem (1967). Synergies do not fully solve this problem because the movement pattern that eventually emerges, when performing a task, depends on many other factors that exist in a particular context. For example, during unimanual goal-directed actions (i.e., one-handed reaching or pointing), the CNS can configure the joints a number of ways when performing an action. However, given an infinite number of potential possibilities, people of similar skill levels perform actions in a comparable way under similar task demands. Many theories/models have attempted to address this redundancy problem (Haken et al.,1985; Uno, Kowato, & Suzuki, 1989). One particular model of interest, put forward by Karl Newell (1985), states that a coalition of constraints force the CNS to organize a unique action when many are possible. Individual, environmental, and/or task factors or constraints can all impose positive and negative limits on the emerging action and affect the nature of spatial-temporal relations (i.e., synergies) between the respective elements (Newell, 1985). When examining the nature of emerging voluntary movements, in the context of intra-limb organization in people with stroke, it is important to delineate the most influential constraints and understand the degree to which they affect the process of movement organization. From the three types of constraints, as task and individual constraints are expected to most impact the nature of upper limb unimanual actions, emphasis will be placed on these constraints and less on environmental constraints.

Task constraints. One constraint that affects the number of possible joint configurations is the task goal. Although this constraint alone does not ensure a unique movement pattern will emerge (Heuer, 1996), the nature of the task can reduce the number of potential configurations substantially. For example, if a person was to grab a stationary object, there are numerous joint configurations that can complete this task. However, if the object was a small and heavy stationary paperweight, the number of possible joint configurations would be reduced. Generally, when the task constraints are enhanced, namely made more challenging, the number of possible functional solutions decreases. For example, when actions are taken under external time demands (e.g., catching task) (Mazyn, Montagne, Savelsbergh, & Lenoir, 2006), the participants exhibited tighter coupling between the elbow-wrist and the shoulder-elbow joints, as compared to self-paced tasks such as reaching. In addition, the nature of elbow-wrist coupling during one-handed catching (Mazyn et al,, 2006) is different than in uni-manual reaching (Lacquaniti & Soechting, 1982), thus this fact once again supports the notion that the same anatomical structures are coordinated differently, based on the goal of the action and its constraints.

Individual constraints. Another factor that affects the nature of coordination (i.e., spatial relationships) between joints are individual constraints. A coalition of task and individual constraints force unique movement patterns to emerge. Individual or structural constraints can be defined as soft or hard in nature and have to do with the intrinsic physical structural or psychological functional makeup of the individual (Heuer, 1996). Soft constraints are associated with preferred or learnt coordination tendencies for the individual (or intrinsic dynamics) that are utilized to achieve a task goal. Bernstein's original hypothesis (1967) was that as people become more skilled, they progress from freezing to freeing tendencies. In the context of goal-directed actions, freeing means that the CNS allows relevant joints to move through their respective degrees of freedom. However, a more recent interpretation of coordinative tendencies suggests that a more skilled or developed performance is not always governed by freeing as originally stated by Bernstein (Newell & Vaillancourt, 2001). Depending on the task demands, either freeing or freezing may represent the most favorable tendency (Newell & Vaillancourt, 2001). For instance, adults tend to “freeze” the wrist joint when performing pointing actions to keep a straight wrist path (Marraso, 1981), but they tend to “free” the wrist when one-handed catching task is performed (Mazyn et al., 2006). Likewise, adults may free one joint (shoulder), but freeze another (elbow) in order for the action to be functional. Furthermore, individuals with motor impairment, such as that seen in stroke, have various individual factors (severity, time since stroke, and location) that impact the nature of coordination and control. A more detailed discussion of biomechanical constraints and factors that influence torque production follows below.

Structural constraints. Aside from soft constraints, hard constraints also play a role in generating functional actions. The two main types of such structural factors are neuromuscular and biomechanical constraints. Depending on the level of coordination examined (i.e., intra-limb vs. inter-limb), the impact of either constraint may be more or less pronounced. In intra-limb coordination, biomechanical constraints play a more prominent role (Carson, Byblow, Goodman, & Swinnen, 1994; Carson, Riek, Smethurst, Parraga, & Byblow, 2000). Biomechanical constraints that are relevant to intra-limb movements are bi-articular muscles and limb dynamics.

Bi-articular Muscles. Muscle articulation is a biomechanical structural constraint that influences uni-manual movements, such as reaching or pointing. Muscles can span either one or two joints and during multi-joint actions, mono-articular muscles create the majority of muscular force. On the other hand, biarticular muscles also produce force, but their secondary role is to control the direction of the force applied by the individual muscles (van Ingen Schenau et al., 1987). A bi-articular muscle assists movement organization because it controls two different joints. For example, when performing voluntary intra-limb arm movements, the biceps brachii contributes to both shoulder and elbow flexion (Lacquaniti & Soechting, 1986). This anatomical structure is a biomechanical constraint on the emerging action as the biceps brachii activation can potentially force the shoulder and elbow to couple their angular displacement. Nevertheless, biarticular muscles do not always assure tight coupling between joints, as evident from the fact that decoupling can emerge between the elbow and wrist in pointing/reaching actions (Lacquaniti & Soechting, 1982), whereas a tight coupling can be evident between the shoulder and the wrist in dart throwing, yet the two joints are not spanned by the same muscle groups.

Passive limb dynamics. Another biomechanical structural constraint that influences movement organization is the production of passive force. The magnitude of muscular force produced at one joint (e.g., elbow) is dependent on the passive force, or torque, produced by the other joints (e.g., shoulder and wrist) and the environment. There are different sources of passive torque, and this torque is produced as a result of ligament and tendon preflexes, gravitational force, centripetal and coriolis forces, as well as inertial properties of other segments (Hollerbach & Flash, 1982). Gravitational force produces passive torque, and it is most influential in the coordination of slower movements in the sagittal plane (Yamasaki, Tagami, Fujisawa, Hoshi, & Nagasaki, 2008). As long as the action does not occur on a horizontal surface, and the line between the axis of rotation and the center of mass of a segment is not parallel to the gravitational pull, a passive torque will be applied to the joint attached to that segment. Depending on the emerging movement pattern, this torque can be constant or constantly changing. It does not matter if the movement is static or dynamic. The CNS must adapt the muscular torque to modulate/control gravitational torque during both types of actions (e.g. Yamasaki et al., 2008). Since most goal-directed actions are dynamic, other passive forces are present during such multi-joint movements.

Regardless of the presence of bi-articulate muscles, the acceleration of one segment and its inertial properties will affect the overall net torque of the other joints involved in the action (Hollerbach & Flash, 1982). For example, during reaching due to acceleration of the shoulder joint, and its moment of inertia, an additional torque can be translated to the elbow and the wrist. This torque is also known as inertial coupling force (Zatsiorsky, 2002). This force constrains action because it contributes to angular displacement of the other joints involved in the action. Hence, the CNS must adapt or regulate the magnitude of muscular torque at the joint that is affected by inertial coupling torque (Hollerbach & Flash, 1982).

Two other passive forces produced during multi-joint actions are centripetal and Coriolis forces. While inertial coupling force is produced from acceleration, these forces are based on the velocity of a segment (Hollerbach & Flash, 1982). Centripetal force acts through the axis of rotation, while, depending on the other joints' direction of motion, the Coriolis force acts perpendicular to the end-point path. The Coriolis force represents the phenomenon where the closer an object is to the access to rotation, the faster it moves, and the farther away, the slower it moves. (Hollerbach & Flash, 1982). If one joint is stationary, these forces are not present. When all joints are in motion, however, the frame of reference becomes non-inertial and the centripetal and Coriolis forces affect joint rotations constituting an additional passive torque on the joints involved. In the past research, the term interactive torque was used to describe the combination of centripetal, Coriolis, and inertia coupling forces (Hollerbach & Flash, 1982). As evident, the nature of intra-limb coordination, or spatial relations, is constrained by the production of active (muscular) and passive torques at each joint involved in the action and these torques must be effectively modulated or utilized to stabilize/control an intended action (Hollerbach & Flash, 1982). Methodologically, torque modulation tendencies can be inferred from inverse dynamics, as it will be discussed in the later sections (e.g., Zatsiorsky, 2002). Collectively each of these biomechanical component function in a coalition to impact how spatial relations transpire.

Factors Affecting Torque Modulation. Similar to how spatial relations emerge, task constraints also influence how torque is modulated. Evidence from the research carried out by Dounskaia and colleagues (2002), revealed that in continuous horizontal drawing actions, the proximal joint (i.e., shoulder) was the leading joint, while the distal joint (i.e., elbow) was subordinate. During one of the actions, the proximal and distal joints switched roles, as the distal joint became the leading joint and, due to limited range of motion, the proximal joint became subordinate. Differences in torque modulation can also be task and joint specific (Newell &

Vaillancourt, 2001). During uni-manual actions in typically functioning adults, the wrist is known to move in a relatively straight path (Morasso, 1981). To produce this outcome, the muscles that control the wrist contract to perfectly oppose movement due to interactive force from the proximal joints (Koshland, Galloway, & Nevoret-Bell, 2000). This torque modulation strategy is optimal because it requires a small magnitude of muscle (active) force to produce the desired movement pattern, therefore making the movement energy efficient (Dounskaia, 2005). In cyclical elbow-wrist actions (Dounskaia, Swinnen, Walter, Spaepen, & Verschueren, 1998), however, the passive torque from the elbow was used to contribute to or counteract movement at the wrist depending on what type of action was being performed (i.e., bi-directional, uni-directional, or free-wrist pattern). Although the task goal largely influences torque modulation, other task constraints affect the underlying dynamics. In fact, modulation of interactive torque is more influential in fast movements, while gravitational torque has a larger role in slower vertical actions (Yamasaki et al., 2008). For instance, throwing a fast-ball would rely largely on modulation of interactive torque (Hirashima, Kudo, Watarai, & Phtsuki, 2007), while reaching for a stationary object is a much slower movement, therefore, relatively speaking, torque modulation would rely more on gravitational torque. Thus, the nature of torque modulation is dependent on the nature of the task, with its speed representing an important specific constraint.

Intra-limb Coordination and Control: Movement Planning

Synergies, or movement organization in general, have been examined at muscular, kinematic, as well as kinetic levels. Bernstein (1967) proposed that due to lack of one to one relations between muscles and behaviour, which is known as the motor equivalence issue as discussed earlier, actions are likely organized at the kinematic level. Thus, in order to organize movement trajectory in uni-manual tasks, the CNS must complete an inverse kinematics calculation to determine the required joint angles, in space and time, to define the emerging action (Soechting, 1989). This process is also known as joint space organization and it represents an effective method to examine how synergies form or change due to practice, learning or development. However, other researchers proposed that due to emerging invariant features of control (e.g., bell shape velocity profile of the wrist), the movements could also be planned in effector space, also known as forward kinematics. This framework, widely used in a clinical setting, examines motor impairment such as that seen after a stroke.

Forward Kinematics

Conceptual Considerations. The notion of forward kinematics suggests that the CNS plans movement around the final position of the end effector. For example, when pointing to a target or reaching for a cup of water, the CNS pre-plans motion of the shoulder and elbow so that the wrist (end effector) can arrive at its desired position. In terms of spatial planning, this process can be described mathematically as a nonlinear coordinate transformation from intrinsic coordinates (joint space) to extrinsic coordinates (hand space). Given a set of joint angular velocities in the temporal domain, the CNS by some means performs a coordinate transformation and calculates the corresponding hand velocities. One model developed by robotics uses the mathematical operation referred to as the Jacobian (a matrix-valued function encodes the relationships between joint and hand position changes) to shift between different frames of reference (Hollerbach, 1990).

The Equilibrium Point Hypothesis. This theoretical assumption led to the formation of the equilibrium point hypothesis (EP) by Anatol Feldman in the 1960 and 70’s. The fundamental concept behind the EP is that threshold position control governs intentional motor actions (Feldman, 2011). When performing a movement, electrochemical signals descending from the brain, and proprioceptive feedback to motor neurons, are transformed into changes in threshold muscle lengths or joint angles. As this process occurs, motor neurons are recruited, and the spatial activation range about body geometry is specified. This permits the CNS to specify where muscles are activated in relation to spatial coordinates without being concerned about the details of how and when the individual muscles are activated. The most advanced model of EP suggests that muscle activity is not governed by programming but rather the difference between the actual and threshold configurations and their corresponding rate of change (Feldman, 2011).

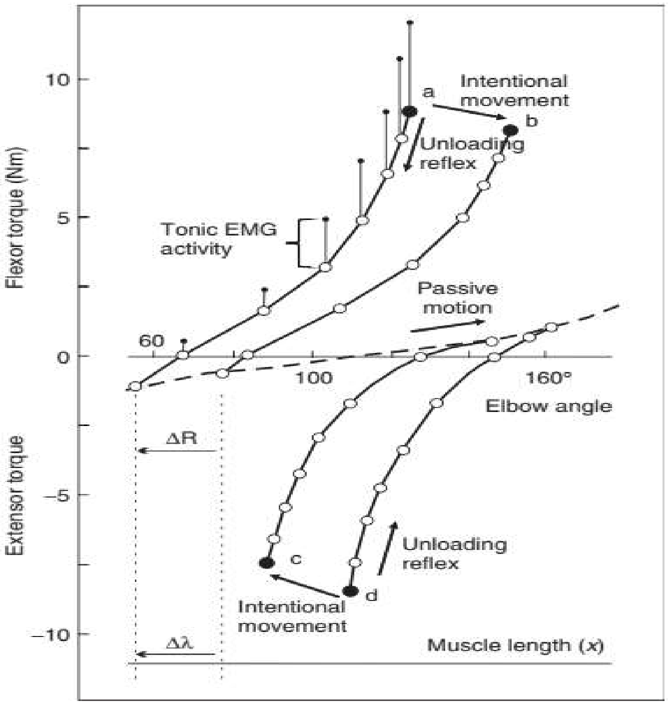


Figure 2. A visual representation of threshold position control. Static torque angle characteristics were obtained from a series of unloading experiments. The black circles represent the mean equilibrium point established by the subject unloading. The open circles represent the final equilibrium point after differing amounts of unloading. From “Space and time in the context of equilibrium-point theory” by Feldman, 2011, *Cognitive Science*, *2*(3), 287–304. (https://doi.org/10.1002/wcs.108). Copyright 2011 by WIREs Cognitive Science. Reprinted with permission.

In the original work, a series of unloading experiments carried out by Asatryan and Feldman (1965) examined the involuntary behaviour of the elbow joint when the forearm was subjected to various positions and load torques while placed on a horizontal manipulandum. The system's equilibrium point (EP), composed of a position and associated torque, was defined as the initial state in a fully relaxed position. During successive trials from each initial position, the elbow flexors were sequentially unloaded. Each participant performed three conditions. First, they were instructed not to voluntarily intervene and correct the movement but instead let the arm move to a new natural position. Second, they were asked to voluntarily change the initial position in response to the load. And third, the participants were instructed to fully relax their arms while the manipulandum extended the elbow. After plotting the flexor torque against the elbow angle, data showed that each equilibrium point generated from the first two conditions produced similar nonlinear curves that merged with the passive joint characteristics from the third condition a point R (Figure 2). In this context, "R" represented the point at which muscle activity diminished, causing active torque to cease. The researchers concluded that the threshold angle, hence "R" was invariant for the given initial command or set point. Thus, the CNS would specify a new R-value for each intentional initial arm position change. Additionally, for the muscle to be fully relaxed or active, a new R-value was shifted beyond the upper or below the lower biomechanical range of the elbow joint, respectively. Collectively, these findings suggested that the CNS uses an equilibrium point R, to plan movement. Each R contains an associated torque and angle characteristics which the CNS regulates within a angular joint range.

In individuals with a CNS injury such as stroke, the regulation of the range of R is compromised (Levin & Feldman, 1994). This impairment is classified using the tonic stretch reflex threshold (TSRT), which describes the angle that is required for spasticity to be present (Levin, 2000). Where spasticity is a state of abnormal muscle tone or stiffness that interferes with movement (Shumway-Cook & Woollacott, 2012, p. 107). The process for determining the TSRT involves first measuring the dynamic stretch reflex threshold (DSRT) from stretches at various velocities and extrapolating to a value of zero (Levin, 2000). In normal healthy individuals without motor impairment, the DSRT is normally induced at high velocities, approximately 300 radians per second (Levin, 2000). In comparison, in individuals with stroke, the DSRT is substantially lower, approximately eight radians per second (Levin, 2000). This means that when individuals with stroke attempt to move even at a slow speed, their muscles may enter a state of spasticity that hinders their ability to complete the task. At the behavioural level that can often be evident in the actions that are jerky or overflowing.

Methodological Considerations. From a methodological standpoint, Tamar Flash and Neville Hogan have combined the EP with the minimum jerk hypothesis (Flash & Hogan, 1985). This hypothesis suggested that the brain plans and controls movement based on some optimal criterion specified by a task-related cost function. To demonstrate this, in a series of experiments involving aiming towards visual targets, Flash and Hogan discovered notable endpoint characteristics that are indicative of forward kinematic control. They observed that certain invariant characteristics of the emerging velocity profiles are stable across the performance of reaching tasks, suggesting that such variables are used to plan the movement. More specifically, they showed that the velocity profiles of the end effector had a characteristic bell shape. This qualitative observation indicates that the hand starts slow, speeds up during the middle portion of the movement, and slows back down near the end, as the hand approached the target (Figure 3). They discovered that the jerk (the third derivative of position) was able to predict the smoothness of the movement (Flash & Hogan, 1985). Typically, the endpoint reaching trajectory in healthy individuals is characteristically smooth and bell-shaped. In comparison, it is uneven and discontinuous in those with stroke (Figure 4) (Cirstea & Levin, 2000).

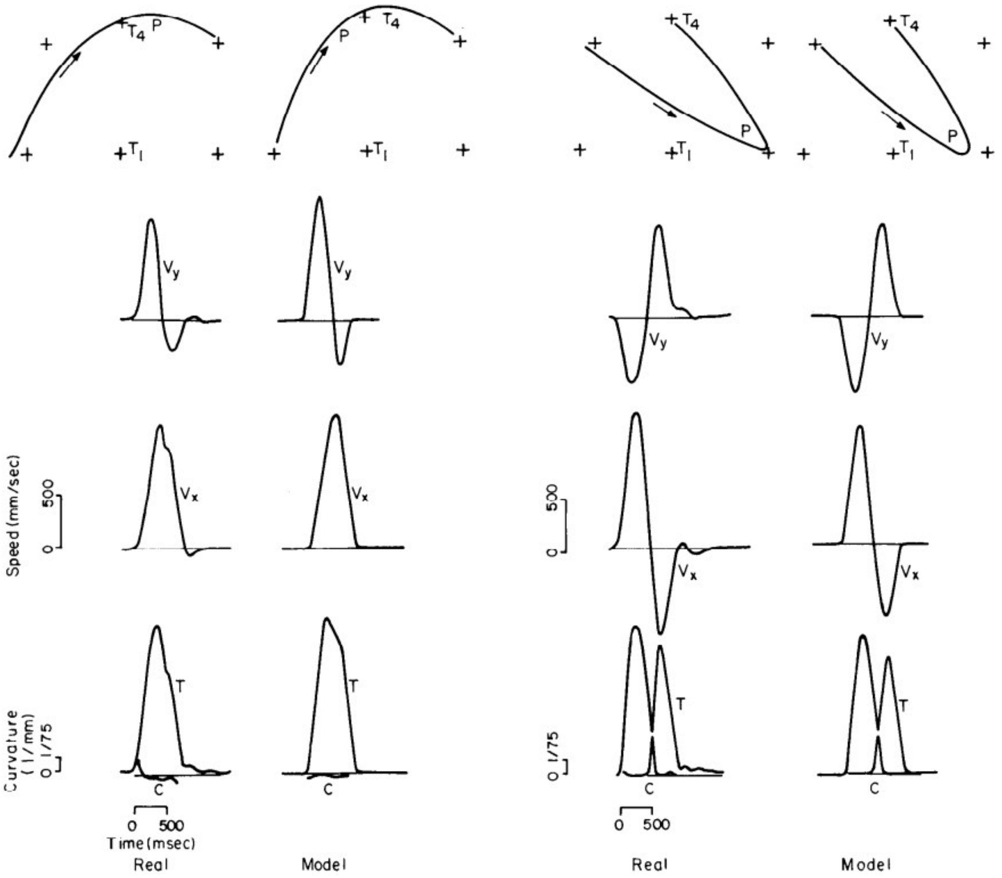


Figure 3. Example of end point trajectories between the actual (Left) and predicted model (Right) from a pointing experiment. The movement reversed direction along x and y directions. From "The Coordination of Arm Movements: An Experimentally Confirmed Mathematical Model" by Flash and Hogan, 1985, *Journal of Neuroscience*, *5*(7), 1688–1703. (https://doi.org/10.1523/JNEUROSCI.05-07-01688.1985). Copyright 1985 Society for Neuroscience. Reprinted with permission.

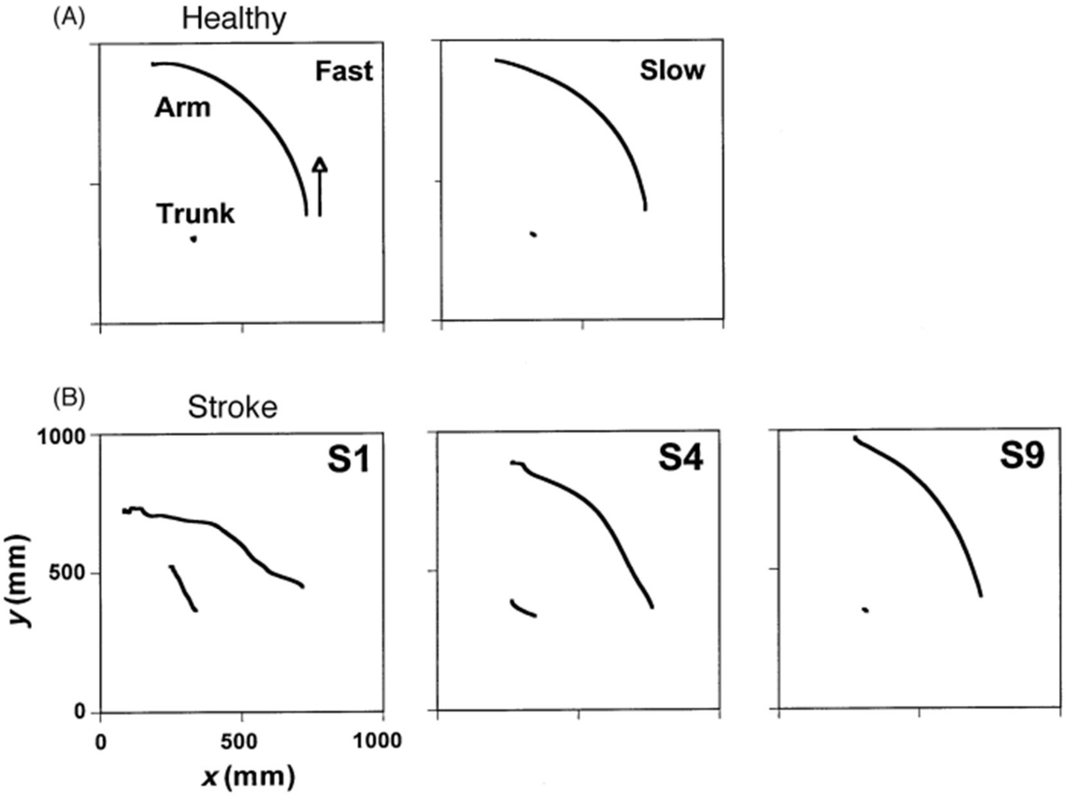


Figure 4. The average endpoint trajectories for one healthy subject performing fast and slow movements (A) and three-stroke subjects (S1, S4, S9). From "Compensatory strategies for reaching in stroke" by Cirstea and Levin, 2000, *Brain*, *123*(5), 940–953. (https://doi.org/10.1093/brain/123.5.940). Copyright 200 Oxford University Press. Reprinted with permission.

Inverse Kinematics

Conceptual Considerations. In line with assumptions of inverse kinematics it has been postulated that the CNS plans movements around the complex interactions between joints. This concept of movement planning originated in the 1920s when Bernstein conducted his famous blacksmith study. In his study, Bernstein examined the endpoint and joint kinematics of professional blacksmiths striking a chisel with a hammer (Bernstein, 1930). The results revealed that the variability of the tip of the hammer was smaller compared to the trajectories of the individual joints. This was surprising, as during a striking movement, deviation of any joint from its average angular trajectory was expected to produce a larger deviation in the location of the hammer tip compared to the deviation of individual joints. Given that the brain cannot transmit signals to the hammer, Bernstein argued that joints do not act separately but rather in functional units known as synergies to correct each other's errors.

When examining how movements are organized from an inverse kinematics perspective, spatial characteristics are primarily considered. These issues, which are typically examined in the form of angular joint positions, are used to infer how two joints couple or work together (Hollerbach, 1990). In the context of intra-limb coordination, temporal coupling can also be examined but it is methodologically complicated, and kinematically it is difficult to infer the qualitative differences of emerging movement patterns (Hollerbach, 1990). Thus, spatial organization of movement is of primary importance when examining intra-limb coordination and control in an intrinsic or extrinsic frame of reference (Hollerbach, 1990). As it was mentioned before, one main factor that shapes the nature of the emerging patterns, their kinematic parameters, and the underlying control mechanisms is the nature of the task.

Decades after Bernstein's initial investigations, Soechting and Lacquaniti (1981) identified the existence of invariant spatial relationships between the joints during goal-directed reaching. These invariant relationships are essential as they provide insight into which parameters are controlled by the CNS when organizing actions. For example, when performing a simple reach with the upper limbs, angular displacement of the shoulder and elbow are tightly coupled. This indicates that as one joint moves in space so does the other, in a stable synergistic relationship. More importantly, this relationship is invariant or unchanging across people with similar skill levels and different task demands (e.g., different movement speeds) (Soechting, 1984). Thus, the shoulder and elbow relationship represents an essential unit of action when performing goal-directed pointing/reaching actions.

Another important characteristic of uni-manual goal-directed actions is the relationship between the shoulder and wrist and the elbow and wrist joints. Similar to the shoulder-elbow spatial relations, the shoulder-wrist and the elbow-wrist joints are also controlled as one coordinative structure. However, as indicated by previous research the degree of the emerging coupling is smaller, and the relationship is weaker (Figure 5) (e.g., Lacquaniti & Soechting, 1982). This is likely due to the skeletal / muscular constraints, as the magnitude of angular displacement of the wrist (i.e., its range of motion) is smaller as compared to the range of motion of the shoulder and elbow. Additionally, given that wrist actions must accommodate spatial demands of the task, it is plausible that at some point when performing a reaching action, the wrist maybe controlled more independently, thus resulting in a lower degree of coupling, yet one that is still functional and task-goal specific. These changes, in the emerging coupling between the respective joints have been well documented in the work of Lacquaniti and Soechting, (1982; 1981) (see Figure 5).

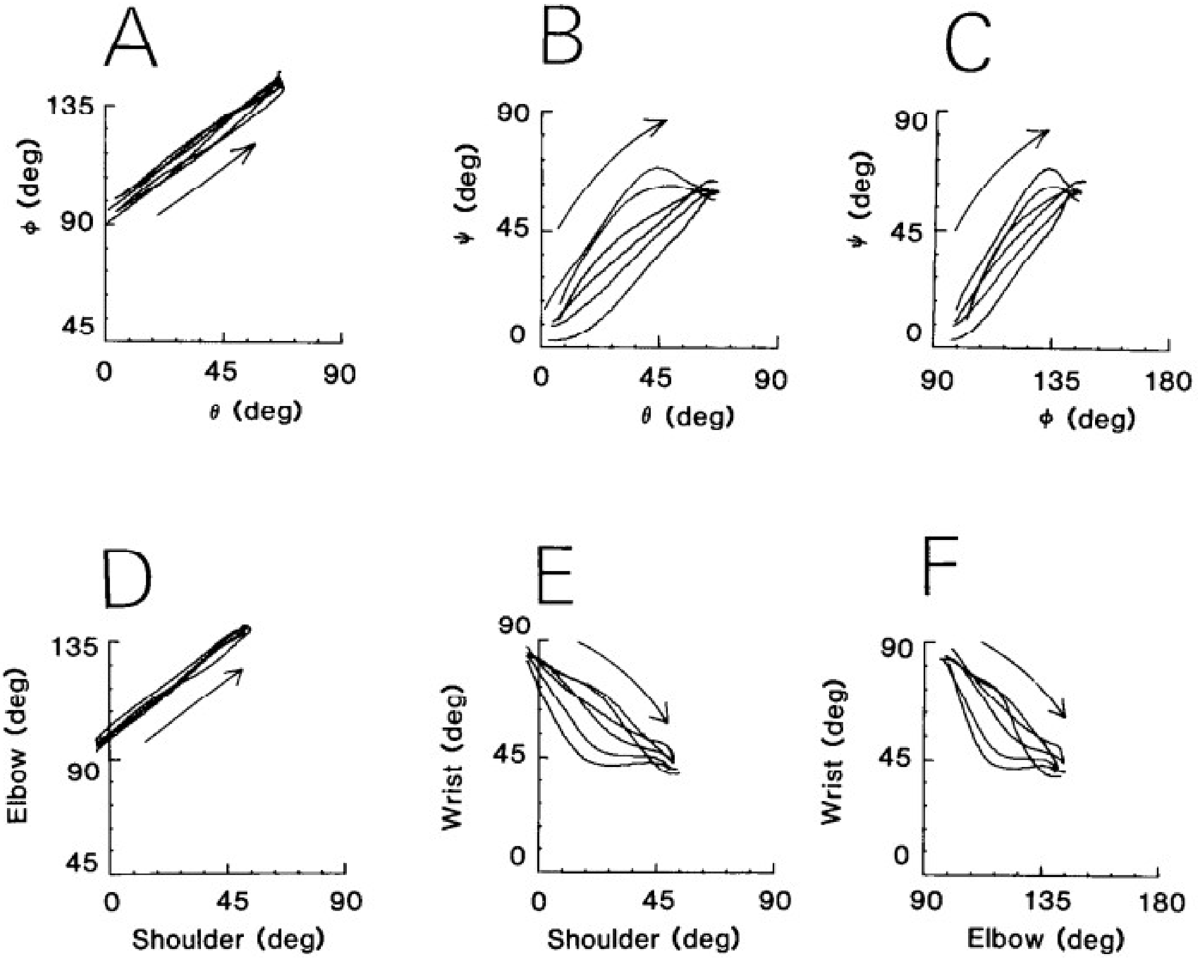


Figure 5. Angle-angle diagrams depicting relations between the wrist, shoulder, and elbow while performing a reaching task. The top row represents trials involving pronation of the wrist while the bottom represents trials involving supination. This figure illustrates that elbow-shoulder motion is tightly coupled when compared to the wrist-shoulder, and wrist-elbow motion. From "Coordination of Arm and Wrist Motion During A Reaching Task" by Lacquaniti and Soechting, 1982, *The Journal of Neuroscience*, *2*(4), 399–408. Copyright 1982 Society for Neuroscience. Reprinted with permission.

Uncontrolled Manifold

The need to better understand and quantify the synergistic relations between the joints led to the development of the uncontrolled manifold (UCM) hypothesis, within the field of synergetics (Schoner, 1995; Scholz & Schoner, 1999; Latash et al., 2007). This hypothesis was originally formulated when attempting to explain how Bernstein was able to compare end-effector trajectories and joint level trajectories. The main problem of interest was that a direct comparison between the end effector paths and joint trajectories is not possible as the latter is measured in linear variance (centimeters squared), while the former is measured in angular variance (radians or degrees squared) (Latash et al., 2010). To solve this issue, one solution involves the use of joint space as an embedded space where all variance is evaluated. This subspace, known as the UCM, contains all the combinations of joint angles that relate to any particular end-effector position. A unique UCM is generated for each possible end-effector position. The hypothesis behind the UCM is that during a movement, joint configurations fluctuate within the subset rather than outside of it for any end-effector position (Latash et al., 2010).

To analyze the variability on joint space, a mathematical operation creates two components within the UCM (V_{UCM}) and one orthogonal to the UCM (V_{ORT}) (Scholz & Sconer, 1999). At the level of the spatial task variable, V_{UCM} is considered good variability while V_{ORT} is bad variability. The hypothesis is that a synergy contain more V_{UCM} than $V_{ORT,}$ and vice versa for a none syergy. This means that the CNS preferentially adopts combinations of joint angles that stabilize the spatial task variable and are within V_{UCM}. For example, when considering a task involving two joints where both joints are constrained to couple together to produce a combined force of 40newtons under various perturbations. If the two joints can be coupled, to adapt and maintain a constant force of 40newtons, this indicates a strong synergy, as the system exhibits has stability via compensation. In contrast, if the two elements fail to maintain the functional outcome, and the total force deviated above or beyond 40newtons, this would indicate a non-synergistic relation where the system lacks flexibility and stability (Latash, 2008b).

Even though the UCM is a powerful tool used to examine the flexibility and stability of synergies, it contains a few notable limitations. First, many data points are required to analyze the variance in the space of a set of motor elements (Latash et al., 2010). This can be an issue for certain populations as they may be limited in their ability to perform many trials. Second, the UCM requires relatable changes in a hypothesized task variable to changes in the space of the motor elements (Latash et al., 2010). For kinematics, this is not an issue as the Jacobian parameters of the system allow the representation of task-specific variables in the space of elemental variables (joint angles) (Latash et al., 2010). Third, the appropriate task variable must be selected for the particular movement in relation to the nervous system (Latash et al., 2010). The relative importance of these variables can be estimated by examining the variance of elemental variables relative to different task variables. For example, Scholz and Schöner (1999) found that the joint variance was organized to stabilize the horizontal center of mass (COM) position for sit-to-stand movements compared to the vertical COM. Lastly, there is debate on the correct method of interpreting the two variance components (V_{UCM} and V_{ORT}) to determine the strength of a synergy (Latash et al., 2010). For example, two common methods include the use the ratio or the relative difference between the two components with a greater value indicating a stronger synergy. However, this approach should be interpreted with caution, as each component's individual magnitude should be taken into account. For example, a study examining the reaching ability between healthy control participants and those who experienced a stroke found similar synergy strengths using either method (Reisman & Scholz, 2003). However, the individuals with stroke exhibited significantly more overall joint variance in V_{UCM} and V_{ORT} and greater task error, indicating that their synergies were in fact being coordinated in less-than-optimal fashion.

Methodological Considerations. When inferring coordination, more specifically intra-limb coordination, the emphasis is on examining the qualitative nature of the emerging actions. This is often accomplished by capturing the nature of the emerging spatial relations between the joints via angle-angle diagrams, or by quantifying them with the use of correlations. When the two joints couple, this indicates that the change in spatial location of one joint is unfolding proportionally to the changes in the other joint. For intra-limb coordination, when neurologically intact individuals perform reaching and grasping, shoulder and elbow relations generally exhibit such coupling (Lacquaniti & Soechting, 1982). However, the nature of such relations can change when a different task is carried out or in individuals whose motor performance is jeopardized by stroke are performing the skill. When individual joints are considered (e.g., angular displacement of the elbow or shoulder), this type of information provides an insight into the “control” issue, rather than coordination. It is plausible that the coupling between the joints may remain intact while the control of individual joints changes. This would imply that the possible issue that a participant has is in the domain of control rather than coordination. When the entire pattern changes qualitatively, this could coincide with changes in coupling, hence changes/differences in movement coordination. Although the temporal aspect of movement organization can also be examined at the intra-joint level, as it was mentioned previously, this approach is not implemented as frequently as it is the case in the inter-limb coordination where such temporal relations between the same joints across the two limbs.

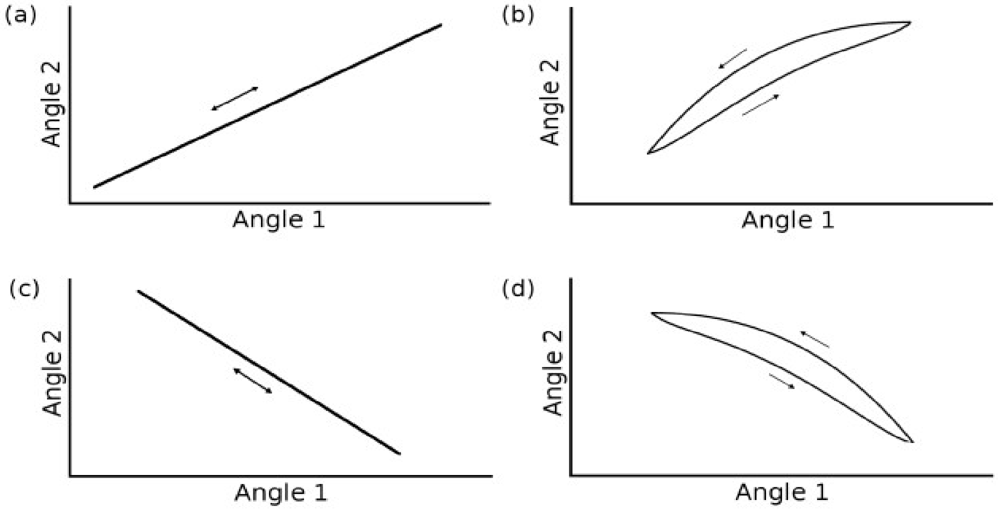


Figure 6. Angle-angle diagrams indicate two basic types of coordination, in-phase, and anti-phase. Upper (a) and (b) represent in-phase coordination. Lower (c) and (d) represent anti-phase coordination. From "Assessing Movement Coordination" (p. 3) by Lamb and Bartlett, 2017, Routledge. Copyright 2017 Taylor and Francis (Books) Limited UK. Reprinted with permission.

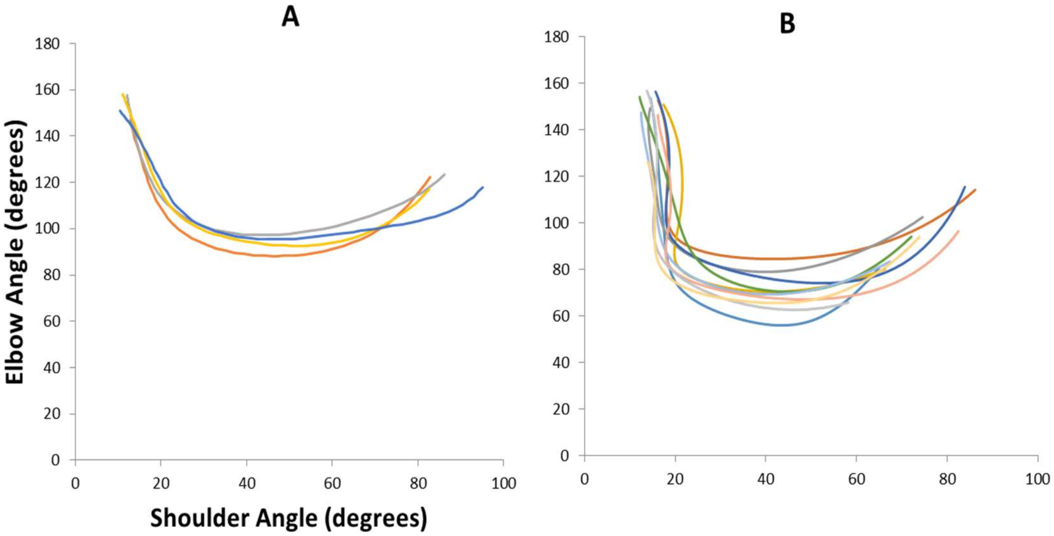


Figure 7. Angle-Angle diagrams indicating the change in inter-individual variability of elbow and shoulder relations for individuals with a minor (A) and more severe impairment (B). "Example of angle-angle plots"

Qualitative Approaches. When examining coordination patterns qualitatively, the most widely used method involves angle-angle diagrams. These diagrams show how two angles 'co-vary', hence how one angle changes as a function of the second. Two joints are in phase or have 'turning point' coordination when both joint angles change in the same direction (see Figure 6, a and b) (Lamb & Bartlett, 2017). For example, when reaching, the elbow and shoulder are considered to be 'in phase' when the elbow extends while the shoulder flexes. Likewise, the two joints are said to be 'out of phase' when the two joint extends or flex simultaneously, or when one joint adducts and the other abducts (see Figure 6, c and d) (Lamb & Bartlett, 2017). For example, when reaching, the shoulder and elbow are out of phase when the shoulder flexes while the elbow extends.

There are many advantages to using angle-angle diagrams. First, they allow for easy visual examination of how two joints co-vary without the need to flip between angle-time graphs, Second, it is easy to display even the most subtle difference in movement coordination between the two joints. Third, they afford the ability to examine intra-individual and intra-group variability. For example, individuals with less severe stroke coordinate the shoulder and elbow joint in a more stable fashion as compared to those with more severe stroke (Figure 7). In contrast, the main disadvantage of using angle-angle diagrams is that it prevents analysis of the degree of coordination in terms of movement outcome measures. As a result, this leads to difficulties when comparing the nature of the emerging coordination patterns across groups, tasks, joints, or all of the above statistically or quantitatively. Also, from the standpoint of precision and accuracy the inferences emerging from the angle-angle plots are subjective and can be interpreted differently, without any normative data or gold-standard to relay on.

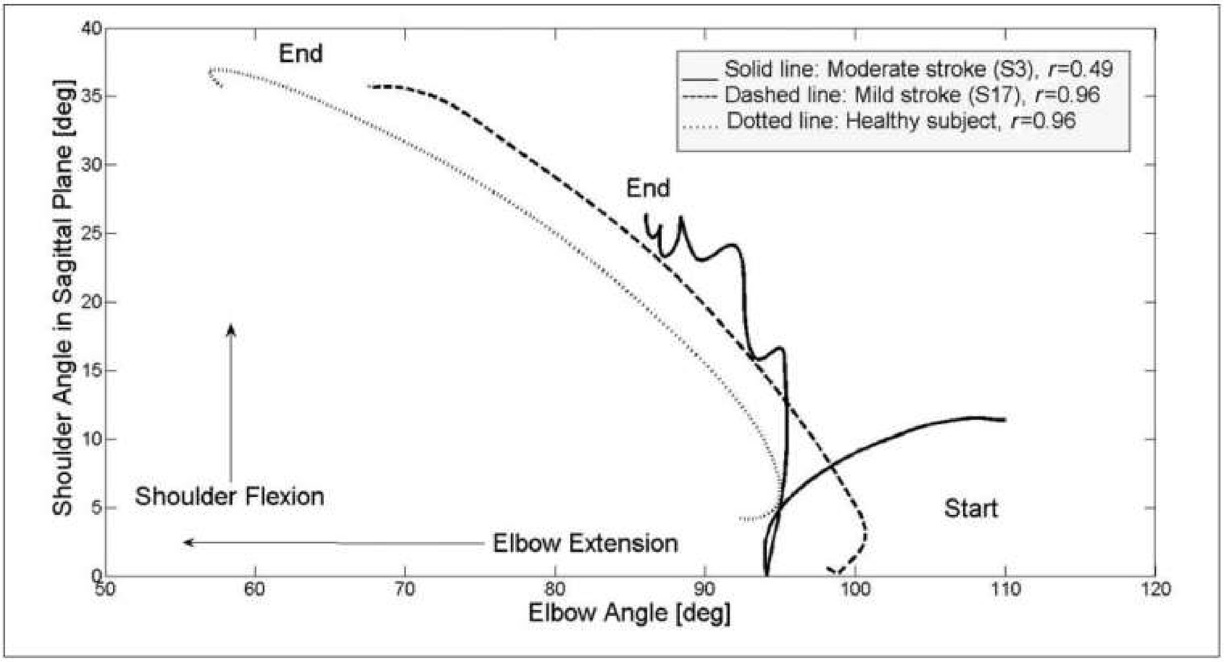


Figure 8. An angle-angle diagram showing the inter-joint coordination and correlation coefficients between the shoulder and elbow joints while reaching for a glass for healthy participants and those with mild and moderate impairment post-stroke. Reprinted with from "Kinematic Variables Quantifying Upper-Extremity Performance After Stroke During Reaching and Drinking from a Glass" by Alt Murphy et al., 2011, *Neurorehabilitation and Neural Repair*, *25*(1), 71–80. (https://doi.org/10.1177/1545968310370748). Copyright 2010 by SAGE Publications.

Quantitative Approaches. To address the issues related to the usefulness of angle-angle diagrams, researchers drew upon the work of statisticians and applied the use of correlations. The most widely used correlation technique, Pearson Product Correlations Coefficient (r), is implemented to quantify the degree and stability of spatial and temporal coordination between two joints (inta-limb) or between limbs (inter-limb). An r-value closer to one indicates greater coupling between the two joints, while an r-value closer to zero indicates decoupling and more asymmetric actions, where one joint moves independently of the other joint. For example, when reaching, healthy individuals exhibit tighter coupling (r = .96) between the shoulder and elbow compared to those with series motor impairment such as stroke (r = .49) (Figure 8). As evident from the diagram below in Figure 8 the differences emerging at the qualitative level are captured by the outcome measures, in this case the Pearson r. One of the main advantages associated with correlations is that they can reveal aspects of coordination that may not be apparent in other approaches. For example, it is easy to determine if one joint lags behind the other. However, even though the calculations associated with correlation functions are quantitative; their interpretation is mainly used to infer the qualitative aspect of the movement.

Collectively, inverse kinematics offers a conceptual and methodological insight into the issues of intra-limb coordination and control. This contrasts with forward kinematics which can only address the issue of control. The nature of the relationship between the joints can be captured qualitative and quantitatively, each with its own advantages and disadvantages. In addition, it is also important that the nature of the approach taken to be considered in the context of the task, and individual constants of the participants (e.g., biomechanical properties of their system).

Inverse Dynamics

Conceptual Considerations. The nature of intra-limb coordination, especially in the spatial domain of organization, is constrained by the production of active (muscular) and passive forces at each joint involved in the action, as these torques must be effectively modulated to control an intended action (Hollerbach & Flash, 1982). In regards to the motor equivalence issue, planning action at the kinetic level provides a unique solution as there is one-to-one correspondence between the action that emerges and the forces that produce it. However, an important issue that needs to be overcome is that methodologically performing inverse dynamics is rather complex (e.g., Zatsiorsky, 2002). In order to carry out an inverse dynamics calculation, the kinematic data, along with anthropometric data, must be used to estimate the forces produced at the joints involved (e.g., Jensen, 1986; Zatsiorsky, 2002).

From a motor control standpoint, there are two hypotheses regarding the role of torque modulation in movement organization (Dounskaia, 2010). One hypothesis suggests that to organize functional actions the CNS completes an inverse dynamics calculation to determine the required torques for a given configuration of the joints (Hollerbach, 1982). The problem with this hypothesis is that a very detailed model of the joints' underlying kinetics and kinematics is needed, making it complicated to adjust torque production when small perturbations are present (Dounskaia, 2010). Another hypothesis is that optimal movement organization is marked by the ability to utilize passive torque at the distal joints due to acceleration/deceleration of the most proximal joint. For example, in goal-directed actions such as reaching (e.g., Galloway & Koshiand, 2002; Gribble & Ostry, 1999), the shoulder produces a large muscular torque that would transfer an interactive torque to the elbow. The muscles that control the elbow joint would utilize the interactive force to assist in producing an effective action across the arm, meaning less active muscular torque is required to move the elbow joint.

This evidence is also consistent with Bernstein's (1967) original notion that optimal movement is marked by an individual utilizing the reactive phenomenon that arises from multiple joint interactions and the environment. Bernstein's idea was extended and further developed by Dounskaia (2005) in the leading joint hypothesis. According to this hypothesis, the leading joint's underlying dynamics are similar to a single-joint movement, as the majority of joint displacement is due to muscular torque and only partially depends on interactive torque. In most cases, the more proximal joint (e.g., shoulder) is the leading joint because it moves through a large range of motion. When the leading joint is proximal, the more distal joints (e.g., elbow and wrist) are subordinate and modulate the passive torque from the leading joint to contribute to their own displacement.

Less than optimal torque modulation has been studied in many populations while performing simple goal-directed actions such as reaching or pointing. These populations include, but are not limited to, infants (e.g., Dichgans & Konczak, 1997; Jensen, Thelen, Ulrich, Schneider, & Zernicke, 1995; Zernicke & Schneider, 1993), elderly individuals (e.g., Ketcham, Dounskaia, & Stelmach, 2004), and persons with a neurological impairment (e.g., Bastian, Martin, Keating, & Thach, 1996; Bastian, Zackowski, & Thach, 2000; Dounskaia, Ketcham, Leis, & Stelmach, 2005; Ghez & Sainburg, 1995). Developmentally, it is known that tasks requiring force/torque adaptations (e.g., catching, reaching) are adult-like by the age of 9-12 years old (e.g., Savelsburgh & van Santvoord, 1996). However, it remains unclear when torque modulation becomes mature in voluntary movements, particularly those taking place under external time demands when speed is a primary task constraint. When infants organize goal-directed reaching movements, the elbow joint precedes the motion of other joints in the limb (Konczak & Dichgans, 1997; Zernicke & Schneider, 1993). This sequence results in decoupling or segmentation at the behavioural level of analysis. To move each joint independently, the passive force must be counteracted at the joint that is frozen out by utilizing the passive torque (Zernicke & Schneider, 1993). In early reaching, this tendency is not present and the result is a segmented movement pattern (Zernicke & Schneider, 1993).

Another consequence of less than optimal torque modulation is the lack of ability to utilize large magnitudes of interactive torque at the subordinate joint(s) (Bastian et al., 1996; Bastian et al., 2000). This tendency is problematic because the muscles are not able to control the passive torque. For example during a pointing task, adults with cerebellar lesions were required to keep the shoulder stationary, but the interactive torque from the elbow (i.e., leading joint) was ineffectively regulated (Bastian et al., 2000). At the behavioural level, this transfer of passive torque ultimately produced an excessive, ineffective freeing of the shoulder joint and an erroneous trajectory of the hand (Bastian, et al., 2000). Thus, freezing can be underlined by less than optimal torque modulation and ineffective freeing can be due to a different tendencies to manage interactive torque.

Methodological Considerations. Similar to how spatial relations emerge, the task also influences how torque is modulated out of the relationship between the different constraints. Evidence from the research carried out by Dounskaia and colleagues (2002), revealed that in continuous horizontal drawing actions, the proximal joint (i.e., shoulder) was the leading joint, while the distal joint (i.e., elbow) was subordinate. During one of the actions, the proximal and distal joints switched roles, as the distal joint became the leading joint and, due to limited range of motion, the proximal joint became subordinate. The nature of torque modulation can also be task and joint specific (Newell & Vaillancourt, 2001). During uni-manual actions in typically functioning adults, the wrist is known to move in a relatively straight path (Morasso, 1981). In order to produce this outcome, the muscles that control the wrist contract to perfectly oppose movement due to interactive force from the proximal joints (Koshland, Galloway, & Nevoret-Bell, 2000). This torque modulation strategy is optimal because it requires a small magnitude of muscle (active) force to produce the desired movement pattern, therefore making the movement energy efficient (Dounskaia, 2005). However, in cyclical elbow-wrist actions (Dounskaia, Swinnen, Walter, Spaepen, & Verschueren, 1998), the passive torque from the elbow was used to contribute to or counteract movement at the wrist depending on what type of action was being performed (i.e., bi-directional, uni-directional, or free-wrist pattern).

Collectively, due to one to one relation between torque modulation and the emerging actions (e.g., coupling or decoupling), inverse dynamics represent an important tool into examining the underlying causes of less than optimal movement organization, especially at intra-limb level of coordination and control. However, as stated earlier, this methodological approach is complex, hence the majority of the studies tend to describe the emerging coordination and control at kinematic or muscular level of organization, and devote less attention to the underlying causes of the emerging actions via inverse dynamics.

Stroke and Intra-limb Coordination

Existing Reviews

Research on unimanual upper limb coordination post-stroke first originated in the second half of the 1990s. Early descriptive studies using kinematic analysis were conducted to establish the methodology and evaluate reaching performance when compared to healthy controls. Approximately a decade later, intervention studies using kinematic-based outcome measures were performed to investigate movement performance during recovery. Since the initial investigations, the interest and the scope has increased, and a substantial number of new descriptive and intervention-based studies have been published. As a result, numerous reviews have been conducted to synthesize and interpret the findings.

An initial scoping review by Murphy and Hager (2015) comprehensively reviewed research using kinematic movement analysis of the upper extremity in individuals with stroke with a focus on objectives, methodology, and findings. After searching only one database (PubMed), the researchers accumulated a total of 93 studies. The studies were examined in the context of their kinematic methodologies, the task used, the ability of the kinematic measures to differentiate between different levels of impairment, the relationships between kinematic measures and clinical measures, as well as the reliability of the kinematic measures. The main findings indicated that most studies used optoelectronic motion capture systems, used a discrete reaching task, examined individuals with mild to moderate motor impairment in the chronic stage of stroke, and used both temporal and spatial based kinematic measures. The authors did not classify them in terms of the level of planning being examined, hence forward vs. inverse kinematics. In relation to tasks, only a brief discussion on the difference between discrete (i.e. simple pointing tasks) and more real-life (i.e. grasping a cup filled with water) was provided. Also, the authors did not distinguish between issues in coordination or control. In relation to kinematics, only a brief general description of the difference between temporal and spatial measures was provided. More importantly, there was no attempt to make a connection between the emerging data and the underlying conceptual models related to coordination or control, as discussed earlier.

Furthermore, four more recent systematic reviews have been published. Based on the neuroscience perspective, Roby-Brami and collegues (2021) published the most recent review. Two other papers were written by the same group of authors and focused on the methodological considerations (Mesquita, Fonseca et al., 2019; Mesquita, Pinheiro et al., 2019). The remaining study by Schwarz et al (2019) summarized the kinematics of upper limb assessment post-stroke in relation to the task, measurement systems, as well as performance and clinical based metrics. After searching four databases (PUBMED, EMBASE, CINAHL, and IEE Explore) 225 studies were analyzed. These studies were classified based on the assessment tasks, measurement systems, and kinematic metrics. Regarding the assessment tasks 81 examined two-dimensional pointing, 16 used two-dimensional shape drawing, 67 examined three-dimensional pointing, 50 used three-dimensional reach to grasp, and 24 examined other tasks. The measurement systems were categorized into three groups A, B, and C with 130, 69, and 26 in each category respectively. Group A contained measurement systems with minimal influence on movements such as inertial or electromagnetic motion capture, group B contained systems with minimal influence such as end effector or motion capture systems, and group C contained systems with high influence such as exoskeletons. In line with the purpose, the main findings were primarily designed to help guide clinicians towards selecting appropriate kinematics measures and provide recommendations to enhance the standardization of kinematics across future studies. The conceptual relevance of the findings, in regards to the existing models of coordination and control were not addressed.

In a similar fashion, Mesquita, Pinheiro and colleagues (2019) first installment analyzed the kinematics of upper limbs in relation to sampling and motor tasks in both healthy and post-stroke individuals. After searching PubMed and the resource aggregator 'B-on' using the EBSCO EDS interface, a total of 14 studies were included in the review. Of these studies, four included only healthy participants, three studies only post-stroke individuals, and seven included both healthy and post-stroke participants. In comparison to the study by Murphy and Hager (2015) and Schwarcz et al (2019), this small sample size was primarily the result of excluding literature related to robots, exoskeletons, or the use of virtual reality methodologies. The analysis was limited to identifying participant characteristics (age, weight, sex, clinical motor impairment score, time since stroke) and motor tasks (reaching and grasping, drinking, solving a puzzle using a touch screen) used in each study. For the motor tasks, a brief discussion was provided about the analysis of activity of daily living tasks such as drinking. However, no details were provided about the nature of the tasks related to coordination or control issues. In the second part of this project, Mesquita, Pinheiro and colleagues (2019) analyzed the motion capture systems and kinematic metrics (Mesquita, Pinheiro et al., 2019). For the motion capture systems, seven studies used optoelectronic systems with passive markers, two used optoelectronic systems with active LED markers, one used the Microsoft Kinect system, three used electromagnetic systems, and one article used inertial measurement systems. Regarding kinematics metrics, each was subcategorized as joint or endpoint measures. Similar to Alt Murphy and Hager (2015) and Schwarz et al. (2019), only the kinematic metrics were reported. None of them were interpreted into a corresponding conceptual model such as forward kinematics, inverse kinematic, or inverse dynamics.

Most recently a review based on the neuroscience perspective was published by Roby-Brami and colleagues (2021). This was a scoping review that focused on motor impairment and compensation in dexterous upper-limb function after stroke (Roby-Brami et al., 2021). Only one small section was devoted to the kinematics of reaching to grasping movements in their analysis. In this section, a brief discussion of temporal and spatial measures and their link to corresponding issues of coordination and control were provided. However, only very few studies were examined, and they were mainly descriptive. In addition, there was relatively limited analysis and discussion of the role of different constraints on movement organization, and once again, no attempt was made to systematically examine the degree to which existing conceptual models have been applied in the published work being reviewed.

Collectively, due to the increase in interest in research examining intra-limb coordination post-stroke, numerous reviews have been published. Two scoping reviews provided a thoughtful explanation of the importance of temporal and spatial measures (Murphy & Hager, 2015; Roby-Brami et al., 2021). Moreover, three systematic reviews, two of which provided insight on how to standardize kinematics and tasks for future rehabilitative studies (Mesquita, Fonseca, et al., 2019; Mesquita, Pinheiro, et al., 2019; Schwarz et al., 2019). Although these reviews represent a positive starting point to provide an overview of the existing literature, still many issues need further analysis and systematic review.

Summary and Purpose

Stroke results in substantial difficulties in motor actions. These problems may emerge at different levels of coordination and control, in spatial as well as in the temporal domains. In the context of daily activities, these problems may affect a person's balance, gait, and in many instances, the ability to perform upper limbs actions, such as reaching for a cup while drinking coffee in the morning. Much research has been devoted to these issues over the last two decades, and there are few studies that attempted to provide an overview of what was done, and how. However, these reviews fell short on attempting to provide researchers and clinicians with a clear "picture" of the emerging trends, in particular when related to the link between the studies and the motor behaviour theories and models.

This study will examine the existing literature related to uni-manual (intra-limb) coordination and control in individuals who suffered a stroke. As a result, the purpose of this review is three fold. The first purpose is 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 done within the conceptual framework of forward and inverse kinematics, or inverse dynamics. Here, also a particular interest will be placed on identifying specific theories of motor control (e.g., Equilibrium Point Hypothesis) that have been used in those studies. The second purpose is to delineate which constraints on coordination and control have been examined, in regards to different tasks, most importantly individual constraints (e.g., biomechanical), and environmental constraints. The third purpose is to address the methodological aspects of the existing studies, hence the prevalence of different measures of coordination (angle-angle plots; correlations) and control. The review culminated with exploring the potential avenues for future research, from both conceptual as well as methodological standpoints.

Method

Search Strategy

A systematic, literature search was performed to identify all relevant research articles. The primary search method involved an electronic database search results of the CINAHL PubMed, Medline, and Web of Science databases. To include literature since the last published systematic review (Schwarz et al., 2019) each database was searched from January 1 2019 until March 31, 2022. The search terms used included keywords such as "stroke", "unimanual", "coordination", "upper limb" (please refer to Appendix A, Table 2 for a complete list of terms). The secondary search method involved an electronic search using Google Scholar. In addition, relevant articles were identified from the reference list from each study obtained from the primary and secondary search methods.

Eligibility Criteria

Inclusion Criteria

Participants Characteristics. To be included in this review, each study contained participants that meet the following: are either or both male and female sex, have a minimum age of at least 18 years of age, have been diagnosed to have a stroke, classified as 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). Chronicity as defined above is the time since the cerebral vascular accident with hyper acute as less than 24 hours, acute as one to seven days, early subacute as seven days to three months, late subacute as three to six months, and choric as greater that six months since the event (Bernhardt et al., 2017).

Study Designs. This review analyzed both rehabilitation interventions and descriptive studies that examine upper limb unimanual coordination in individuals with stroke. The types of study designs included randomized controlled trials (RCTs), cohort studies, case-control studies, cross-sectional studies, and case reports and series.

Exclusion Criteria

This review excluded the following literature: 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 (Schwarz et al., 2019).

Data Collection and Analysis

Selection and Characteristics of Studies

All of the search results were initially screened by one researcher (MP) using the Rayyan mobile application (Ouzzani et al., 2016). Rayyan is a free web application tool designed to aid researchers working on systematic reviews, by significantly speeding up the screening and selection process. 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 (Appendix B, Figure 9).

Data Collection

The data from each study was collected by using a collection form (Appendix E, Table 4), that was piloted by two reviewers (EP and MP). This form included information about the first author and publication year; title; participants (number, gender distribution, age, type of stroke (ischemic/hemorrhagic), side of brain lesion (left/right), stroke chronicity, upper limb motor function), aim/purpose, methods/design, main findings, limitations, and conclusions. These data were then checked by a second reviewer for accuracy. Lastly, the PRISMA 2020 checklist (Appendix B) was used as a reference to ensure all components are included.

Quality Assessment

The quality of each study and this review were examined using validated assessment tools. The methodological quality of each study was evaluated using the Downs and Black (Downs & Black, 1998) (Appendix C, Table 3) checklist. This checklist consists of 26 items in total, with nine items assessing reporting, three examining external validity, seven assessing bias, six examining confounding factors, and one assessing power. The maximum achievable score is 31. The recorded quality index score was calculated as the percentage of the maximum value. Lastly, the AMSTAR-2 (Appendix D) tool was used to assess the methodological quality of the systematic review (Shea et al., 2017).

Analysis of Conceptual Scope

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. These data were organized in a summary table (Appendix E, Table 5).

Analysis of Constraints

In line with the second purpose, each study was ranked and labelled based on the task performed and the associated 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).

Analysis of Methodological Aspects

In line with the third purpose, each study was ranked and categorized based on their included coordination and control-based outcome measures. Coordination-based outcome measure labels included qualitative (e.g., angle-angle plots) and quantitative (e.g., correlations) measures. The control-based outcome measure labels consisted of categories that include 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). All labels were recorded in a summary table (Appendix E, Table 5). In culmination, the results of the first, second, and third purposes were used to synthesize suggestions for future research in terms of conceptual and methodological considerations. This will attempt to move the field of study towards exploring potential avenues for research from a conceptual and methodological standpoint.

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. A list of excluded studies is available upon request. 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) (Adans-Dester et al., 2020; Adomavičienė et al., 2019; Demers & Levin, 2020; Ellis et al., 2017; Gandolfi et al., 2019; Garro et al., 2021; Kitago, 2019; Krakauer et al., 2021; Lai et al., 2019; Moretti et al., 2021; Pellegrino et al., 2021; Rech et al., 2020; Saes et al., 2021; Sousa et al., 2021; Thrane et al., 2019). As a result, 20 articles were deemed relevant and included in this review as each study examined unimanual actions and contained participants that were either male and female genders, have a minimum age of at least 18 years of age, have been diagnosed to have a stroke, classified as hemorrhagic, ischemic, or transient ischemic stroke (TIA), and included one or all three stages of stroke chronicity (acute, subacute, and chronic) (see PRISMA flowchart, Figure). Nine of the studies were descriptive studies (Feingold-Polak et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021; Raj et al,. 2020; Tomita et al., 2020, 2021), and 11 were interventions (Carpinella et al., 2020; Cho & Song, 2019; Gomes et al., 2021; Hussain et al., 2021; Lencioni et al., 2021; Liao et al., 2020; Montoya et al., 2022; Nibras et al., 2021; Park et al., 2020; Teremetz et al., 2022; Thrane et al., 2020). Lastly, when conducting the review neither researcher, MP, or EP experienced any conflict of interest.

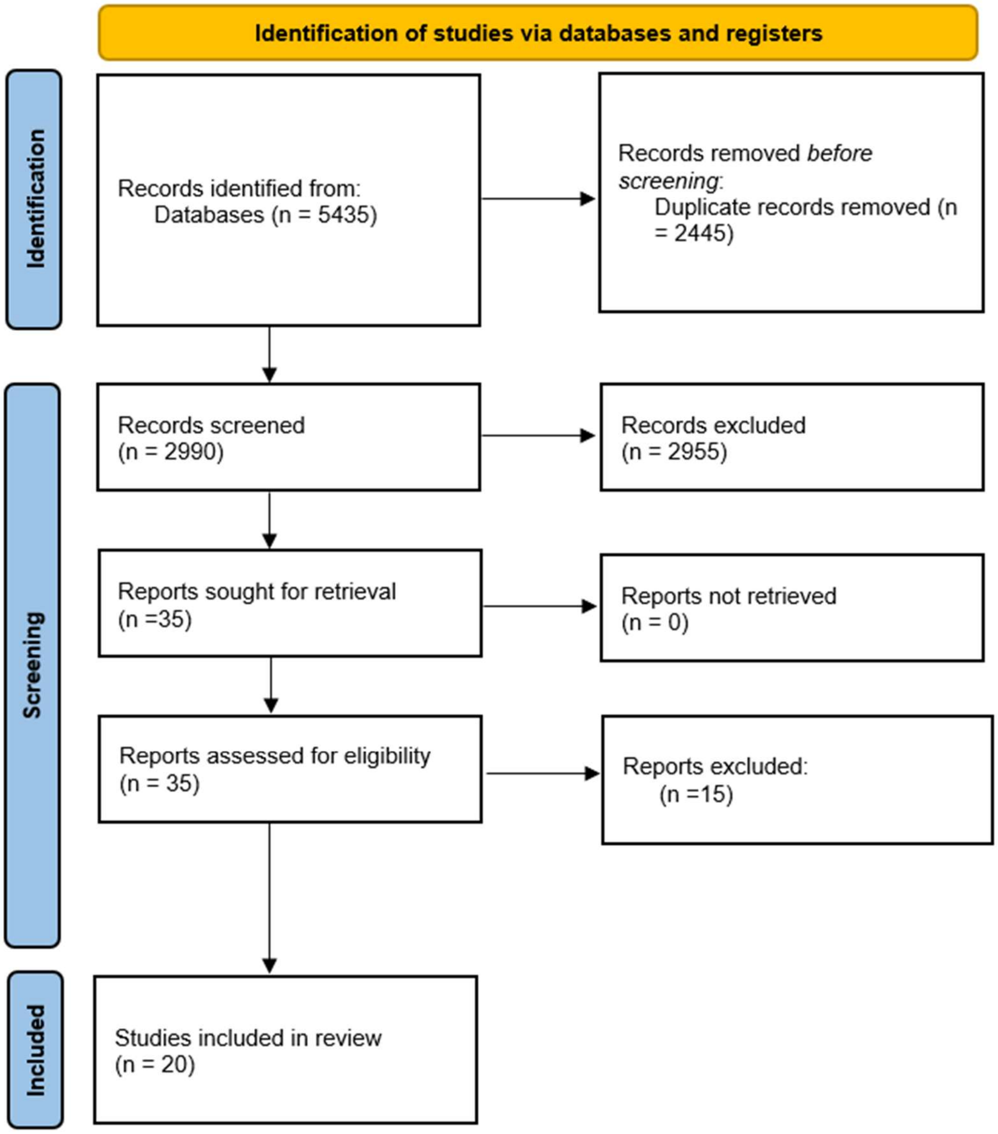


Figure 9. The PRISMA flow Chart for new systematic reviews that include searches from databases and registers only. This diagram represents the flow of information through the different phases of a systematic review. Adapted from "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews" by Page et al., 2021, *BMJ*, *372*(1), 71. (https://doi.org/10.1136/bmj.n71). Copyright 2021 by the BMJ Publishing Group Ltd.

Collected Information About Samples

The authors of the articles included an extensive description of the participants involved. All studies included information about the age of the participants (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Nibras et al., 2021; Park et al., 2020; Raj et al., 2020; Térémetz et al., 2022; Thrane et al., 2020; Tomita et al., 2020, 2021) where the mean age ranged from 54.9 ± 10.7 years (Park et al., 2020) to 70.3 ± 9.3 years (Feingold-Polak et al., 2021). The sample size of the included participants ranged from 9 participants (Raj et al., 2020) to 66 participants (Hussain et al., 2021). A total of 19 studies did not include justification for their sample size (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Nibras et al., 2021; Park et al., 2020; Raj et al., 2020; Térémetz et al., 2022; Thrane et al., 2020; Tomita et al., 2020, 2021). Only one study explicitly stated that a power analysis was performed (Cho & Song, 2019) and two studies explicitly stated that no power analysis was performed (Cho & Song, 2019; Hussain et al., 2021). More details about the participants are discussed below under individual constraints.

Quality Assessment

The quality of each study was assessed using the Downs and Black checklist (Downs & Black, 1998). In line with criteria put forward by Mesquita et al. (2019), studies that received a quality index score of less than 60.0% were classified as low quality, those that received a quality index score between 60.0% and 75.0% were considered moderate quality, and those above 75.0% were considered as high quality (Table 1). Among the 20 studies considered for this review, none were considered of low quality, five were of moderate quality (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi -Shirmard et al., 2020; Raj et al., 2020; Tomita et al., 2020), and 15 were of high-quality (Carpinella et al., 2020; Cho & Song, 2019; Hasanbarani et al., 2021; Hussain et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Nibras et al., 2021; Park et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021) (see Table 1). Lastly, the quality of this systematic review was assessed using the AMSTAR-2 checklist (Appendix D). The results indicated that the quality of this review was moderate quality. This indicates that this review has more than one weakness, no critical flaws and may provide an accurate summary of the results of the available studies included.

Table 1.

The scoring results of the Downs and Black Checklist for each study.

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

Constraints on Coordination and Control:

Individual Constraints

Structural. A variety of individual constraints were identified in all of the studies (see Appendix E, Table 5). The structural constraints included sex, time post-stroke, type of stroke, brain lesion location, hand dominance, and affected limb. Regarding sex, with the exclusion of one study (Tomita et al., 2021), all of the studies provided information about sex with both males and females equally combined in the same sample.

In relation to time post-stroke, most studies examined participants that were in the chronic phase of stroke, ranging from 6.3 months to 5.9 years (Carpinella et al., 2020; Cho & Song, 2019; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Lencioni et al., 2021;

Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Park et al., 2020; Raj et al., 2020; Térémetz et al., 2022; Tomita et al., 2020). Two studies recruited participants in the subacute phase which ranged within three days post-stroke (Hussain et al., 2021 Thrane et al., 2020) and three studies focused on individuals who exhibited subacute symptoms ranging from 33.9 days to 56.0 days (Feingold-Polak et al., 2021; Nibras et al., 2021; Tomita et al., 2021). Only one article failed to provide any details about time post-stroke (Jayasinghe et al., 2020).

In regards to the type of stroke, all studies included participants that had both ischemic and hemorrhagic stroke. Only 14 studies included details about the specific type (ischemic vs hemorrhagic) (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Hasanbrani et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mullick et al., 2021; Park et al., 2020; Tomita et al., 2020, 2021).

In terms of the brain lesion location, a total of 12 studies included detailed information about the location of the brain lesion (right or left hemisphere) (Carpinealla et al., 2020; Feingold-Polak et al., 2021; Hasanbrani et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mullick et al., 2021; Raj et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021).

In regards to hand dominance, all articles included a mix of right and left-hand dominant participants with the majority being right-handed (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Nibras et al., 2021; Park et al., 2020; Raj et al., 2020;

Térémetz et al., 2022; Thrane et al., 2020; Tomita et al., 2020, 2021). Only one article included exclusively right-handed participants (Jayasinghe et al., 2020).

In relation to the affected limb, all studies examined the more affected arm. However, only 10 studies included details that specified if the affected side was right or left (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Lencioni et atl., 2021; Mochizuki et al., 2019; Mullick et al., 2021; Raj et al., 2020; Teremetz et al., 2022).

Functional. Only a few functional constraints were identified in this review. These consisted of anxiety (Hejazi-Shirmard et al., 2020), self-perceived ability to perform meaningful activities (Tomita et al., 2021), attentional focus (Gomes et al., 2021), and attention during dual tasking (Mullikk et al., 2021).

Tasks Constraints

This review identified a variety of different tasks used to examine intra-limb organization (see Appendix E, Table 5). A total of eight utilized a reaching task (Carpinella et al., 2020; Cho & Song, 2019; Jayasinghe et al., 2020; Liao et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021 Park et al., 2020; Teremetz et al., 2022) and five studies used a reach to grasp task (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Raj et al., 2020; Tomita et al., 2020). Furthermore, three studies implemented variations of reaching, which included reaching, grasping, and lifting an object (Tomita et al., 2021); reaching in an egocentric and exocentric frame of reference (Hasanbarani et al., 2021); maximum forward reaching (Montoya et al., 2022), and the Apley Scratching Test (Montoya et al., 2022). Other tasks consisted of pointing (Hussain et al., 2021; Nibras et al., 2021), an object pacing and pronation task (Lencioni et al., 2021), and a drinking task (Thrane et al., 2020).

Regarding rules associated with the task, two studies incorporated performing a reaching movement under a time limit (Mullick et al., 2021; Nibras et al., 2021), and one study involved performing the reaching movement at a constant speed between trials (Tomita et al., 2021).

In relation to the devices used to perform the task, two studies utilized robotic rehabilitation apparatuses (Carpinella et al., 2020; Cho & Song, 2019), and three utilized robotic exoskeletons (Mochizuki et al., 2019; Nibras et al., 2021; Park et al., 2020). For a detailed description of the task from each study please refer to Appendix E, Table 5.

Environmental Constraints

Lastly, environmental constraints include factors that are external to the individual's body. The environmental constraints from this review included posture position, trunk restraint, availability of visual information, and different types of sensory inputs (see Appendix E, Table 5). For posture position, most articles performed reaching actions from a sitting position with unconstrained arm action (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Nibras et al., 2021; Park et al., 2020; Raj et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021). Only three studies utilized a standing posture (Montoya et al., 2022; Mullick et al., 2021; Tomita et al., 2020).

Regarding trunk constraints, most studies did not restrain the degrees of freedom of the trunk (Carpinella et al., 2020; Feingold-Polak et al., 2021; Gomes et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Park et al., 2020; Raj et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2020; Tomita et al., 2021). However, two studies restricted trunk motion using a belt or harness (Cho & Song, 2019; Hejazi-Shirmard et al., 2020). In addition, one study utilized an electromagnet, which allowed trunk motion to be randomly constrained or unconstrained (Hasanbarani et al., 2021). Lastly, two studies did not explicitly indicate if the trunk was constrained or not (Hussain et al., 2021; Nibras et al. 2021).

In relation to the availability of visual information. Most studies performed the tasks with eyes open (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Lencioni et al., 2021; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Nibras et al., 2021; Park et al., 2020; Raj et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021). Only two studies performed the tasks in both eyes open and closed conditions (Hasaranbrani et al., 2021; Tomita et al., 2020).

In terms of the different types of sensory input, most studies were conducted in a real environment in a laboratory setting (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejarzi-Shirmard et al., 2020; Liao et al., 2020; Muchizuki et al., 2019; Montoya et al., 2022; Park et al., 2020; Raj et al., 2020; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2020). A total of eight incorporated a virtual environment where the participants were asked to perform the task using a haptic stylus (Hussain et al., 2021), electromagnetic sensor (Carpinella et al., 2020) end effector robot (Cho & Song, 2019; Lencioni et al., 2021), KineReach (Jayasinghe et al., 2020), 3D head-mounted display (Mullick et al., 2021), and ArmeoSpring exoskeleton (Nibras et al., 2021).

Movement Planning at the Intra-Limb Level of Organization

Conceptual Scope

In the area of research examining issues of movement organization at the intra-limb level, the topics of interest may be classified as those examining the issues of coordination, which is more rudimentary, the issues of control, or both. In the current review, 14 of the articles were framed within a conceptual scope that focused on the issues of movement control **(**Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Lencioni et al., 2021;Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Mullick et al., 2021; Park et al., 2020; Teremetz et al., 2022; Thrane et al., 2020). While a total of six studies examined issues of both coordination and control (Carpinella et al., 2020; Hasanbarani et al., 2021; Nibras et al., 2021; Raj et al., 2020; Tomita et al., 2020, 2021), no studies examined coordination issues exclusively. Please refer to Appendix E, Table 5 for more details.

Conceptual Framework

In regards to the conceptual framework, which specifies how actions are planned and executed, 11 of the studies implemented a forward kinematics approach (Cho & Song, 2019;; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Liao et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021; Park et al., 2020; Teremetz et al., 2022; Thrane et al., 2020). Three studies based their inferences on inverse kinematics (Carpinella et al., 2020; Lencioni et al., 2021; Montoya et al., 2022), and five studies incorporated a more eclectic approach involving both forward and inverse kinematics (Feingold-Polak et al., 2021; Hasabrani et al., 2021; Nibras et al., 2021; Tomita et al., 2020, 2021). Only one article examined the complex issues of torque modulation using inverse dynamics (Raj et al., 2020). Please refer to Appendix E, Table 5 for more details.

Motor Control Theories

In terms of motor control theories, 14 studies failed to explicitly mention any motor control theories (Carpinella et al., 2020; Cho & Song, 2019; Feingold-Polak et al., 202; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Jayasinghe et al., 2020; Liao et al., 2020; Mochizuki et al., 2019; Montoya et al., 2022; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021). Only three studies explicitly mentioned any motor control theories in the introduction or the rationale for the experiment, which included the Equilibrium Point Hypothesis (Hasanbarani et al., 2021), the Uncontrolled Manifold Hypothesis (Tomita et al., 2020), and the Leading Joint Hypothesis (Raj et al., 2020). In addition, three other studies framed their results within the context of the Uncontrolled Manifold Hypothesis (Lencioni et al., 2021; Mullick et al., 2021; Nibras et al., 2021). Please refer to Appendix E, Table 5 for more details.

Dependent Variables and Conceptual Relevance

Intra-limb organization can be examined in relation to the nature of the emerging actions (coordination), their flexibility (control), or both. In regards to the kinematic level of analysis, measures can be further categorized as those making interpretations about spatial and temporal organization in joint or effector space. Alternatively, a highly complex innovative approach involves the examination of the nature of torque production, was only addressed by one study in this review (Raj et al., 2020).

Movement Control

In regards to movement control, which can be examined from a forward and inverse kinematics perspective, measures occur in either joint space or end effector space in both the spatial and temporal domains. The studies in this review included various measures in both spaces and domains (see Appendix E, Table 4).

Joint Space in the Spatial Domain. The control measures related to joint space in the spatial domain consisted of: maximum joint angles of the shoulder (Montoya et al., 2022; Mullick et al., 2021; Thrane et al., 2020), elbow (Feingold-Polak et al., 2021; Montoya et al., 2022; Mullick et al., 2021; Tomita et al., 2021), wrist (Montoya et al., 2022; Mullick et al., 2021), forearm (Montoya et al., 2022), range of motion of the shoulder (Carpinella et al., 2020; Hasanbarani et al., 2021; Montoya et al., 2022), elbow (Carpinella et al., 2020; Feingold-Polak et al., 2021; Hasanbarani et al., 2021; Lencioni et al., 2021; Montoya et al., 2022), wrist (Montoya et al., 2022), and forearm (Lencioni et al., 2021; Montoya et al., 2022), root mean square of the angle between the trunk and shoulder (Lencioni et al., 2021), and angular displacement profiles of the shoulder and elbow (Carpinella et al., 2020).

Joint Space in the Temporal Domain. The control measures related to joint space in the temporal domain included angular velocity of the elbow (Montoya et al., 2022; Thrane et al., 2020), shoulder, wrist, and forearm (Montoya et al., 2022), execution time (Montoya et al., 2022).

End Effector Space in the Spatial Domain. In the end-effector space, spatial measures consisted of an index of curvature (Feingold-Polak et al., 2021; Hasanbarani et al., 2021; Mullick et al., 2021; Teremetz et al., 2022; Tomita et al., 2021), trajectory length (Hasanbarani et al. 2021; Mullick et al., 2021), reaching trajectories (Mullick et al., 2021; Park et al., 2020), spectral arch length (Park et al., 2020), constant final position error (Jayasinghe et al., 2020), path length ratio (Muchizuki et al., 2019), normalized total displacement of the hand (Liao., 2020), and variability of endpoint position (Tomita et al., 2020).

End Effector Space in the Temporal Domain. In end effector space, temporal measures included movement duration of the hand (Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Liao et al., 2020;

Mochizuki et al., 2019; Teremetz et al., 2022; Thrane et al., 2020), peak velocity of the hand (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Hussain et al., 2021; Mochizuki et al., 2019; Mullick et al., 2021; Teremetz et al., 2022; Thrane et al., 2020; Tomita et al., 2021), number of velocity peaks (Gomes et al., 2021; Hussain et al., 2021; Lencioni et al., 2021; Mochizuki et al., 2019; Mullick et al., 2021; Nibras et al., 2021; Teremetz et al., 2022; Tomita et al., 2021), mean endpoint velocity (Cho & Song, 2019; Feingold-Polak et al., 2021; Gomes et al., 2021; Hasanbarani et al., 2021; Hussain et al., 2021; Park et al., 2021; Tomita et al., 2020), time to peak velocity (Feingold-Polak et al., 2021; Mullick et al., 2021; Thrane et al., 2020), end effector velocity profiles (Mullick et al., 2021)**,** normalized jerk (Feingold-Polak et al., 2021), percentage of movement time in which peak velocity occurred (Hejazi-Shirmard et al., 2020), and reaction time of the hand (Liao et al., 2020).

Movement Coordination

With respect to movement coordination, inferences can be made by examining the quantitative and qualitative aspects of the movement. In this review, studies that examined coordination included a variety of both quantitative and qualitative coordination-based measures (see Appendix E, Table 4).

Quantitative Measures. The quantitative measures consisted of correlations between the shoulder and elbow (Carpinella et al., 2021), correlations between the shoulder elevation angle and forearm angle, and between the shoulder horizontal angle of the elbow angle (used to examine vertical and horizontal synergies) (Nibras et al., 2021), cross-correlations between the synergy index, the endpoint velocity (Tomita et al., 2021), synergy index (proportion of VUCM and VORT) (Tomita et al., 2020), and the slope of elbow and shoulder angle-angle diagrams (Tomita et al., 2021).

Qualitative Measures. The qualitative measures consisted of angle-angle diagrams of the shoulder and elbow (Hasanbarani et al., 2021; Tomita et al., 2021) and angular velocity profiles of the shoulder and elbow (Nibras et al., 2021).

Discussion

This review aimed to explore literature related to unimanual (intra-limb) coordination and control in individuals who suffered a stroke. A total of 20 studies were retrieved and examined in relation to the conceptual frameworks of forward kinematics, inverse kinematics, and inverse dynamics. Also, the impact of different individual, task and environmental constraints on movement organization in these goal directed actions was reviewed, along with the related methodological approaches implemented to examine the spatial and temporal domains of control and coordination.

Quality of the Systematic Review and Characteristics of the Samples

After assessing the methodological quality of each study using the Downs and Black checklist, the results indicated that most studies achieved a score of 75% or greater, corresponding to a high-quality rating. This score represents a single global measure used to assess the methodological quality of randomized and non-randomized studies in five domains: reporting, internal validity (confounding and bias), power, and external validity. A limitation associated with this type of quality assessment is that a single measure does not specify where the issue is located. For example, two studies may achieve the same score, but one is lacking in internal validity, while the other is lacking external validity. Of the studies included in this review that received a moderate rating, four were descriptive, and one was an intervention. As, the Downs and Black checklist was primarily designed to examine intervention studies, this may have affected the scoring of the descriptive research. Lastly, we acknowledge that more stringent quality rating categories and more rigorous assessment tools could have been used, however, the decision was made to use the Down and Blacks checklist and follow the scoring criteria put forward by Mesquita et al. (2019).

One strength of this review is that the quality was examined using the AMSTAR-2 checklist. The results indicated that the quality of this review was moderate. This means that the review has more than one weakness, but no critical flaws, and that this review may provide an accurate summary of the studies included. However, this score should be interpreted with caution as the AMSTAR-2 checklist was mainly designed as an aide to help guide researchers while conducting their review rather than evaluating their final report. The rating of moderate may have likely emerged as no meta-analysis was conducted in this review and that both intervention and descriptive studies were included.

In terms of the sampling implemented, 14 articles used purposive sampling, while three implemented convenience sampling (Hussain et al., 2021; Jayasinghe et al., 2020; Thrane et al., 2020). Given the scope of research and the population of interest the former approach is generally deemed as most appropriate as it aids in controlling for confounding variables assuring sample homogeneity. However, from the external validity standpoint, the latter approach may provide a higher degree of generalizability. In regard to sample size, numbers 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 (Cho & Song, 2019). Although often power analysis is impractical in research involving atypically functioning individuals, who are difficult to seek and recruit, the fact remains that the smaller the sample size, the larger the possibility of occurrence of Type 2 error. This is particularly important in rehabilitation studies as the implemented approach may lead to changes in behaviour, as examined via kinematics, yet show a lack of desired statistical difference. 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 again this variable was not considered a factor in the design or analysis. This approach warrants caution as the impact of stroke on men and women and on the age of those affected by the condition varies. Since the gender x age interaction was not examined, variability in the data, and a lack of significant differences when expected, represents an important methodological limitation that may impact the validity of the emerging inferences.

Movement Planning at the Intra-Limb Level of Organization

There are three broad conceptual frameworks that attempt to explain how actions, such as reaching and grasping, are planned and executed at the intra-limb level of organization. These include forward kinematics, inverse kinematics, and inverse dynamics. Whereas the first two deal with delineation of how the motion of the joints or end effector are planned in the spatial and temporal domains, inverse dynamics represents a more sophisticated but also more complex explanation of how different passive and active torques are modulated in order to assemble such actions. The first purpose of this review was to extract and examine articles in relation to the conceptual frameworks of forward kinematics, inverse kinematics, and inverse dynamics. From this review, as is the case with the volumes of research examining intra-limb organization over the last few decades, most studies incorporated either a forward or inverse kinematics framework, and only one examined the issues of inverse dynamics (forces/torques) (Raj et al., 2020).

Forward Kinematics

The forward kinematics approach suggests that the CNS plans movement around the final position of the end effector, in this case, the hand. For example, when reaching for a cup of coffee, the CNS plans the motion of the shoulder and elbow in order for the hand to arrive at a particular location in space at a particular time. 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 a series of experiments carried out by Bernstein (1967), nearly a century ago involving a hammering action, and in more modern times the work by Flash and Hogan (1985) involving reaching. Bernstein (1967) observed that despite the abundance of patterns that could emerge when hammering a nail, and the different alignments of the respective joints, the motion of the hand and the hammer it was holding was spatially invariant, hence it coincided with the same or very similar spatial trajectory. A similar observation was made by Flash and Hogan (1985) while examining reaching actions, that the linear velocity of the hand remained stable across successive trials, regardless if the task was the same or altered. The emergence of such invariant behaviour showed experimentally that when the reaching movement is planned, the essential kinematic variable that the CNS has to control is the temporal (and spatial) organization of the end effector hand, rather than the contribution of the respective joints within the arm. Individuals who had a stroke exhibit movement patterns that are not only different in terms of their spatio-temporal characteristics, but are also more variable when compared to the behaviours exhibited by typically functioning individuals (Levin & Feldman, 1994). Kinematically, these patterns are expected to reveal themselves at the behavioural level via analysis of the end effector (the hand), in both the spatial and temporal domain.

In order to make inferences about spatial movement organization, the location or trajectory of the hand is often examined as the effector is moving on a pathway from the initial position until it reaches the object to be grasped. In the present review, this issue was examined in several studies however the expected differences emerged in only two descriptive studies which examined reaching tasks in individuals in the subacute phase (Feingold-Polak et al., 2021) and in the chronic phase (Mullick et al., 2021). The measures that revealed the most pronounced differences included the index of curvature and 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, which represents the most rudimentary type of control within the movement organization hierarchy (Burton, 1992). From the methodological perspective, this is to be expected as both the index of curvature and trajectory length are the kinematic derivatives of the distance travelled between two points. These findings were also in line with earlier research, which was not included in this review. For example, Cristea and Levin (2000) in their study examined a reaching movement in a sample of participants in the subacute and chronic stages after stroke. In line with the inferences emerging here, the results from their study showed that the reaching trajectory of individuals with stroke was also longer and less smooth when compared to healthy functioning individuals. 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 (Park et al., 2020; Liao et al., 2020; Teremetz et al., 2022; Tomita et al 2021). 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). One potential confounding variable that may have impacted the emerging trend, and lack of changes due to training, was the length of the rehabilitation. Each study used a protocol which lasted four weeks, with a relatively low frequency of the rehabilitation sessions. Also, from the standpoint of task constraints, the degree of difficulty that the participants were facing may not have been stringent enough for a training effect to emerge. Also, as per previous suggestion, the presence of a person by treatment interaction effect, that can emerge due to variability associated with heterogeneous samples, may have contributed to the additional potential Type 2 error.

Another important aspect of movement control, as related to the performance of self-paced goal-directed actions, is the issue of timing as inferred from different kinematic derivatives of movement time or velocity (e.g., time to peak velocity; peak velocity; percentage of acceleration and deceleration phase). In this review, six descriptive (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021), and two rehabilitation studies (Hussain et al., 2021; Thrane et al., 2020) examined the nature of temporal control. 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 behaviours would be characterized as slow, jittery, and lacking smoothness. Whereas the differences in movement time or velocity may not be as critical given the self-paced nature of the action. Several "stops and goes" as evident from multiple peaks and valleys, 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. The emerging consistency across these studies can be attributed to several factors. In terms of individual constraints, the studies involved participants in the subacute (Feingold-Polak et al., 2021; Hussain et al., 2021; Thrane et al., 2020) and chronic phase post stroke (Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021). Thus, the emerging performance was derived from a relatively homogenous sample. From the task standpoint, the studies examined reaching (Feingold-Polak et al., 2021; Gomes et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020; Mochizuki et al., 2019; Mullick et al., 2021; Thrane et al., 2020) as well as pointing actions (Hussain et al., 2021). Considering that both of these tasks are self-paced, but are controlled via different mechanisms, the fact that they are consistently showing temporal issues confirms that temporal organization and efficiency represents a rate limiter for individuals with stroke when performing uni-manual intra-limb tasks.

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 (Hasanbarani et al., 2021; Teremetz et al., 2022; Tomita et al., 2021). The results from these investigations did not reveal statistically significant differences between the groups in the case of comparative studies (Hasabarani et al., 2021), and failed to show changes among individuals with stroke as a result of rehabilitation (Termeetz et al., 2022; Tomita et al., 2021). For example, Hasanbarani et al. (2021) found no statistical difference in movement time and mean velocity, while both Termetz et al. (2022) and Tomita et al. (2021) found no difference in peak velocity of the hand after training. 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. (2021) 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. Termeetz et al. (2022) 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. Lastly, as previously discussed, Tomita et al. (2021) examined a reach-to-grasp-to-reach but required the participants to reach with the same speed before and after the intervention. Thus, it is plausible that the inconsistencies emerging from the studies reviewed here may be attributed to the differences in the relevant constraints. This fact suggests that studies which replicate previous work with, even subtle alterations to the respective methodologies, without an explicit model or theory, render the results contradicting and unequivocal.

Collectively, the analysis of movement trajectories via forward kinematics revealed that individuals with stroke exhibit spatial and temporal control issues in effector space. However, in both instances, the emerging trends have to be interpreted with caution as some studies lent support to this hypothesis, whereas others did not. As an example, the current results did confirm the expected spatial control issues that often are evident in individuals with stroke. This is surprising as, from the neurological perspective, stroke often impacts the motor cortex, which interfaces with other brain regions that send signals to the corticospinal tracts to control voluntary movement (Ma et al., 2022; Schulz et al., 2015).

In addition to the differences or changes in the emerging spatial or temporal patterns, the stability and flexibility of the underlining mechanisms is often examined. In the current review, none of the studies examined intra-individual variability of the participants via measures of variability such as standard deviation or coefficient of variation. This is surprising as conceptually it is plausible that a participant may not exhibit changes in behaviour, as captured by the mean of a particular variable, however, they may exhibit changes or differences in terms of the variability or consistency of the output, whereas a smaller amount of “noise” represents evidence of improved performance. Thus, a patient may still exhibit a curvilinear reaching trajectory or a different temporal pattering, however, these adaptations may be more stable or consistent as a result of training. From the clinical standpoint, different, yet stable movement patterns, can be considered as functional and therefore effective movement patterns.

Inverse Kinematics

In contrast to forward kinematics, which examines control of the end effector, the inverse kinematics approach assumes that the CNS preplans movements around the complex interaction between joints. For example, when reaching for a cup of coffee, the angular displacement of the shoulder couples with the angular displacement of the elbow, and alters the respective degrees of freedom of the wrist in order to place the hand in the proximity of the object to be grasped. 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 deals with both control as well as coordination (Hollerbach, 1990). In regards to the former, this is accomplished by making inferences about the nature of spatial, and at times, temporal coupling. The analysis of such synergistic relations is generally based on coupling between the shoulder, elbow and wrist joints, at both the qualitative (angle-angle plots) and quantitative (correlations) levels of measurement. In reaching for example, in terms of intra-limb organization, the nature of the emerging relations can be examined based on the relations between the distal components, responsible for the transport phase of the reaching action. Also, they can be examined based on relations between the elbow and wrist, responsible for the homing phase of the movement, when the hand approaches and grasps the desired object (Lacqunti & Soechting, 1982).

Surprisingly, given that movement patterns exhibited by individuals with stroke are often qualitatively different than those without stroke, only a few studies have examined this issue. In this review, only one descriptive (Hasanbarani et al., 2021) and one intervention study (Tomita et al., 2021) attempted to examine the nature of the spatial relationship between the shoulder and elbow, and there were no studies which addressed the degree to which more proximal joints were coordinated. Hasanbrani et al. (2021) examined the degree of coupling between the shoulder and elbow via angle-angle plots. The comparison was made between healthy individuals and those in the chronic stage of stroke while reaching in an egocentric and exocentric frame of reference, with and without trunk restraint. The results indicated that regardless of the condition, individuals with stroke exhibited a segmented type of movement where shoulder and elbow extension were decoupled (Hasanbrani et al., 2021). In comparison, the angle-angle plots of the healthy individuals revealed smooth coupling between the two joints. Thus, in the context of the solution to the degrees of freedom problem, while performing reaching actions both groups exhibited different synergistic relations. The study did not make any inferences about the degree of coupling between more proximal joints, nor about the stability of the emerging actions based on the qualitative data provided. Tomita et al. (2021) 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. The findings indicated that with training the degree of spatial coupling between the joints changed to resemble patterns that were similar to those evident in other studies involving individuals without stroke (Lacquanti & Soechting, 1982). As per previous research, here the nature (degree/stability) of coupling between other joints was also not examined.

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 interventional study (Carpinella et al., 2021) utilized this methodological approach. 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 (r=-0.32), as compared to healthy individuals (r=-0.92). After training, individuals in the chronic stage experienced a tighter coupling of the shoulder and elbow (r=-0.54) as compared to conventional rehabilitation (r=-0.33). In comparison, those in the subacute phase did not exhibit significant differences in spatial coupling when robotic therapy (r=-0.47) and conventional rehabilitation (r=-0.39) were compared. These results, although limited, suggested that the individual constraints, related to the magnitude of the stroke-related neurological changes, should be considered as they have an impact on the nature of movement organization. This fact has important clinical as well as conceptual relevance. In addition to correlations, the study by Tomita et al. (2020) quantified spatial coupling between the shoulder and elbow joint via the slope of the angle-angle diagram in those with subacute stroke. The results confirmed previous inferences indicating that the shoulder and elbow were more tightly coupled after rehabilitation. Thus, the nature of the emerging coordinative tendencies, exhibited at the intra-limb level of organization, appeared to change as a result of an intervention and, progressed from a decoupling tendency to a more fluent action as evident from the qualitative and quantitative measures. Collectively, although issues in coordination are expected to emerge in this population, the existing research reviewed here was limited in terms of its methodological and conceptual scope. As expected, the existing studies showed that individuals with stroke exhibited decoupling within the shoulder and elbow. The fact that the studies did not examine the nature of the coupling between other joint pairs, as well they did not address the issue of stability, remains an important shortcoming of the reviewed work.

In addition to coordination, inverse kinematics allows to make inferences about movement control in joint space. Compared to end effector space, which examines control in the spatial and temporal domain, issues of control in joint space with inverse kinematics are primarily examined in the spatial domain. Qualitatively, this can be accomplished by examining the angular displacement profiles of the shoulder and wrist joints to make inferences about how individual joints contribute to the trajectory formation of the movement. In this review, only one study examined the angular displacement profiles of the shoulder and elbow joints (Carpinella et al., 2020). The results indicated that after rehabilitation, the angular displacement profile of the elbow changed from an atypical pattern, involving mostly flexion, to one that resembled extension as exhibited by a typically functioning individual. Issues of spatial control in joint space were also examined quantitatively by examining measures such as angular displacement of the shoulder, elbow, and wrist. Individuals with stroke typically exhibit a reduced ability to release degrees of freedom in the shoulder and elbow as indicated by decreased angular displacement when compared to healthy functioning individuals (Cristea & Levin, 2000). In this review, this pattern of results was confirmed by three intervention studies (Carpinella et al., 2020;

Mullick et al., 2021; Thrane et al., 2020) and two descriptive studies (Feingold-Polak et al., 2021; Hasanbarani et al., 2021). The emerging consistencies may be attributed to various factors. In terms of individual constraints, the studies involved participants in the subacute (Carpinella et al., 2020; Feingold-Polak et al., 2021; Thrane et al., 2020) and chronic phases (Hasanbarani et al., 2021; Mullick et al., 2021). From a methodological standpoint, all the studies examined reaching. Only one study failed to reveal the expected difference as a result of rehabilitation (Tomita et al., 2021). This can be attributed to the fact that Tomita and colleagues (2021) required participants to perform a different reaching task, thus It is plausible that this difference may be attributed to the varied task demands. Collectively, considering that these studies consistently show spatial issues in performance, and only one study found conflicting results which can be explained via the task constraints, this suggests that spatial organization in joint space is a limiter for individuals with stroke performing intra-limb action. However, as was the case with previous measures of coordination and control, the analysis of stability has been neglected in these investigations.

Similar to forward kinematics, another aspect of movement planning control that can be examined in joint space is timing. This aspect of organization is inferred from different kinematic derivatives of velocity (e.g., angular velocity). In this review, only two intervention studies (Montoya et al., 2022; Thrane et al., 2020) examined the nature of temporal control of the elbow, and there were no studies which examined the issue in the more proximal joint (wrist). Overall, both studies showed a pattern of results indicating that the angular velocity of the elbow was lower compared to healthy counterparts, however, it increased as a result of rehabilitation. This pattern was consistent regardless of the task or current phase of stroke. Thus, these findings, even though limited, suggest that temporal organization in joint space is a limiter for individuals with stroke when performing unimanual reaching tasks. However, similar to the previous studies, the analysis of intra-individual variability was neglected.

Collectively the analysis of the emerging movement patterns, via inverse kinematics, revealed that individuals with stroke exhibit coordination as well as control issues within joint space. In terms of coordination, individuals with stroke tended to release degrees of freedom with practice, which at the behavioural level coincides with more fluent movement patterns. This was inferred from both angle-angle diagrams and correlation coefficients derived from the examination of shoulder-elbow spatial relations. In terms of control, the actions also appeared to be slow and involved only minimal use of the shoulder and elbow joints as inferred from the measures of angular velocity and displacement, respectively. As per research involving forward kinematics, an important shortcoming of studies implementing inverse kinematics is 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, as noted in descriptive as well as rehabilitation studies, are stable, or become more stable with practice and time.

Constraints on Intra-Limb Coordination

Karl Newell's (1985) model of constraints asserts that a coalition of different factors from the individual, task and environment “channels” the CNS to coordinate and control actions in a particular way, even when an infinite number of possible outcomes are available. This assumption indicates that individuals who exhibit similar individual constraints are expected to perform similar stable movement patterns under certain constraints. Changes or differences in such characteristics are also expected to reveal themselves in differences in coordination and or control. Subsequently, the analysis of such behaviours, at the kinematic level of analysis, provides an insight into the nature of the underlying processes that CNS incorporates to plan and execute such actions. In regards to individuals affected by stroke, which in itself represents a constraint, such assumptions may or may not be true as many different variables affect how these individuals organize goal-directed actions. The presence of such variability indicates that the notion of "typical movement patterns in atypically functioning individuals" at times is difficult to delineate. As such, the second purpose of this research was to examine and delineate the impact of different constraints on the nature of intra-limb movement organization of individuals with stroke when performing reaching and pointing goal-directed actions involving multiple degrees of freedom.

Individual Constraints

Individual constraints represent characteristics of an individual which can be broadly classified as structural and functional (Newell, 1985). 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 hand dominance and 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. There are three main categories within this time period, as the patient can be in the acute, subacute, or chronic phase. Individuals considered to be in an acute stage are those who suffered a stroke within the last 24 hours. Individuals who had a stroke within seven days are considered to be in the subacute phase. Lastly, to be considered in the chronic phase, the stroke had to occur more than six months ago (Bernhardt et al., 2017). Since it may have been difficult to recruit participants who recently suffered a stroke, and due to the spontaneous changes that occur in the acute phase (Sun et al., 2015), most studies reviewed here involved individuals who were in the chronic stage. Whereas, only three studies, two descriptive (Feingold-Polak et al., 2021; Nibras et al., 2021), and one intervention (Tomita et al., 2021) recruited participants in the subacute stage. 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 (Hussain et al., 2021; Thrane et al., 2020). Both studies examined upper limb kinematics at three days, 10 days, four weeks, three months, six months, and twelve months post stroke. Hussain et al. (2021) examined a pointing task, while Thrane et al. (2020) examined a drinking task, and both focused on the nature of temporal control in effector space. Thrane et al. (2020) observed that movement time and the number of movement units significantly decreased, and peak hand velocity significantly increased until six months. Similarly, Hussain et al. (2021) showed that movement time and the number of velocity peaks significantly decreased up to three months, while the mean velocity increased at six months post-stroke. Collectively, the inferences from these two longitudinal studies suggested that those in the subacute phase represent a different group and exhibit different control mechanisms than those in the chronic phase. The reason for this may be due 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 (Bernhardt et al., 2017).

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 (Campbell & Khatri, 2020). Based on a model put forward by Mani et al. (2013), the left hemisphere is responsible for predicting and adjusting for limb dynamics, while the right hemisphere stabilizes limb positions. 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 model, most of the studies reviewed here included a heterogeneous mix of participants with right and left hemisphere damage. Only one descriptive study included the side of the lesion as an independent variable (Jayasinghe et al., 2020). 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 in that, the individuals with right hemisphere damage had higher variability at the end of the movement. This may suggest that individuals with right hemisphere damage have deficits in movement control, while individuals with left hemisphere damage have deficits related to coordination (Jayasinghe et al., 2020). However, more research is required where the design of the study allows for the comparison of coordination and control between individuals with right and left hemisphere damage.

The nature of intra-limb organization can also be further impacted by morphological characteristics related to the performance of a particular task, in this case, one-handed reaching. The issue of hand dominance, in the context of rehabilitation, is an important one as generally, the non-dominant arm is less able to begin with, as compared to the limb that is used most frequently. Thus, the recovery of the non-dominant limb may unfold differently as compared to the changes that would take place when the dominant limb is recovering (McCombe Waller &

Whitall, 2005). In this review, all studies examined the more affected arm, regardless of the person's hand dominance. Thus, the kinematic data pertaining to the nature of spatio-temporal coordination and control for the non-dominant limb were collapsed within those exhibited by the dominant arm, affected by stroke. Intuitively, this may represent an issue for analysis as variability may jeopardize the validity of the emerging inferences. This assertion was confirmed by Feingold-Polak et al. (2021) who found that when the dominant arm was affected, the mean and peak grasping forces were higher than when the non-dominant arm was affected, indicating that previous experience does play a role in the way stroke affects motor output. Thus, arm dominance may represent an important variable that needs to be considered when carrying out descriptive and experimental studies designed to improve motor output. It is likely that difficulties with recruiting the required number of participants forces the researchers to sample heterogeneous groups, including those whose dominant or non-dominant limb was affected.

Task Constraints

Task constraints are factors related to the goals, protocol, rules and equipment involved in the performance of motor skills (Newell, 1985). This represents an important constraint as the degree of similarity or difficulty between the tasks will have an impact on the degree to which certain behaviours are invariant across participants from the same or different samples. In turn, this may aid in delineating how stroke affects the ability of the person to solve the degrees of freedom problem in goal-directed actions. 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. This is an important distinction as reaching to grasp is organized by different control mechanisms, involving both open and closed loop control, whereas reaching alone is a more ballistic skill that does not require as much of sensory feedback (Buneo & Andersen, 2006).

Hence, the kinematic characteristics derived from the performance may be substantially different (e.g., velocity profiles). Also, two descriptive studies examined three unique variations of reaching (Hasanbarani et al., 2021; Thrane et al., 2020). Thrane et al. (2020) 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. In fact, from the clinical perspective, this task may be too difficult to accomplish by those who experience more pronounced stroke-related deficits, as both movement coordination as well as control may be jeopardized when negotiating the required degrees of freedom. In addition, Hasanbarani et al. (2021) analyzed reaching in an egocentric frame of reference, meaning that the participant reached toward their own body. The data showed that the endpoint trajectories (e.g., linear displacement of the wrist) differed from those of healthy controls, thus confirming that individuals with stroke have difficulty performing actions that are moving the limb away from the body and when the arm is moving in the opposite direction (Rodrigues et al., 2017).

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 (50cm, 75cm, and 92.3cm above the ground) and two weights (273g and 443g) (Feingold-Polak et al., 2021). 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. Thus, as the demands of the task affect the nature of the emerging movement patterns, under certain constraints, spatio-temporal differences may emerge, indicating motor deficit, where even seemingly subtle changes in task dimensions may result in differences in performance.

Environmental Constraints

There are also several important environmental constraints that are expected to have an impact on the nature of intra-limb organization in individuals who suffered a stroke. In this context the notion of environmental constraint is broadly defined as any aspect of performance, outside of the task and individual constraints, which may impact the emerging behaviour (Newell, 1985). In the existing papers examined for the purpose of this review, these constraints are related to the impact of posture on the emerging movement patterns, as well as the availability of sensory information, which inevitably affects the performance of reaching actions. Regarding posture, 17 of the studies in this review incorporated motor tasks initiated from a seated position. Biomechanically, sitting differs from standing, as removing trunk and lower leg movement reduces the number of necessary degrees of freedom that need to be controlled to reach and grasp an object. This, in turn, forces the CNS to generate adaptations that will afford the end effector to complete the task effectively. In this review, no studies incorporated posture (i.e., reaching from standing vs. sitting position) as the independent variable. Also, only one study by Tomita et al. (2020) examined how individuals with stroke organized multiple degrees of freedom while reaching in a standing position. As expected, data showed that the endpoint trajectories in individuals with stroke were less stable, as compared to their healthy counterparts. One possible reason for such limited data on this topic is that stroke often affects posture and balance. Thus, the ability to reach for an object may be jeopardized due to less than optimal intra-limb organization, inter-segmental coordination required to control the trunk while moving the upper limb, or a combination of both. However, due to limited research involving posture and a variable of interest, it remains unclear if, or to what degree, the necessity to control for additional degrees of freedom is more challenging to individuals with stroke as compared to their performance from the sitting position.

Another methodological approach used in the studies included in this review involved a trunk harness. A total of three descriptive studies used a simple harness to restrict the motion of the trunk as the individuals were attempting to reach for an object (Cho & Song, 2019; Hasanbarani et al., 2021; Hejazi-Shirmard et al., 2020; Jayasinghe et al., 2020). Both Cho & Song. (2019) and Hejazi-Shirmard et al. (2020) utilized a simple harness attached to the back of a chair. In contrast, Hasanbarani et al. (2021) was the only one to utilize a trunk harness which was activated randomly as, on some trials, the reaching actions were restricted, while on others the effect of harness was minimal. The randomly activated harness allowed the researchers to examine how individuals with stroke rapidly modified shoulder-elbow inter-joint coordination when reaching trajectories were blocked and unblocked. The nature of upper limb kinematics were examined under four conditions, with and without a trunk restraint, and in two different frames of reference, egocentric and exocentric. It was determined that when reaching in an exocentric frame of reference, with a harness, the individuals with stroke produced more variable endpoint trajectories and exhibited more impaired inter-joint shoulder and elbow joint coordination compared to other conditions. This finding indicated that when using a trunk harness, the nature of intra-limb organization in individuals who suffered a stroke was adversely impacted. In addition to the biomechanical constraints, it is plausible that the use of a harness may also alter the anxiety of the participant performing the upper limb action and further exacerbate the degree to which the nature of intra-limb organization is impacted. However, this hypothesis was not confirmed by Hejazi-Shirmard et al. (2020) who showed that individuals with stroke with low and high anxiety exhibited no differences in kinematic profiles while performing a drinking task with a trunk harness. Collectively, unless the reason for using the harness is related to safety issues, it remains unclear why this particular variable is examined as it introduces constraints that are not ecologically valid, hence the participants would not be exposed to them in their environment in a real life situation.

Another manipulation that was implemented in the reviewed research involved the availability of visual information, which is essential when reaching and grasping and object. Among the 20 studies, only two studies included an eyes closed conditions (Hasanbarani et al., 2021; Tomita et al., 2020). The remaining 18 studies required participants to perform the upper-limb movements with eyes open, and no studies used eyes open or closed as an independent variable. Tomita et al. (2020) examined the variability of the endpoint position when reaching without vision for an object previously exposed to the participant. From the motor control perspective, this kind of manipulation examines if the spatial orientation of the object and the desired actions are stored in the memory and subsequently pre-planned, with minimal necessity to rely on the ongoing sensory inputs. Surprisingly, neither study found a difference in endpoint positioning between individuals with and without stroke. This finding suggests that stroke, at least in this particular sample, did not affect the nature of movement planning of the emerging actions as both groups exhibited a similar degree of variability. Thus, more research is warranted regarding this issue, particularly when the availability of the sensory information is manipulated as modulation of this kind of sensory processing is often impaired in those with stroke.

General Implications

The impact of stroke on the ability of those affected to perform even seemingly simple tasks is undeniable. As such, there is a rather large amount of basic and clinical research which focuses on describing the issues, systematically delineating the different constraints that affect the nature of the emerging actions, and ultimately examining the different rehabilitation strategies that aim at helping these individuals regain their skill. In the context of research on intra-limb organization, generally, these studies have focused on issues of coordination or control or both. Hence, a person may be able to coordinate their actions but may lack flexibility associated with their control, or if the deficits are too pronounced even the ability to produce stable coordinative patterns may be jeopardized.

In the context of previous literature (e.g., systematic reviews; descriptive or rehabilitation studies), the majority of research examining unimanual upper limb actions in individuals who had a stroke focused primarily on issues of control as examined via forward kinematics (Murphy & Hager, 2015; Mesquita, Fonseca, et al., 2019; Mesquita, Pinheiro, et al., 2019; Schwarz et al., 2019).

Although forward kinematics represents an essential tool in examining the nature of trajectory formation via analysis of the end effector, its application is limited. When examining movement, the degrees of freedom problem states that there is an overabundance of degrees of freedom in the body required to perform a given motor task (Bernstein, 1967). One solution initially introduced by Bernstein (1976) and further developed by Gelfand and Tsetlin (1966) and by Latash (1967) is the concept of synergies, which at intra-limb level of organization can be examined in spatial domain. 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. In the current review only a very few studies examined the issue of coordination explicitly, and those which did focused primarily on relationship between shoulder and elbow. The nature between more distal components was not examined at all. From the functional standpoint, adaptations of the wrist in relation to the elbow are of critical importance, especially in those with stroke who exhibit problems with gross as well as fine motor actions. Another important aspect of movement organization that gained little attention in the reviewed literature was the issue of stability.

At the intra-individual level, this level of analysis allows for inferences to be made about the degree of learning and recovery. In the context of rehabilitation, movements can be different but still stable and functional across the same or similar task demands. Hence, quantification of variability represents an important aspect of any research in motor control and learning. Also, in the case of within-group variability, this type of level of analysis examines the presence of the person-by-treatment interaction effect. Given the heterogeneous nature of the population examined in the studies of this review, it would be logical to expect substantial differences across the participants in both descriptive and rehabilitation research. However, as it stands none of the studies in this review explicitly examined this issue, thus from an internal validity standpoint it remains unclear if, for example, different rehabilitation approaches impacted all or the majority of the participants to the same degree in either of these issues.

Another important issue that was examined was the presence of explicit theoretical models in the reviewed research. Surprisingly only three studies included in this review explicitly referred to either the Uncontrolled Manifold, Equilibrium Point Hypothesis, or the Leading Joint Hypothesis (Hasanbarani et al., 2021; Raj et al., 2020; Tomita et al., 2020). These theories are vital as they help to translate conceptual constructs into rehabilitative practices (Shumway-Cook

& Woollacott, 20012). Also, they allow us to predict changes in behaviour 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. A critical shortcoming in this field of study is a general lack of theory-based research.

The second purpose of this review was to delineate which constraints on coordination and control have been examined, and their potential impact on movement organization. Identifying relevant constraints is an essential task for researchers in motor behaviour when examining voluntary actions. At the intra-limb level, when individuals with stroke were examined, the reviewed studies evaluated a number of factors, some of which have impacted the emerging patterns, whereas others had little effect on them. Across the discussed individual constraints, it seems 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 sex/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 behaviour are often non-linear and confounded by both variables. In all, the findings that emerged from this review support those of previous reviews (Murphy & Hager, 2015; Mesquita, Fonseca, et al., 2019; Mesquita, Pinheiro, et al., 2019; Roby-Brami et al., 2021; Schwarz et al., 2019).

Future Directions and Conclusions

In summary, this review aimed to systematically examine literature related to unimanual (intra-limb) coordination and control in individuals who suffered a stroke. Studies were examined in relation to their conceptual scope, hence if the coordination and/or control were investigated, in the context of different theories of movement planning. Also, as the actions emerge from the coalition of different constraints, various characteristics of the individuals, task and environmental factors were identified across the existing research. Collectively, the results showed that the majority of research focused on issues of control, as inferred from forward kinematic approach. However, it remains unclear if those issues were more rudimentary and related to spatial adaptations, or if they were embedded in the temporal parametrization of the end effector. One potential issue with this approach, and the inferences gained, is that due to the motor equivalence issue, an infinite number of trajectories could be generated. Thus, different patterns may actually not be deficient, they are just different and reflect the fact that CNS is no longer the same as compared to the pre-stroke status prior to the stroke. Generally, in order to make the clinical distinction between “different” vs “deficient”, the functionality of the movement can be examined via measures of movement product such as mean constant error, among others. However, this dimension of performance was not examined.

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, though our choice was in line with those of a prior two-part systematic review on the topic (Mesquita, Fonseca et al. 2019; Mesquita, Pinheiro et al., 2019). Finally, the number of chosen investigations was relatively low. However, the primary goal was to examine research studies that have been published most recently, and as such were not considered in previous reviews.

In order to gain further insight into the nature of the emerging actions, the issues of stability should also be investigated. At the intra-individual level, this is an important indicator of learning and recovery as the emerging action could be different, yet stable and functional if the variability across the same or similar task demands are examined. In the case of intra-group variability, the important issue to examine is the presence of person-by-treatment interaction effects. Hence, given the heterogonous nature of the population of interest, one would expect substantial differences across the participants, in both descriptive and more importantly rehabilitation research. This is particularly true when the samples are composed of individuals of both genders and various ages. Yet again, these issues were not explicitly examined in the reviewed research. As it stands, the issue of the degrees of freedom problem and the understanding of how individuals with stroke attempt to solve it, remains an important question. Although forward kinematics represents an important tool in examining the nature of trajectory formation via analysis of end effector, its applicability is limited. The notion of coupling and decoupling, and more broadly how the synergies form and change with training in individuals with stroke remains unclear.

It is imperative that future research focuses more on theories of motor control as well as coordination via methodological approaches such as inverse kinematics, and eventually inverse dynamics. Lack of theory driven (deductive) research represents an important shortcoming in this field as study, as data driven investigations add little to our understanding of the issues at hand. From the standpoint of different constraints, the issue of heterogeneity of the population has been scarcely addressed. Time after stroke, as well as gender and age, represent significant individual constraints which need to be embedded into future research designs to delineate their impact on movement organization, and particularly the process of rehabilitation. The issue of task complexity 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.

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Tyson, S. F., Hanley, M., Chillala, J., Selley, A., & Tallis, R. C. (2006). Balance Disability After Stroke. *Physical Therapy*, *86*(1), 30–38. https://doi.org/10.1093/ptj/86.1.30

Vilela, P. (2017). Acute stroke differential diagnosis: Stroke mimics. *European Journal of Radiology*, *96*(1), 133–144. https://doi.org/10.1016/j.ejrad.2017.05.008

Weiss, P., & Jeannerod, M. (1998). Getting a Grasp on Coordination. *Physiology*, *13*(2), 70–75. https://doi.org/10.1152/physiologyonline.1998.13.2.70

Whiteley, W. N., Wardlaw, J. M., Dennis, M. S., & Sandercock, P. A. G. (2011). Clinical scores for the identification of stroke and transient ischaemic attack in the emergency department: A cross-sectional study. *Journal of Neurology, Neurosurgery and Psychiatry*, *82*(9), 1006. http://dx.doi.org.ezproxy.lakeheadu.ca/10.1136/jnnp.2010.235010

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement* (4th ed). Wiley.

Appendix A: Database Search Terms

Table 2.

The search terms used to search the Embase, Medline, PubMed, and Web of Science Databases.

Search terms in each database	
CINAHL (2019 to First week of March 2022)	((stroke OR poststroke* OR stroke* OR apoplex*) OR ((brain* OR cerebr* OR cerebell* OR intracran* OR intracerebral* OR vertebrobasilar*) AND (vascular*) AND (disease* OR accident* OR disorder*)) OR ((cerebrovascular) AND (disease* OR disorder* OR accident*)) OR ((brain* OR cerebr* OR cerebell* OR intracran* OR intracerebral* OR vertebrobasilar*) AND (bleed* OR hemorrhag* or ischemi* OR infarct* OR hematoma*)) OR (paresi* OR hemipar* OR hemipleg* OR pareti*)) AND ("upper extremity" OR "upper limb" OR "upper limb*" OR "upper extremity*" OR arm OR shoulder* OR elbow* OR wrist* OR hand OR hands OR forearm* OR grasp OR grasp* OR point OR reach OR reach* OR point*) AND (biomechani* OR dynami* OR kinemat* OR coordin* OR synerg* OR stabilit* OR compensat* OR "degrees of freedom" OR trajector* OR smoothness OR velocit* OR accelerat* OR jerk OR spatiotemporal OR spatial OR temporal) NOT ("cerebral palsy" OR "parkinson disease" OR dementia OR pediatric* OR child* OR bilateral* OR bimanual* OR interlimb* OR "inter limb" OR "inter-limb" OR "bi manual" OR "bi-manual" OR "between limb*" OR "between-limb*" OR bilateral OR animal* OR "lower limb*" OR "lower extremit*" OR "lower bod*" OR gait OR knee* OR foot* OR ankle* OR review OR "case report*" OR "meta-analy*" OR "meta analy*")

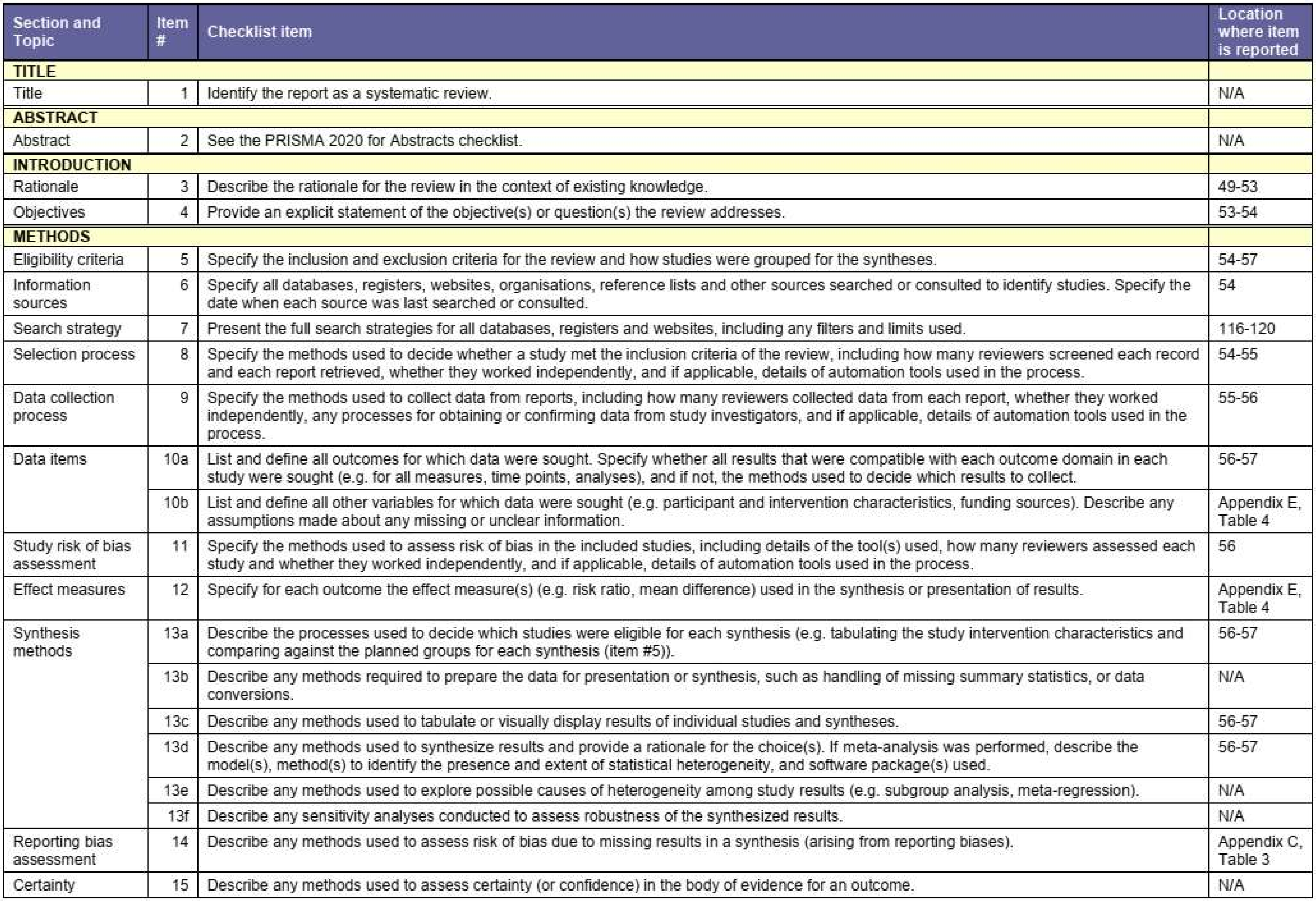
EMBASE (2019 to First week of March 2022)	((exp 'cerebrovascular accident' / OR poststroke*.ti,ab,kw OR stroke*.ti,ab,kw OR apoplex*.ti,ab,kw) OR ((brain*.ti,ab,kw OR cerebr*.ti,ab,kw OR cerebell*.ti,ab,kw OR intracran*.ti,ab,kw OR intracerebral*.ti,ab,kw OR vertebrobasilar*.ti,ab,kw) AND (vascular*.ti,ab,kw) AND (disease*.ti,ab,kw OR accident*.ti,ab,kw OR disorder*.ti,ab,kw)) OR ((cerebrovascular.ti,ab,kw) AND (disease*.ti,ab,kw OR disorder*.ti,ab,kw OR accident*.ti,ab,kw)) OR ((brain*.ti,ab,kw OR cerebr*.ti,ab,kw OR cerebell*.ti,ab,kw OR intracran*.ti,ab,kw OR intracerebral*.ti,ab,kw OR vertebrobasilar*.ti,ab,kw) AND (bleed*.ti,ab,kw OR hemorrhag*.ti,ab,kw or ischemi*.ti,ab,kw OR infarct*.ti,ab,kw OR hematoma*.ti,ab,kw)) OR (exp 'muscle paresis'/ OR paresi*.ti,ab,kw OR hemipar*.ti,ab,kw OR exp 'hemiparalysis'/ OR hemipleg*.ti,ab,kw OR pareti*.ti,ab,kw)) AND (exp 'upper limb'/ OR 'upper extemity'.ti,ab,kw OR 'upper limb'.ti,ab,kw OR 'upper limb*'.ti,ab,kw OR 'upper extremity*'.ti,ab,kw OR arm.ti,ab,kw OR shoulder*.ti,ab,kw OR elbow*.ti,ab,kw OR wrist*.ti,ab,kw OR hand.ti,ab,kw OR hands.ti,ab,kw OR forearm*.ti,ab,kw OR grasp.ti,ab,kw OR grasp*.ti,ab,kw OR point.ti,ab,kw OR reach*.ti,ab,kw OR point*.ti,ab,kw) AND (biomechani*.ti,ab,kw OR dynami*.ti,ab,kw OR kinemat*.ti,ab,kw OR coordin*.ti,ab,kw OR synerg*.ti,ab,kw OR stabilit*.ti,ab,kw OR compensat*.ti,ab,kw OR "degrees of freedom".ti,ab,kw OR trajector*.ti,ab,kw OR smoothness.ti,ab,kw OR velocit*.ti,ab,kw OR accelerat*.ti,ab,kw OR jerk.ti,ab,kw OR

	spatiotemporal.ti,ab,kw OR spatial.ti,ab,kw OR temporal.ti,ab,kw) NOT (exp 'cerebral palsy'/ OR 'cerebral palsy'.ti,ab,kw OR exp 'parkinson disease'/ OR 'parkinson disease' OR exp 'dementia'/ OR dementia.ti,ab,kw OR pediatric*.ti,ab,kw OR child*.ti,ab,kw OR bilateral*.ti,ab,kw OR bimanual*.ti,ab,kw OR interlimb*.ti,ab,kw OR 'inter lim'.ti,ab,kw OR 'inter-limb'.ti,ab,kw OR 'bi manual'.ti,ab,kw OR 'bi-manual'.ti,ab,kw OR 'between limb*'.ti,ab,kw OR 'between-limb*'.ti,ab,kw OR bilateral.ti,ab,kw OR animal*.ti,ab,kw OR exp 'lower limb'/ OR 'lower limb*'.ti,ab,kw OR 'lower extremit*'.ti,ab,kw OR 'lower bod*'.ti,ab,kw OR gait.ti,ab,kw OR knee*.ti,ab,kw OR foot*.ti,ab,kw OR ankle*.ti,ab,kw OR review.ti,ab,kw OR 'case report*'.ti,ab,kw OR 'meta-analy*'.ti,ab,kw OR 'meta analy*'.ti,ab,kw)
PubMed (2019 to First week of March 2022)	(("stroke"[Mesh] OR poststroke*[tiab] OR stroke*[tiab] OR apoplex*[tiab]) OR ((brain*[tiab] OR cerebr*[tiab] OR cerebell*[tiab] OR intracran*[tiab] OR intracerebral*[tiab] OR vertebrobasilar*[tiab]) AND (vascular*[tiab]) AND (disease*[tiab] OR accident*[tiab] OR disorder*[tiab])) OR ((cerebrovascular[tiab]) AND (disease*[tiab] OR disorder*[tiab] OR accident*[tiab])) OR ((brain*[tiab] OR cerebr*[tiab] OR cerebell*[tiab] OR intracran*[tiab] OR intracerebral*[tiab] OR vertebrobasilar*[tiab]) AND (bleed*[tiab] OR hemorrhag*[tiab] or ischemi*[tiab] OR infarct*[tiab] OR hematoma*[tiab])) OR ("paresis"[Mesh] OR paresi*[tiab] OR hemipar*[tiab] OR

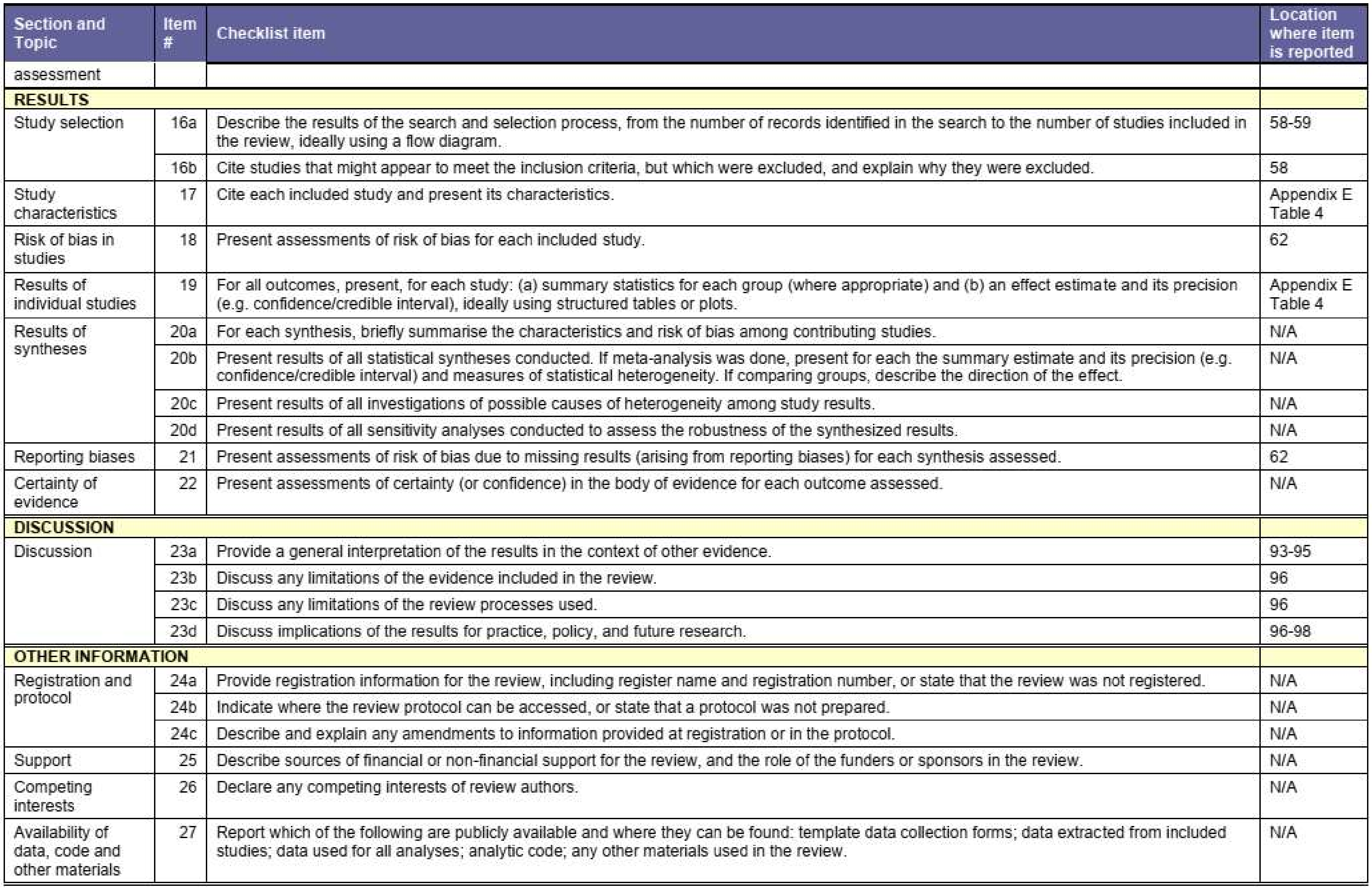
"hemiplegia"[Mesh] OR hemipleg*[tiab] OR pareti*[tiab])) AND ("upper extremity"[Mesh] OR "upper extremity"[tiab] OR "upper limb"[tiab] OR "upper limb*"[tiab] OR "upper extremity*"[tiab] OR arm[tiab] OR shoulder*[tiab] OR elbow*[tiab] OR wrist*[tiab] OR hand[tiab] OR hands[tiab] OR forearm*[tiab] OR grasp[tiab] OR grasp*[tiab] OR point[tiab] OR reach*[tiab] OR point*[tiab]) AND (biomechani*[tiab] OR dynami*[tiab] OR kinemat*[tiab] OR coordin*[tiab] OR synerg*[tiab] OR stabilit*[tiab] OR compensat*[tiab] OR "degrees of freedom"[tiab] OR trajector*[tiab] OR smoothness[tiab] OR velocit*[tiab] OR accelerat*[tiab] OR jerk[tiab] OR spatiotemporal[tiab] OR spatial[tiab] OR temporal[tiab]) NOT ("cerebral palsy"[Mesh] OR "cerebral palsy"[tiab] OR "parkinson disease"[Mesh] OR "parkinson disease"[tiab] OR "dementia"[Mesh] OR "dementia"[tiab] OR pediatric*[tiab] OR child*[tiab] OR bilateral*[tiab] OR bimanual*[tiab] OR interlimb*[tiab] OR "inter limb"[tiab] OR "inter-limb"[tiab] OR "bi manual"[tiab] OR "bi-manual"[tiab] OR "between limb*"[tiab] OR "between-limb*"[tiab] OR bilateral[tiab] OR animal*[tiab] OR "lower extremity"[Mesh] OR "lower limb*"[tiab] OR "lower extremit*"[tiab] OR "lower bod*"[tiab] OR gait[tiab] OR knee*[tiab] OR foot*[tiab] OR ankle*[tiab] OR review[tiab] OR "case report*"[tiab] OR "meta-analy*"[tiab] OR "meta analy*"[tiab])

Web of Science (2019 to First week of March 2022)	((stroke OR poststroke* OR stroke* OR apoplex*) OR ((brain* OR cerebr* OR cerebell* OR intracran* OR intracerebral* OR vertebrobasilar*) AND (vascular*) AND (disease* OR accident* OR disorder*)) OR ((cerebrovascular) AND (disease* OR disorder* OR accident*)) OR ((brain* OR cerebr* OR cerebell* OR intracran* OR intracerebral* OR vertebrobasilar*) AND (bleed* OR hemorrhag* or ischemi* OR infarct* OR hematoma*)) OR (paresi* OR hemipar* OR hemipleg* OR pareti*)) AND ("upper extremity" OR "upper limb" OR "upper limb*" OR "upper extremity*" OR arm OR shoulder* OR elbow* OR wrist* OR hand OR hands OR forearm* OR grasp OR grasp* OR point OR reach OR reach* OR point*) AND (biomechani* OR dynami* OR kinemat* OR coordin* OR synerg* OR stabilit* OR compensat* OR "degrees of freedom" OR trajector* OR smoothness OR velocit* OR accelerat* OR jerk OR spatiotemporal OR spatial OR temporal) NOT ("cerebral palsy" OR "parkinson disease" OR dementia OR pediatric* OR child* OR bilateral* OR bimanual* OR interlimb* OR "inter limb" OR "inter-limb" OR "bi manual" OR "bi-manual" OR "between limb*" OR "between-limb*" OR bilateral OR animal* OR "lower limb*" OR "lower extremit*" OR "lower bod*" OR gait OR knee* OR foot* OR ankle* OR review OR "case report*" OR "meta-analy*" OR "meta analy*")

Appendix B: PRISMA Checklist



Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	N/A
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	N/A
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	49-53
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	53-54
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	54-57
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	54
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	116-120
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	54-55
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	55-56
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	56-57
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Appendix E, Table 4
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	56
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Appendix E, Table 4
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	56-57
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N/A
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	56-57
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	56-57
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	N/A
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Appendix C, Table 3
Certainty	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	N/A



Section and Topic	Item #	Checklist item	Location where item is reported
assessment			
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	58-59
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	58
Study characteristics	17	Cite each included study and present its characteristics.	Appendix E Table 4
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	62
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Appendix E Table 4
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	N/A
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	N/A
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N/A
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/A
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	62
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	N/A
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	93-95
	23b	Discuss any limitations of the evidence included in the review.	96
	23c	Discuss any limitations of the review processes used.	96
	23d	Discuss implications of the results for practice, policy, and future research.	96-98
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	N/A
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	N/A
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	N/A
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	N/A
Competing interests	26	Declare any competing interests of review authors.	N/A
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	N/A

Figure 10. PRISMA Checklist. This figure represents a 27-item checklist that is used to guide authors when creating a systematic review. Adapted from “The PRISMA 2020 statement: An updated guideline for reporting systematic reviews” by Page et al., 2021, *BMJ*, *372*(1), 71. (https://doi.org/10.1136/bmj.n71). Copyright 2021 by the BMJ Publishing Group Ltd.

Appendix C: Down and Black Checklist

Table 3.

The Down and Black Checklist. This Table figure represents the checklist used to assess the quality of each study.

Item	Criteria	Answers
	Reporting	
1	Is the hypothesis/aim/objective of the study clearly described?	Yes = 1 No = 0
2	Are the main outcomes to be measured clearly described in the introduction or Methods section? If the main outcomes are first mentioned in the results section, the questions should be answered no.	Yes = 1 No = 0
3	Are the characteristics of the patients included in the study clearly described? In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for the control should be given.	Yes = 1 No = 0
4	Are the interventions of interest clearly described? Treatments and placebo (where relevant) that are to be compared should be clearly described.	Yes = 1 No = 0
5	Are the distributions of principal confounders in each group of subjects to be compared clearly described? A list of principal confounders is provided.	Yes = 1 No = 0
6	Are the main findings of the study clearly described? Simple outcome data (including denominator and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions. (This question does not cover statistical test which are considered below).	Yes = 1 No = 0
7	Does the study provide an estimate of the random variability in the data for the main outcomes? In non-normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, and standard deviation of confidence intervals should be reported. If the distribution of the data is not described, it must be assumed that the estimates used were appropriate and the question should be answered yes.	Yes = 1 No = 0

Item	Criteria	Answers
8	Have all important adverse events that may be a consequence of the intervention been reported? This should be answered yes if the study demonstrated that there was a comprehensive attempt to measure adverse events. (A list of possible adverse events is provided).	Yes = 1 No = 0
9	Have the characteristic of patients lost to follow-up been described? This should be answered yes where there were no losses to follow-up or where losses to follow-up were so small that findings would be unaffected by their inclusion. This should be answered no, where a study does not report the number of patients lost to follow up.	Yes = 1 No = 0
10	Have probability values been reported (e.g., 0.035 rather than <0.05) for the main outcomes expect where the probability value is less than 0.001	Yes = 1 No = 0
	External Validity	
11	Were the subject asked to participate in the study representative of the entire population from which they were recruited. The study must identify the source population for patients and describe how the patients were selected. Patients would be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant population exists. Where a study does not report the proportion of the source population from which the patients are derived, the question should be answered as unable to determine	Yes = 1 No = 0 Unable to determine = 0
12	Were those subjects who were prepared to participate representative of the entire population from which they were recruited? The proportion of those asked who agreed should be stated. Validation that the sample representative would include demonstrating that the distribution of main confounding factors was the same in the study sample and the source population	Yes = 1 No = 0 Unable to determine = 0
13	Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive? For the question to be answered yes, the study should demonstrate that the intervention was representative of that in use in the source population. The question should be answered no if, for example, the intervention was undertaken in a specialist center unrepresentative of the hospitals most of the source population would attend.	Yes = 1 No = 0 Unable to determine = 0

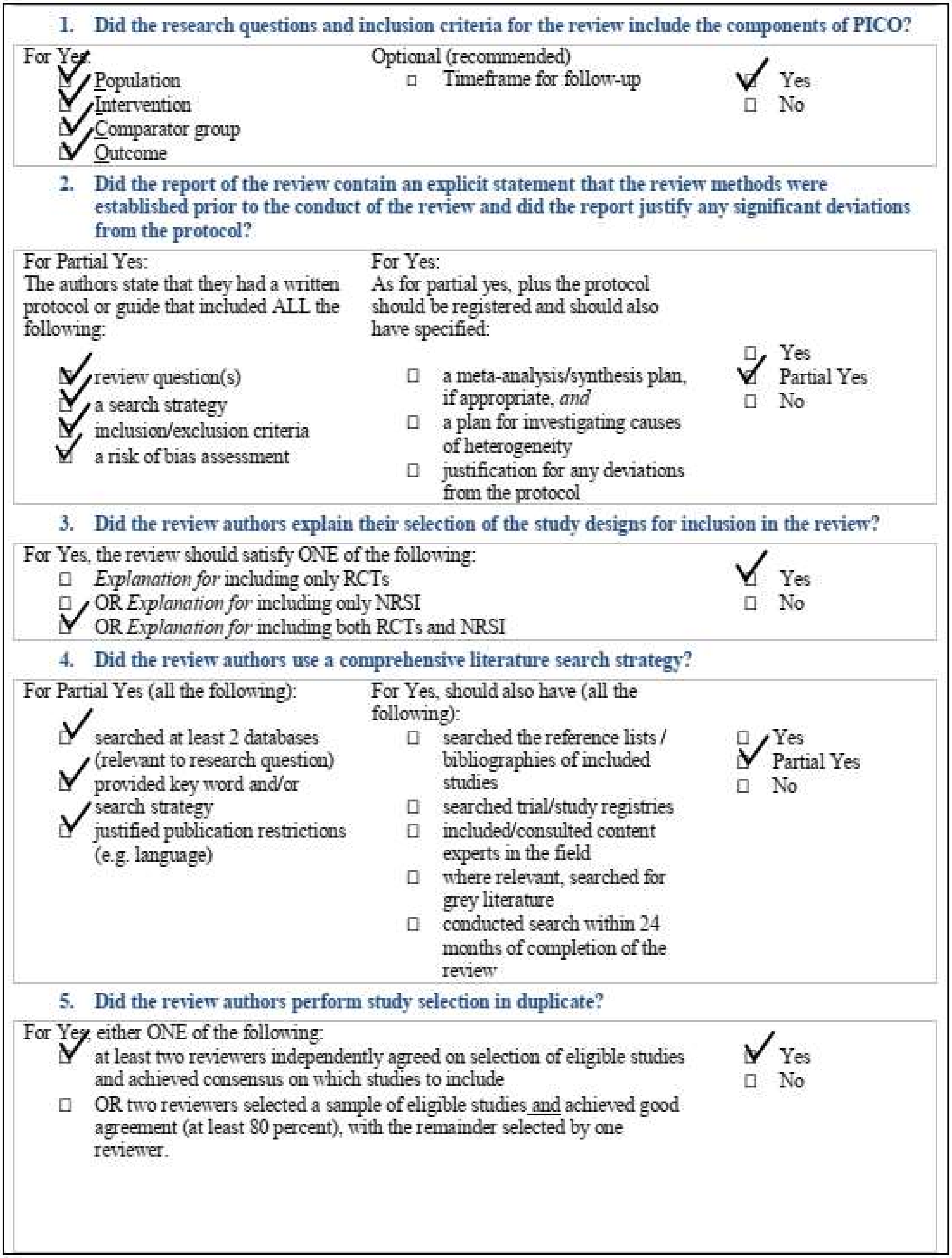
Item	Criteria	Answers
	Internal Validity Bias	
14	Was an attempt made to blind the study subjects to the intervention received? For studies where the patients have no way of knowing which intervention they received, this should be answered yes.	Yes = 1 No = 0 Unable to determine = 0
15	Was an attempt made to blind those measuring the main outcomes of the intervention?	Yes = 1 No = 0 Unable to determine = 0
16	If any of the results of the study were based on "data dredging", was this made clear? Any analyses that had not been planned at the outset of the study should be clearly indicated. If no retrospective subgroup analyses were reported, then answer yes.	Yes = 1 No = 0 Unable to determine = 0
17	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls? Where follow-up was the same for all study patients the answer should yes. If different lengths of follow-up were adjusted for by, for example, survival analysis the answer should be yes. Studies where differences in follow-up are ignored should be answered no.	Yes = 1 No = 0 Unable to determine = 0
18	Were the statistical tests used to assess the main outcomes appropriate? The statistical techniques used must be appropriate to the data. For example, non-parametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described, it must be assumed that the estimated used were appropriate and the question should be answered yes.	Yes = 1 No = 0 Unable to determine = 0
19	Was compliance with the interventional reliable. Where there was noncompliance with the allocated treatment or where there was contamination of one group, the question should be answered no. For studies where the effect of a misclassification was likely to bias an association to the null, the question should be answered yes.	Yes = 1 No = 0 Unable to determine = 0
20	Were the main outcome measures used accurate (valid and reliable)? For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work	Yes = 1 No = 0 Unable to determine = 0

Item	Criteria	Answers
	or that demonstrated the outcome measures are accurate, the question should be answered yes.	
	Internal Validity – Confounding (Selection Bias)	
21	Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same populations? For example, patients for all comparison groups should be selected from the same hospital. The question should be answerable to determine from cohort and case-control studies where there is no information concerning the source of patients included in the study.	Yes = 1 No = 0 Unable to determine = 0
22	Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time? For a study which does not specify the time period over which patients were recruited, the question should be answered as unable to determine.	Yes = 1 No = 0 Unable to determine = 0
23	Were study subjects randomized to intervention groups? Studies which state the subjects were randomized should be answered yes except where method or randomization would not ensure random allocation. For example, alternate allocation would score no because it is predictable.	Yes = 1 No = 0 Unable to determine = 0
24	Was the randomized intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable? All non-randomized studies should be answered no. If assignment was concealed from patients but no from staff, it should be answered no.	Yes = 1 No = 0 Unable to determine = 0
25	Were there adequate adjustments for confounding in the analyses from which the main findings were drawn? This question should be answered no for trials if: the main conclusions of the study were based on analyses of treatment rather than intention to treat, the distribution of known confounders in the different treatment groups was not described, or the distribution of known confounders differed between the treatment groups but was not taken into account in the analyses. In non-randomized studies if the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analyses the question should be answered as no.	Yes = 1 No = 0 Unable to determine = 0

Item	Criteria	Answers
26	Were losses of patients to follow-up taken into account? If the numbers of patients lost to follow-up are not reported, the questions should be answered as unable to determine. If the proportion lost to follow-up was too small to affect the main findings, the question should be answered yes.	Yes = 1 No = 0 Unable to determine = 0
	Power	
27	Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%? Sample sizes have been calculated to detect a difference of x% and y%.	N<1 = 0 N (1-2) = 1 N (3-4) = 2 N (5-6) = 3 N (7-8) = 4 N>8 = 5

Note. Adapted from "The feasibility of creating a checklist for assessment of the methodological quality both of randomised and non-randomised studies of health care interventions" by Down and Blacks, 1998, *Journal of Epidemiology & Community Health*, *52*(6), 377–384. (https://doi.org/10.1136/jech.52.6.377). Copyright 1998 by BMJ Publishing Group Ltd. Copyright with permission.

Appendix D: AMSTAR-2 Checklist



1. Did the research questions and inclusion criteria for the review include the components of PICO?

For Yes:
☑ Population
☑ Intervention
☑ Comparator group
☑ Outcome

Optional (recommended)
☐ Timeframe for follow-up

☑ Yes
☐ No

2. Did the report of the review contain an explicit statement that the review methods were established prior to the conduct of the review and did the report justify any significant deviations from the protocol?

For Partial Yes:
The authors state that they had a written protocol or guide that included ALL the following:
☑ review question(s)
☑ a search strategy
☑ inclusion/exclusion criteria
☑ a risk of bias assessment

For Yes:
As for partial yes, plus the protocol should be registered and should also have specified:
☐ a meta-analysis/synthesis plan, if appropriate, *and*
☐ a plan for investigating causes of heterogeneity
☐ justification for any deviations from the protocol

☐ Yes
☑ Partial Yes
☐ No

3. Did the review authors explain their selection of the study designs for inclusion in the review?

For Yes, the review should satisfy ONE of the following:
☐ *Explanation for* including only RCTs
☐ OR *Explanation for* including only NRSI
☑ OR *Explanation for* including both RCTs and NRSI

☑ Yes
☐ No

4. Did the review authors use a comprehensive literature search strategy?

For Partial Yes (all the following):
☑ searched at least 2 databases (relevant to research question)
☑ provided key word and/or search strategy
☑ justified publication restrictions (e.g. language)

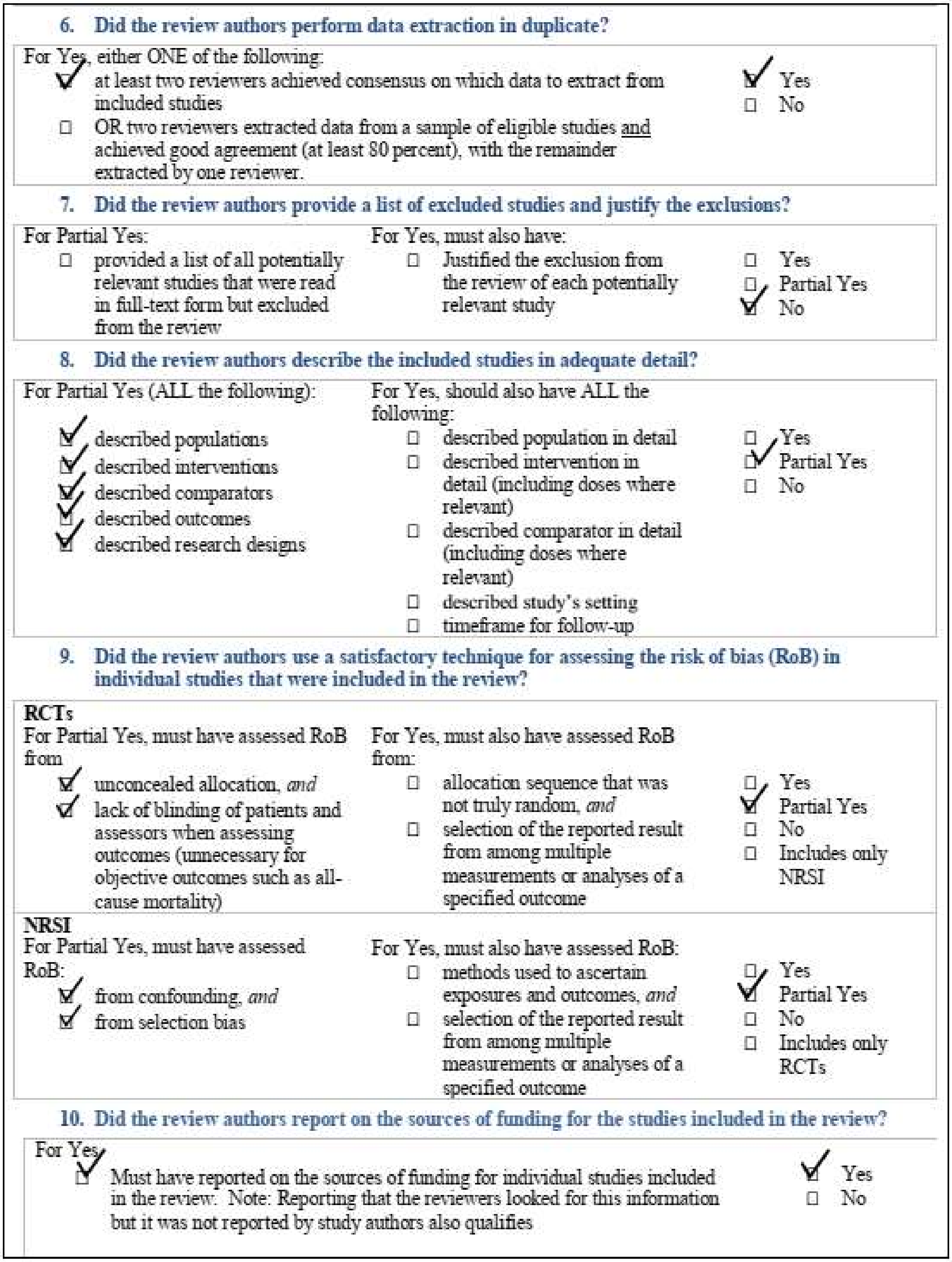
For Yes, should also have (all the following):
☐ searched the reference lists / bibliographies of included studies
☐ searched trial/study registries
☐ included/consulted content experts in the field
☐ where relevant, searched for grey literature
☐ conducted search within 24 months of completion of the review

☐ Yes
☑ Partial Yes
☐ No

5. Did the review authors perform study selection in duplicate?

For Yes, either ONE of the following:
☑ at least two reviewers independently agreed on selection of eligible studies and achieved consensus on which studies to include
☐ OR two reviewers selected a sample of eligible studies and achieved good agreement (at least 80 percent), with the remainder selected by one reviewer.

☑ Yes
☐ No



6. Did the review authors perform data extraction in duplicate?

For Yes, either ONE of the following: ☑ at least two reviewers achieved consensus on which data to extract from included studies ☐ OR two reviewers extracted data from a sample of eligible studies and achieved good agreement (at least 80 percent), with the remainder extracted by one reviewer.	☑ Yes ☐ No

7. Did the review authors provide a list of excluded studies and justify the exclusions?

For Partial Yes: ☐ provided a list of all potentially relevant studies that were read in full-text form but excluded from the review	For Yes, must also have: ☐ Justified the exclusion from the review of each potentially relevant study	☐ Yes ☐ Partial Yes ☑ No

8. Did the review authors describe the included studies in adequate detail?

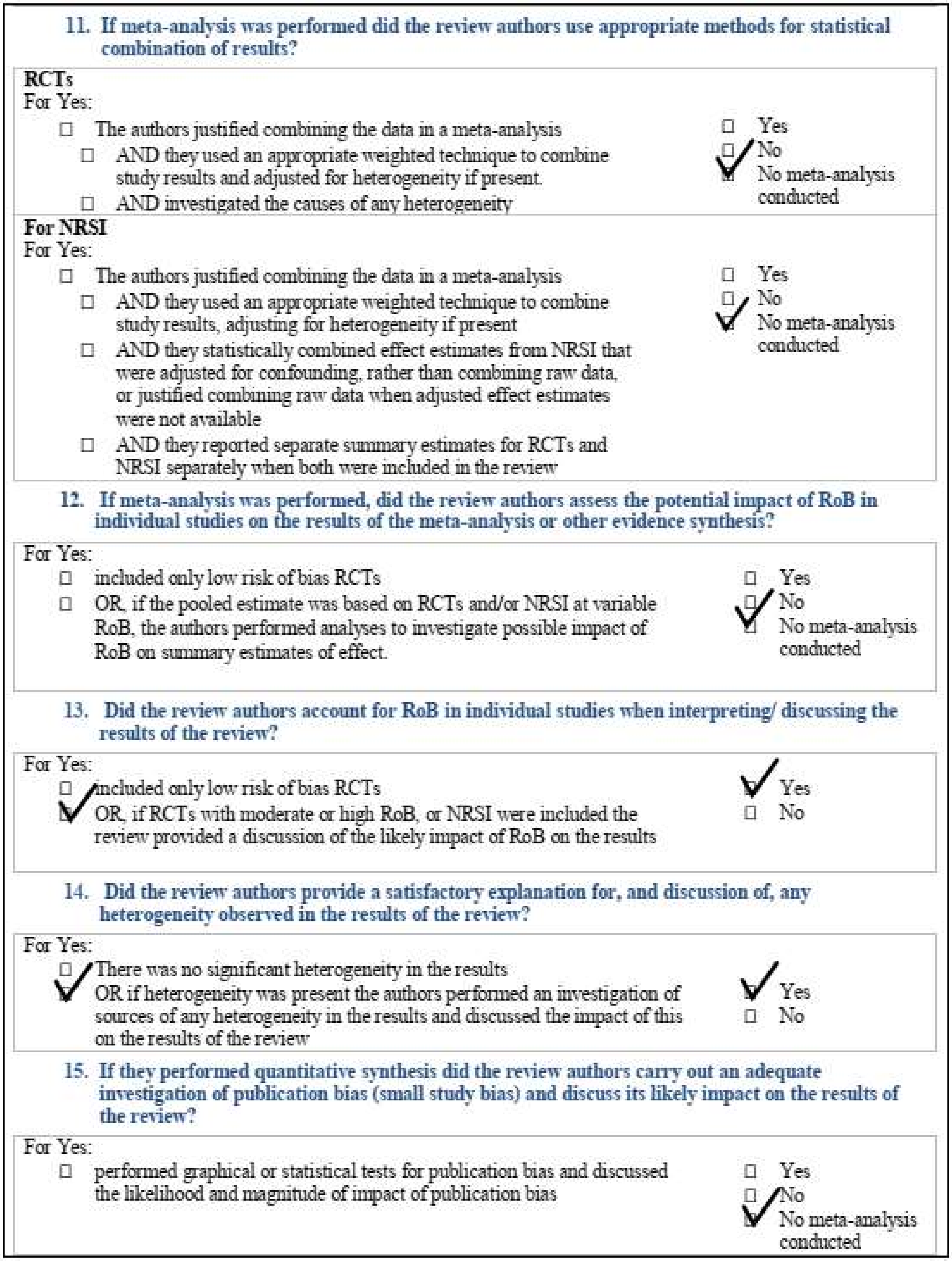
For Partial Yes (ALL the following): ☑ described populations ☑ described interventions ☑ described comparators ☑ described outcomes ☑ described research designs	For Yes, should also have ALL the following: ☐ described population in detail ☐ described intervention in detail (including doses where relevant) ☐ described comparator in detail (including doses where relevant) ☐ described study's setting ☐ timeframe for follow-up	☐ Yes ☑ Partial Yes ☐ No

9. Did the review authors use a satisfactory technique for assessing the risk of bias (RoB) in individual studies that were included in the review?

RCTs For Partial Yes, must have assessed RoB from ☑ unconcealed allocation, *and* ☑ lack of blinding of patients and assessors when assessing outcomes (unnecessary for objective outcomes such as all-cause mortality)	For Yes, must also have assessed RoB from: ☐ allocation sequence that was not truly random, *and* ☐ selection of the reported result from among multiple measurements or analyses of a specified outcome	☐ Yes ☑ Partial Yes ☐ No ☐ Includes only NRSI
NRSI For Partial Yes, must have assessed RoB: ☑ from confounding, *and* ☑ from selection bias	For Yes, must also have assessed RoB: ☐ methods used to ascertain exposures and outcomes, *and* ☐ selection of the reported result from among multiple measurements or analyses of a specified outcome	☐ Yes ☑ Partial Yes ☐ No ☐ Includes only RCTs

10. Did the review authors report on the sources of funding for the studies included in the review?

For Yes ☑ Must have reported on the sources of funding for individual studies included in the review. Note: Reporting that the reviewers looked for this information but it was not reported by study authors also qualifies	☑ Yes ☐ No



11. If meta-analysis was performed did the review authors use appropriate methods for statistical combination of results?

RCTs For Yes: ☐ The authors justified combining the data in a meta-analysis ☐ AND they used an appropriate weighted technique to combine study results and adjusted for heterogeneity if present. ☐ AND investigated the causes of any heterogeneity	☐ Yes ☐ No ☑ No meta-analysis conducted
For NRSI For Yes: ☐ The authors justified combining the data in a meta-analysis ☐ AND they used an appropriate weighted technique to combine study results, adjusting for heterogeneity if present ☐ AND they statistically combined effect estimates from NRSI that were adjusted for confounding, rather than combining raw data, or justified combining raw data when adjusted effect estimates were not available ☐ AND they reported separate summary estimates for RCTs and NRSI separately when both were included in the review	☐ Yes ☐ No ☑ No meta-analysis conducted

12. If meta-analysis was performed, did the review authors assess the potential impact of RoB in individual studies on the results of the meta-analysis or other evidence synthesis?

For Yes: ☐ included only low risk of bias RCTs ☐ OR, if the pooled estimate was based on RCTs and/or NRSI at variable RoB, the authors performed analyses to investigate possible impact of RoB on summary estimates of effect.	☐ Yes ☐ No ☑ No meta-analysis conducted

13. Did the review authors account for RoB in individual studies when interpreting/ discussing the results of the review?

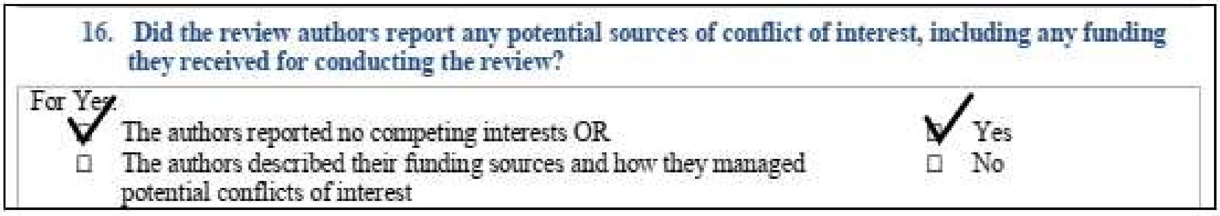
For Yes: ☐ included only low risk of bias RCTs ☑ OR, if RCTs with moderate or high RoB, or NRSI were included the review provided a discussion of the likely impact of RoB on the results	☑ Yes ☐ No

14. Did the review authors provide a satisfactory explanation for, and discussion of, any heterogeneity observed in the results of the review?

For Yes: ☐ There was no significant heterogeneity in the results ☑ OR if heterogeneity was present the authors performed an investigation of sources of any heterogeneity in the results and discussed the impact of this on the results of the review	☑ Yes ☐ No

15. If they performed quantitative synthesis did the review authors carry out an adequate investigation of publication bias (small study bias) and discuss its likely impact on the results of the review?

For Yes: ☐ performed graphical or statistical tests for publication bias and discussed the likelihood and magnitude of impact of publication bias	☐ Yes ☐ No ☑ No meta-analysis conducted



16. Did the review authors report any potential sources of conflict of interest, including any funding they received for conducting the review?

For Yes:

☑ The authors reported no competing interests OR

☐ The authors described their funding sources and how they managed potential conflicts of interest

☑ Yes

☐ No

Figure 11. AMSTAR-2 Checklist. This figure represents the checklist used to assess the quality of this review. From “AMSTAR 2: A critical appraisal tool for systematic reviews that include randomised or non-randomised studies of health care interventions, or both” by Shea et al., 2017, *BMJ*, *305*(1), (https://doi.org/10.1136/bmj.j4008). Copyright 2017 by the BMJ Publishing Group Ltd. Reprinted with permission.

Appendix E: Data Collection Tables

Table 4.

A summary table used to extract information and provide a comprehensive description about each study.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Carpinella et al., 2020	Effects of Robot Therapy On Upper Body Kinematics and Arm Function in Persons Post Stroke: A Pilot Randomized Controlled Trial	The first aim was to assess the effects of planar robotic rehabilitation versus arm-specific physiotherapy in person post-stroke on motor strategies derived from the instrumented kinematic analysis of upper limb and trunk during the execution of a non-trained task involving horizontal and vertical arm movements. The second aim was to compare the effects of the two rehabilitation approaches on arm function as measured by clinical scales.	**Stroke** N=19 Age: 67.0 (58.0-70) years Time Since Stroke: 7.0 (1.7-11.9) Months Sex: 9 F, 10M Stroke Type: 13 Ischemic, 6 Hemorrhagic Paretic Side: 9 R, 10 L Chronicity: 12 Chronic, 7 Subacute **Clinical Assessments** FM-UE MAS **Controls** N= 19 Age: 59.0 (46.0 - 69.0) years Time Since Stroke: 5.3 (1.9 - 89.6) Months Sex: 9 F, 10 M Stroke Type: 12 Ischemic, 7 Hemorrhagic	Participants were randomized to the Robot Group or the Control Group. Both groups received rehabilitation treatment for the affected upper limb which consisted of 20, 45-minute session administered 5 times a week by a trained physiotherapist **Robot Group** Participants received robot-based training using a planar robotic manipulandum that practices shoulder and elbow movements in the horizontal plane. The subjects were seated on a chair while grasping the handle of robot with their affected hand. The task consisted of repeated center out reaching movement and back to a target on a large computer screen. The	Compared to the control intervention, the robotic intervention induced larger improvements in coordination between the shoulder and elbow joints. **Robot-based instrumented parameters** Planar reaching movements became faster and smoother across the sessions. The mean reaching duration decreased significantly ($F_{19,361} = 8.94$, $p < 0.001$) The number of movement units to reach the target decreased significantly ($F_{19,361} = 13.21$, $p < 0.001$). **Robot vs control intervention** ***Primary Instrumented Analysis*** The change score of the shoulder/elbow coordination index was significantly different between groups ($F_{1,35} = 6.04$, $p = 0.019$) (Cohen's $d = 0.82$)	1. Small sample size. 2. Lack of follow-up assessments. 3. The robotic exercise was based on a simple virtual scenario. 4. Lack of distal robotic components on the wrist and hand	Robotic rehabilitation was more effective than conventional physiotherapy in improving inter-joint coordination.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
			Paretic Side: 7 R, 12 L Chronicity:10 Chronic, 9 Subacute	target consisted of five positions arranged in a semi-circle with a 20 cm radius. The reaching movements were performed under two modes, assist-as-needed and resistive. The assist as needed mode had the participants execute the movement while the robot generated a minimal assistive force to help reach the target.	***Secondary Instrumented Analysis*** The R group attained a greater increase in elbow extension (F1,35 = 4.63, p = 0.038) (Cohen's d = - 0.72), and a larger decrease in trunk compensation in the sagittal plane (F1,35 = 11.38, p = 0.002) Cohen's d = - 1.12 The increase in the amount of shoulder flexion was comparable between groups (F1,35 = 1.12, p = 0.297) The stroke subjects executed the task with significant impairment of shoulder/elbow coordination accompanied by a statistically significant reduction of the amount of shoulder flexion and elbow extension. Funding source: Italian Ministry of Health (Ricerca Corrente and Ricerca Finalizzata: grant no. GR-2011-02348942).		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Cho and Song, 2019	Robot-Assisted Reach Training with an Active Assistant Protocol for Long-Term Upper Extremity Impairment Poststroke: A Randomized Controlled Trial	The purpose was to sssess whether a protocol for robot-assisted reach training with assist-as-needed (RT-AAAN) (provides triggered assistive force based on the participants reaching performance) and guidance mode (provides constant assistive force to correct arm movements smoothly in a specific trajectory) can improve the upper extremity function and kinematic performance of chronic stroke survivors	38 Participants with stroke were randomly assigned to a RT-AAN group or RT-G group **RT-AAN Group** n=12, 2 women, 10 left hand paretic, 5 hemorrhagic, 59.94 +/- 7.66 years old, 10.10 +/- 6.57 years since stroke **RT-G Group** n=12, 8 women, 11 left hand paretic, 7 hemorrhagic, 60.21 +/- 8.38 years old, 11.31 +/- 6.34 years since stroke **Clinical Assessments** FMA ARAT BBT	**Procedure** Participants underwent pretest assessment and then were randomized to either an RT-AAN or RT-G group All participants received training 3 times a week for 6 weeks. Each training session lasted 40 minutes and was supervised by an assistant **Experimental Protocol** Participants performed RART while seated on a chair while wearing the Whole Arm Manipulator (WAM). The training consisted of reaching red and gray ball targets on a screen in 3D space in 6 directions. The red ball was matched and linked to the reaching movements of the participants and an auditory signal was given when the red and gray balls matched. The reaching movements comprised of 3 phases, moving	**Kinematics** Both groups showed a significant improvement in all directions of movement velocity ($P<0.05$). There was no significant difference between groups ($P>0.05$). Funding source: Research Program (grant nos. NRCRI13-A-04, NRCTR-IN13004, NRCTRIN14006, NRCTR-IN15005, NRCTR-IN16005, NRCTR-IN17006, NRCTR-IN18006) of the National Rehabilitation Center, Ministry of Health and Welfare, Republic of Korea.	1. No intent to treat analysis was performed. 2. Only high-functioning stroke survivors were included. 3. The inertia generated from the robotic device may affect the difficulty level of certain movements. 4. Technical problem prevented the record of the amount of AAN force used. 5. The long-term effect of RART was not assessed.	Robot-assisted training may be used as an effective intervention to improve upper extremity function in chronic stroke survivors.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				towards the target, manipulating the target, and returning from the target to the hand point. Both RT-AAN and RT-G groups received gravity compensation via WAM. The RT-AAN group received training with additional AAN force and the RT-G group with additional guidance force. The RT-AAN group received a triggered assistive force based on the participants reaching performance. The force was applied if the participant could not move the arm for more than 2 seconds. The RT-G groups received (1) corrective force to the line from the starting point to the target point, and (2) assistive force towards the target at the same time. The guidance force mode provided a simultaneous force for each 1, and 2 that was calculated via the summation of			

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				tangential force and normal force between the current hand position of the robotic arm and the desired trajectory from the starting point to the target. All participants wore a trunk fixation belt to minimize compensatory trunk movement.			

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Feingold-Polak et al., 2021	The effects of an object calibration and kinematics when post-stroke and healthy individuals reach and grasp	The purpose was to evaluate movement quality, efficacy, and force regulation of the affected UL of subacute post-stroke individuals during a functional RTG task at different heights and weights compared to healthy individuals.	**Stroke** N=30 Age: 70.3 ± 9.3 years Sex: 16 males, 14 females Mean time post-stroke 46 ± 19.9 days Chronicity: Subacute Lesion Type: 86.6% Ischemic, 13.4 % Hemorrhagic Lesion Location Affected Side 46.6% R, 53.4% L Dominant Hand Tested 53.3% Yes, 46.7% No **Clinical Assessments** FMA MAS Cherokee Brunnstrom **Healthy Controls** Age: 69.1 ± 11.5 years Sex: 5 males, 11 females	**Evaluation Procedure** All participants were evaluated individually by a physical therapist in two, 45-minute sessions performed on separate days **Experimental Set-Up** Participants sat in a chair at a height-adjustable table without trunk support. Upon hearing a "beep" each participant was instructed to reach their hand at a self-selected speed toward a cup located on the table, lift the cup, and place it on top of a 5cm block positioned on the table. The cup was horizontally aligned with the reaching arm and placed at one of three different heights (low, medium, and high). The participants were instructed to reach, grasp, and lift the cup in one continuous movement to avoid bending the trunk. Two different weights	**Movement Velocity** Those with stroke had significantly lower mean velocity, peak velocity during the reach and lift phase (P<0.001) **Smoothness of movements** The normalized jerk was higher in those with stroke during all phases of the task compared to the controls (*Reach*: F1,808 = 330.74, *p* < 0.001; *Grasp:* F1,811 = 228.04, *p* < 0.001; *Lift:* F1,776 = 161.26, *p* < 0.001; *Total task*: F1,781 = 245.1, *p* < 0.001) Individuals with stroke with greater severity had increased normalized jerk values (F3,276 = 3.65, *p* = 0.013) The individuals withs stroke hade higher normalized jerk values during the reaching phase for the non dominant hand (F1,487 = 44.42, *p* < 0.001) There was a significant effect of height on the normalized jerk *Reach* (F2,511 = 3.08, *p* = 0.047), *Grasp* (F2,532 = 3.39, *p* = 0.034), and *Lift* (F2,570 = 3.38, *p* = 0.035) Weight did not influence the normalized jerk.	1. Small sample size. 2. Lack of gyroscopic measures during the lifting phase. 3. Only the contralesionally hand was examined, and not both hands.	This study extends previous findings by examining motor control and force production during up and downward reaching. The data from this study can be used to help build algorithms to detect compensatory movements and altered forces post-stroke.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				of the cup were used (empty and filled). Each participant was told whether the cup was empty or filled, and the cup was capped to prevent spilling. The starting position for the low height was so that the arm was held vertically at the side of the body, and for the medium and high heights, it was on the ipsilateral thigh with the palm facing down. Each combination of height and weight trial was recorded three times. The combination was randomized using a computer program.	The index of curvature was significantly higher in those with stroke ($P<0.05$) The index of curvature was significantly lower in the high vs medium and low heights ($P<0.001$) The individuals with stroke had significantly greater trunk displacement compared to the controls ($F1,750 = 89.65$, $p < 0.001$) Individuals with stroke had lower elbow angles during the reach and lift phases (*Reach*: $F1,771 = 30.40$, $p < 0.001$; *Lift*: $F2,370 = 134.53$, $p < 0.001$) The max elbow extension angle was larger at the higher height compared to the lower height ($F2,612 = 430$, $p < 0.001$) Funding source: Helmsley Charity Trust through the Agricultural, Biological and Cognitive Robotics Initiative and by the Marcus Endowment Fund, both at the Ben-Gurion University of the Negev. Financial support was provided by the Rosetrees Trust, the Borten Family Foundation, the Robert Bergida bequest, and the Consolidated Anti-Aging Foundation Grants. This		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
					research was also supported by the Israel Science Foundation (Grants No. 535/16 and 2166/16), the Israeli Ministry of Health, and the Israeli National Insurance Institute, and received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No 754340.		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Gomes et al., 2021	Effects of attentional focus on upper extremity motor performance in post stroke patients: A randomized pilot study	The purpose was to examine the effects of Internal Focus (IF) and External Focus (EF) on upper extremity motor performance in post-stroke patients	12 Individuals with Stroke Participants were randomized to two groups Group 1 (G1) or Group 2 (G2). **Clinical Assessments** FMA MMSE **G1** N: 6 Sex: 2 M, 4 F Age: 64 (52.2-70.2) Dominant Hand: Right Chronicity: >6 years **G2** N: 6 Sex: 2 M, 4 F Age: 66 (52.2-70.2) Chronicity: > 3 years	**Procedure** The study consisted of 2 phases separated by a one-week interval. The first phase (phase A) consisted of G1 receiving IF, and G2 receiving EF. The second phase entailed G1 receiving EF and G2 receiving IF. Two tasks were used. In task one (T1) participants were instructed to reach and touch three targets arranged in an "L" shape. In task two(T2) participants were instructed to carry a glass between 2 distinct targets, spaced 15 cm apart. For each task 16 repetitions were performed, with an interval of 15 seconds between each repetition and 3 minutes between each type of task Both tasks were performed with the participants sitting with the back supported. The trunk was unrestricted, the elbow was placed at 90	Both types of attentional focus caused significant positive changes in execution time and mean velocity in the first repetition compared to the final repetition ($P<0.05$). No significant differences between the groups receiving internal and external focus in both phases in the final repetition ($P>0.05$) The benefits of external focus are accentuated when preceded by internal focus, as G1 (internal focus followed by external focus) showed significant values in total time and mean velocity and variables and G2 (external followed by internal focus) presented significant values on time only. It is more important to provide feedback about information of their own movement first and guide them to in the following sessions about the effect of movement on the environment. Funding source: Primary sponsor: Universidade Federal do Rio Grande do Norte, Secondary sponsor: Institution: Faculdade de Ciências da Saúde do Trairi (Facisa), Supporting source: Institution: Universidade Federal do Rio Grande do Norte Institution: Faculdade de Ciências da Saúde do Trairi (Facisa).	1. Small sample size	It is vital that therapists are aware of the importance of providing feedback to the patients and the motor learning variables that can be easily modified to get the expected results.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				degrees flexion, the shoulder at 0 degrees and the hands on the table **Intervention** Before each task, a trained physiotherapist demonstrated once, and the participant practised the movement. Each participant performed one repetition after being given a verbal command.			

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Hasanbarani et al., 2021	Mild Stroke Affects Pointing Movements Made in Different Frames of Reference	The purpose was to identify deficits when performing pointing movements in egocentric and exocentric Frames of Reference (FR) in individuals with stroke	**Stroke** N: 12 Age 58.5 +/-11.8 years Gender: 2F, 10 M Side of Lesion: 6 L, 6 R Dominance: 1 L, 11 R Lesion Site: 6 S, 6 C Type of Stroke: 2 H, 10 I Time since injury: 232.6 +/- 13.6 Months **Clinical Assessments** FMA MoCA MVPT CMSA CSI **Healthy Controls** N: 13 Age: 62.9 +/- 17.1 years Gender: 6 F, 7 M Dominance: 1 L, 12 R	Task 1: Egocentric Reaching. A 30cm rod was attached to the contralateral arm from the mid-forearm and extending beyond the forearm. The arm was held in a 90-degree elbow flexion in the horizontal plane in front of the body. The participants reached down the rod to the final target. Task 2: Exocentric Reaching Two targets were placed 30 cm apart in the same direction and horizontal orientation as that of Task 1 but in the external space. participants were asked to reach the targets without vision. Both Tasks 1 and 2 were performed with and without a blocked trunk (via an electromagnet). Each participant completed 50 trials. In 35 of the trails the	**Individuals with stroke** **Egocentric Task** Movement speed, trajectory length, and straightness were similar between conditions for both groups. **Exocentric Task** In those with stroke participants preserved trajectory straightness in both blocked and unblocked conditions. Movement time was longer by 0.96 seconds (*F*1,23 = 5.11; *P* = .034; ES = 0.182) and trajectory length was longer by 61 mm (*z* = -3.182; *P* = .001; ES = 0.678) in the free- compared with the blocked-trunk condition. Elbow extension was greater in the blocked trunk condition by 15.7° (*F*1,23 = 10.775; *P* = .003; ES = 0.319) and shoulder abduction was smaller by 7.1° (*z* = -2.908; *P* = .004; ES = 1.044) The range of motion of each joint did not differ (P<0.5) The trajectory slopes were 9.2° lower in the blocked compared with the free-trunk condition for the egocentric task (*F*1,23 = 8.086, *P* = .009, ES = 0.260) and 29° greater for	1. Lack of muscle activity analysis. 2. The findings can only be applied to individuals with mild stroke without apraxia or other perceptual deficits. 3. Trunk stability was not assessed. 4. Reaching with the unaffected arm was not examined.	Individuals with stroke have an altered ability to adjust shoulder-elbow inter-joint coordination during both egocentric and exocentric movements. These deficits were not routinely examined and may negatively impact upper extremity motor control in various activities of daily living. This motor planning related to the more complex task should be integrated into future rehabilitation programs.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				electromagnet was chosen at random, to be unlocked (free trunk). In the remaining 15, the electromagnet was activated (blocked trunk).	the exocentric task (*F*1,23 = 16.77, *P* = .0001, ES = 0.422. In the egocentric task the inter-joint coordination sloped was differed where the shoulder flexion/elbow extension was lower by 22.9°; *F*1,23 = 8.592, *P* = .008, ES = 0.272) in the free trunk condition and shoulder abduction/elbow extension was lower by 24.8° (*F*1,23 = 7.756, *P* = .011, ES = 0.252) The divergence point occurred early in the reach for both tasks (egocentric: 11.9%; exocentric: 12.3%). The inter-joint patterns differed early in the reach for the egocentric task and in mid reach (IJC DP: 54.0%-60.0%). **Between groups** ***Egocentric*** The individuals with stroke used 9.2° more elbow extension in the blocked trunk condition compared to controls (*F*1,23 = 10.775, *P* = .003, ES = 0.319). There was an interaction between the group and condition for the trajectory slope (*F*1,23 = 8.086, *P* = .009, ES = 0.260). the stroke group had a lower slop in the blocked conditions (P<0.5).		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
					The stroke group had lower inter-joint coordination slopes of shoulder-abduction/elbow-extension (by ~24.8°; *F*1,23 = 7.11, *P* = .014, ES = 0.236). The divergence point occurred earlier in the trajectory (~15%) compared to the controls (~70%; *t* = 14.91, *P* = .0001, ES = 6.043 The divergence point o the shoulder flexion/elbow extension (*t* = 10.18; *P* = .0001; ES = 4.122) and shoulder abduction/elbow extension (*z* = -4.248; *P* = .0001; ES = 3.577) occurred earlier in the stroke group. **Exocentric** The individuals with stroke used less elbow extension (by ~20.5°; *F*1,23 = 21.468, *P* = .0001, ES = 0.361) and more shoulder abduction (by ~7.5°; *F*1,23 = 12.996, *P* = .001, ES = 0.361) compared to controls. There was a group by condition interactions for trajectory slopes (*F*1,23 = 16.77; *P* = .0001; ES = 0.422). The slopes in the stroke group were lower in the free condition (*P* = .001) and higher in the blocked condition (*P* =.001) compared to controls.		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
					The trajectory divergence points occurred earlier in individuals with stroke compares to controls (*t* = -17.56, *P* = .0001, ES = 7.09). Individuals with stroke had lower shoulder-abduction/elbow-extension inter joint coordination slopes by (~24.8°; *F*1,23 = 6.015, *P* = .022, ES = 0.207) in the blocked condition compared with controls. The inter joint divergence point occurred later in the movement for shoulder flexion/elbow extension (~54%; *z* = -4.246, *P* = .0001, ES = 5.578) and shoulder abduction/elbow extension (~60%; *z* = -4.244, *P* = .0001, ES = 9.00) compared to controls (~13%-15% for both). Funding source: none.		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Hejazi-Shirmard et al., 2020	The effects of anxiety and dual task on upper limb motor control of chronic stroke survivors	The purpose was to investigate whether dual-task interference would be observed in upper limb motor control of stroke survivors when performing a well-learned everyday motor task compared with age- and sex-matched healthy subjects. The study also aimed to determine the effect of anxiety on upper limb motor control of these patients.	34 stroke and healthy controls were grouped into a low and high anxiety group **LA Stroke Group** *Age: 58.24 +/- 11.5 year* *Time Since Stroke: 33.65 +/- 22.28 Months* N: 17 Sex: 8 F, 9 M Dominance: 16 R, 1 L Affected Side: 8 R, 9 L Lesion Type: 15 Isch, 2 Hemorrhage Stroke ***Clinical Assessments*** Localization Information Trail making A Trail Making B FMA Pain (VAS) MMSE HADS-A GAI BAI **HA Stroke Group** Age: 55.76 +/- 9.72 year	Participants sat in a straight-backed chair in front of a table with their trunks stopped to the back of the chair to minimize compensatory movements of the trunk. Participants reached a target under three conditions 1: Single task 2: Easy Dual Task 3: Difficult dual task Dual-Task: backward digit task. 50% difficulty for the easy dual-task condition.	There was a significant main effect of stroke (control vs. stroke), anxiety (LA vs HA) and condition (single vs. easy dual task vs. difficult dual-task) on normalized movement time, peak velocity, and percentage of movement time in which peak velocity occurred (P<0.05) Post hoc analysis revealed a greater anxiety level showed greater anxiety levels in both stroke and control participants with high anxiety compared with both stroke and control participants with low anxiety Funding source: Iran University of Medical Sciences.	1. All participants had mild upper limb impairment (>=50 Fugl-Meyer score). The results are not generalizable to stroke survivors with moderate/severe upper limb motor impairment. 2. The harness used to restrain the trunk may have increased attentional demand in the HA stroke group. 3. Lack of MRI measures	This study identified greater inefficiency of reach and grasp motor control in chronic stroke survivors compared with age and sex-matched control subjects. In addition, this study provided the first evidence about the effect of anxiety on spatiotemporal control of reach-to-grasp movements in individuals with stroke. The individuals with stroke with high anxiety had worse motor control of reach and grasp compared to those with low anxiety under both single and dual-task conditions. Therefore, those

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
			Time Since Stroke: 39.65 +/- 20.24 Months N: 17 Sex: 8 F, 9 M Dominance: 16 R, 1 L Affected Side: 8 R, 9 L Lesion Type: 13 Ischemic, 4 Hemorrhage Stroke ***Clinical Assessments*** Localization Information Trail making A Trail Making B **LA Control Group** Age: 56.59 +/- 9.17 years N: 17 Sex: 8 F, 9 M Dominance: 16 R, 1 L **HA Control Group** 57.12 +/- 7.74 Years N: 17 Sex: 8 F, 9 M Dominance: 16 R, 1 L				with high anxiety may have less capacity to cope with the increasing demand of tasks encountered in everyday life.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Hussain et al., 2021	Recovery of arm function during acute to chronic stages of stroke quantified by kinematics	Quantify the longitudinal changes in upper limb kinematics between day 3 and 12 months after stroke, and identify the factors that affect this change, using the target-to-target pointing task performed in VR.	Participants were recruited from the SALGOT cohort of the Stroke Arm Longitudinal Study of the University of Gothenburg 66 individuals that had a stroke within the last 3 days 65.7 +/- 13.4 years old 41% (n=27) females81/19 Ischemic/haemorrhagic 63 Right-hand dominant 29 Right hemiparesis NIHSS Diabetic Status Score<9 in BNI pre-screening **Clinical Assessments** FMA-UE score Decreased sensation Impaired Passive Joint motion Pain during Passive movements Spasticity of the elbow or wrist joint MAS	**Task** Participants reached and pointed to a round disk-shaped (3.8 cm diameter) virtual target using a haptic stylus as quickly as possible. The stylus was held using the pen grip or the cylinder grip (if incapable of using the pen grip). The target appeared on the screen 32 times in a pseudo-random order. When the participant pointed at the target it disappeared and another appeared in a different location. the short distance between the two targets was 76 mm and the longest was 180mm. Each participant was assessed at 3 days, 10 days, 4 weeks, 3 months, 6 months, and 12 months after stroke.	There was a significant main effect of time (P<0.0001) for movement time, mean velocity and number of velocity peaks between day 3 and 12 months after stroke. Movement time and mean velocity showed improvements between day 3 and 10 (ES = 0.67 and 0.53, p=0.001), and between day 10 and week 4 (ES = 0.75 and 0.56, p<0.001). The number of velocity peaks improved between day 10 and week 4 (ES = 0.65, p<0.0001). Movement time (ES 0.51, p=0.001) and velocity peaks (ES 0.45, p=0.001) improved between three and six months The best performance on number of movements was reached at four weeks Funding source: The Swedish Research Council (VR 2011-2718), The Swedish Heart and Lung Foundation, The Swedish Brain Foundation, Promobilia, The Foundation of the Swedish National Stroke Association, Norrbacka-Eugenia Foundation, Swedish Society for Medical Research (S19-0074) and the	1. There may have been a learning effect from performing the pointing task so many times. 2. Outliers may have impacted the results. 3. The kinematics were endpoint movements (forward kinematics measures), which include compensatory movements. No trunk kinematic measure were included. 4. The study design allowed other participants to join in at a later time. 5. The statistical analysis was not able to adjust to missing data.	The kinematic variables of movement time, and mean velocity were adequate for quantifying upper limb recovery during the first year of stroke. The improvement was seen between three and six months, which is beyond the typically cited interval of only four months post-stroke. These later improvements suggest that improvements can still be able with increasing chronicity and more research is needed to investigate the issue.

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					ALF agreement (ALFGBG-879111, ALFGBG-775561, ALFGBG-826331).		

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Jayasinghe et al., 2020	Motor deficits in the Ipsilesional Arm of Severely Paretic Stroke Survivors Correlate with Functional Independence in Left, but Not Right Hemisphere Damage	The purpose was to determine the motor deficits in each arm of severely paretic chronic stroke survivors with unilateral damage.	20 Right-Handed chronic stroke subjects 10 Left Hemisphere Damage 10 Right Hemispheric Damage Type of Stroke 7 females 58 +/- 10 years of age **Clinical Assessments** Upper extremity portion of the Fugl-Meyer Assessment (UEFM) Jebsen Taylor Hand Function Test (JTHFT) Ipsilesional Arm Grip Strength, Barthel Index (BI) Type of Stroke	Participants were randomized to a robotic or usual care group. Both groups received 20 sessions, each lasting 45 minutes, five times per week by a trained physiotherapist. **Robot Group.** Participants controlled the end effector position of a planar robot with the contralesionally arm. Movements were made forward and backward from a central position to five targets randomly around a 20 cm circumference. The physiotherapist chose either an assist as needed or resistive mode depending on the participant's residual skill/improvement. **Usual Care Group.** Participants underwent usual arm-specific physiotherapy, which consisted of passive and active mobilization of the scapula, shoulder, elbow, and wrist. This was then	The hand path of both groups was generally more variable at the end of the movement compares to during the segment at peak velocity. The right hemisphere damage groups had a significantly greater ration of variable error compared to the left hemisphere damage groups [mixed model ANOVA, $F(1,18) = 8.7$, $p = 0.0086$, 95% CI [-1.16, -0.19] There was a significant main effect of target $F(2,36) = 4.3$, $p = 0.021$] There was a higher ration of the inner target compared to the vertical target [$p = 0.0075$, 95% CI [0.145, 0.89] There was a lower ratio for the outer target compared to the vertical target [$p = 0.045$, 95% CI [-0.75, 0.0097] There was no significant group by target interaction effect [$F(2, 36) = 0.19$, $p = 0.83$] Funding source: National Institutes of Health (R01HD059783 awarded to RS and CW).	1. Small sample size. 2. The Barthel 10-item questionnaire can produce ceiling effects. 3. Lack of a detailed cognitive battery.	This was the first study to examine if kinematic and clinical measures of motor performance and impairment in each arm of severe paretic stroke survivors are differentially correlated with functional independence in left and right hemisphere damage. It was found that both kinematic and clinical measures of ipsilesional motor performance were linearly related to functional independence in left but not right hemisphere damage individuals. It was also found that the measure

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				followed by task-oriented exercises that incorporated single or multi-joint movements, which aimed to improve arm functionality. The exercise was customized to each participant by the physical therapist. **Kinematic Reaching Task.** Participants were seated in a height-adjustable chair with their chins resting on a horizontal mirrored screen, so their hands were not in their field of view. Each participant completed a reaching task with their ipsilesional arm by moving a cursor from a starting circle (2 cm diameter) to a target circle (3.5 cm diameter) that appeared 17 cm away. The target appeared in one of three locations, vertical 90 degrees, 45 degrees clockwise, and 45 degrees counterclockwise.			of contralesional impairment was only linearly related with functional independence in the right hemisphere group.

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Lencioni et al., 2021	A randomized controlled trial on the effects induced by robot-assisted and usual-care rehabilitation on upper limb muscle synergies in post-stroke subjects	The aim was to evaluate the changes in the motor control mechanism of post-stroke subjects induced by robot-assisted planar training, with respect to usual care, during two non trained motor tasks encountered in activities of daily living.	32 Individuals with chronic stroke were randomly assigned to the robot-assisted group (RG) or the Usual Care group UCG. **RG**: Age: 68.0 (54.5-74.5) years Time Since Stroke: 7.76 (0.7-27.3) months Males 6, female 9 Paretic arm 7 R, 8 L Hemorrhagic 4, Ischemic 11 Chronicity: Chronic 9, Subacute 6 **Lesion Location**: brainstem (N = 2 RG, N = 4 UCG), frontal lobe (9 RG, 10 UCG), parietal lobe (7 RG, 11 UCG), temporal lobe (0 RG, 2 UCG), occipital lobe (0 RG, 1 UCG), internal capsule (2 RG, 1 UCG), thalamus (1 RG, 1 UCG) and basal ganglia (2 RG, 0 UCG)	Participants were randomized to a robot group (RG) or a usual care group (UCG). Both groups received training which consisted of 20 sessions, each 46-minute ling, five times per week. Participants completed two tasks, object placing and forearm pronation tasks using a virtual reality system For both tasks, each participant was seated in front of a screen grasping an electromagnetic sensor. The movement of the sensor was represented by the virtual object on the screen.	Object placing task The amount of elbow extension was significantly different between groups and was in favour of the robot group (F(1,29) = 4.76, *P* = 0.037). The robot group had a larger amount of elbow extension after treatment. The robot group had a larger improvement in trunk movement during performance F(1,29) = 6.30, *P* = 0.018) No difference between the groups regarding per to post change of the deviation of the angular curve of the shoulder. The pre- to post-change score of all movement smoothness parameters showed negative values demonstrating an improvement of movement execution, with no significant difference between groups. In addition, there was no difference between groups for the change score of any kinematic measures with regards to the ipsilesional arm. **Forearm pronation task.** With respect to the contralesional arm, the change score of the amount of wrist pronation was significantly different between groups and in	1. Small sample size. 2. Lack of follow-up assessments. 3. The extraction of muscle synergies is dependent on methodological aspects. 4. The sample was homogenous (16 out of 32 subjects had fronto parietal lesions)	Muscle synergies can be used to detect the reorganization of upper limb muscle coordination during rehabilitation. Robotic-based interventions can successfully improve abnormal synergy patterns to healthy controls. Tracking changes of abnormal synergies of both arms can provide new insight into the neural reorganization after stroke which may help determine optimal timing of the interventions.

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			Clinical Assessment FMA **UCG**: 59.0 (46.9-68.4) years old 5.8 (2.9-76.0) months since stroke Males 9, females 8 Paretic arm 6R, 11L Chronicity: Chronic 10, Subacute 7 Hemorrhagic 4, Ischemic 11		favour of the robot group (F(1,29) = 4.81, *P* = 0.036). The change score of the mean RMS of shoulder angle was significantly different between groups in favor of the usual care group (P<0.05). The change score of movement smoothness was significantly worse in the robot compared to the usual car group. In addition, there was no different between groups with respect to the ipsilesional arm. Funding source: Italian Ministry of Health (IRCCS Ricerca Corrente and RicercaFinalizzata: Grant No. GR-2011-02348942).		

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Liao et al., 2020	Timing-dependent effects of transcranial direct stimulation with mirror therapy on daily function and motor control in chronic stroke: a randomized controlled pilot study	The purpose was to examine the timing-dependent effects of tDCS with MT on daily function, upper extremity motor function and motor control in chronic stroke patients.	28 individuals with stroke **SEQ group**: N = 8, 60.18 +/- 4.84 years old 60.18 +/- 4.84 years old Male 5, Female 3 Lesion: 2 R, 6 L Onset time: 19.63 +/- 12.28 months Hemorrhagic 2, Ischemic 6 ***Clinical Assessments*** FMA, MMSE, MAS **CON group**: N = 12, 52.04 +/- 8.68 year old Male 8, Female 4 Lesion 5 R, 7 L Onset time: 21.92 +/- 11.83 months Hemorrhagic 5, Ischemic 7 ***Clinical Assessments*** FMA, MMSE, MAS **SHAM group:** 56.45 +/- 9.88 year old Male 8, Female 0 Onset time: 38.13 +/-	Participants were randomly allocated to one of three groups 1. Sequential combination of tDCS with Mirror Therapy (MT) (SEQ) 2. Concurrent combination of tDCS with MT (CON) 3. Sham tDCS with MT (SHAM) All participants received one of the three interventions for 90min/day, 5 days/week for 4 weeks. SEQ: received 20 min of anodal tDCS over the i[silesional primary motor cortex (IM1) followed by 20 min of MT with sham tDCS and 20 min of MT alone CON: received sham tDCS during the first 20 min followed by 20 min of MT concurrently with anodal tDCS on iM1 and 2- min of MT	**Within groups** There was a significant improvement in the index of movement time for the SEQ group from pre to post intervention (t = - 2.38, P = 0.04, d = 0.3). There was no difference in pre to post intervention kinematic measures for any of the other groups (t = - 2.18 to 1.63, P = 0.07 to 0.98, d < 0.001 to d = 1.01). **Between Groups** There was no difference in the kinematic measures between groups (F (2,22) = 0.15 to 0.9, P = 0.42 to 0.9, η2 = 0.01 to 0.08). Funding source: Chang Gung Memorial Hospital (BMRP553), Healthy Aging Research Center, Chang Gung University from the Featured Areas Research Center Program within the Framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan (EMRPD1I0451), National Health Research Institutes (NHRI-EX108-10604PI),and the Ministry of Science and Technology (MOST 105–2314-B-182-037-MY3, 108–2314-B-182-040-MY3) in Taiwan.	1. The findings may only be applicable to those with mild-to-moderate impairment at the chronic stage of stroke. 2. Lack of neurophysiological and neuroimaging outcome measures. 3. No follow-up assessments. 4. The training was individualized to each participant, with training and duration standardized in all three groups. Future studies should examine if the contents of functional task practice affect treatment effects. 5. Small sample size.	This study demonstrated the importance of timing tDCS when used with mirror therapy. Applying tDCS sequential and concurrently has differential effects. Greater improvements in hand movement efficiency were seen when applied prior to mirror therapy.

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			36.98 months Hemorrhagic 1, Ischemic 7 ***Clinical Assessments*** FMA, MMSE, MAS	concurrently with anodal tDCS oniM1 and 20 min of MT alone Sham tDCS in the SEQ and CON groups was used to keep the tDCS setting consistent between SEQ and CON conditions to blind participants from group allocation and prevent them from noticing any differences in tDCS settings SHAM: the train/stimulation procedures were the same as those for the SEQ and CON except that there was only sham tDCS			

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Mochizuki et al., 2019	Movement Kinematics and proprioception in post-stroke spasticity: assessment using the Kinamr robotic exoskeleton	The purpose of the study was to characterize features of kinematics and proprioception that is impaired in individuals with upper limb spasticity after stroke using the Kinarm robotic exoskeleton.	A total of 70 participants were divided into a spasticity and non spasticity group **No Spasticity**: N=35 Age: 62.8 (27-87) years Sex: 25 M, 10 F Handedness: 3 L, 31 R, 1 A Affected Side: 16 L, 19 R Time post-stroke: 6.28 (1-14.5) months Time to intake: 13.7 (4-34) days ***Clinical Assessments*** CMSA, MAS **Spasticity**: N=35 Age: 56.5 (18-78) years Sex: 24 M, 11 F Handedness: 3 L, 32 R, 0 A Affected Side: 20 L, 15 R Time post stroke: 14.73 (2-154) months Time to intake:19.7 (2-39) days	Individuals with stroke were organized into a Spasticity and No Spasticity group. Both groups performed a visually guided reaching, and arm position matching task. **Visually Guided Reaching Task** Participants reached from a central target to one of four or eight randomized peripheral targets as quickly and accurately as possible. Each target was presented five times for the four-target version and wight timed for the eight-target version of the reaching task. **Arm Position Matching Task** Vision of the limbs was blocked had the robot moved the affected limb to one of four or nine randomized positions in the workplace. The participant was asked to mirror match the position of the limb with the opposite are.	By observation, many participants in both groups displayed deficits in trajectory error, limitation in range of motion, movement during intended periods of fixation on a target, and limitations in target accuracy involving the affected arm. For the arm position matching task, the deficits were seen in trial-to-trial variability, spatial shift, and workspace area covered by the less affected arm. A direct comparison of parameter distributions identified significant differences in movement time (KS = 0.43, p-adj = 0.018), and maximum speed (KS = 0.40, p-adj = 0.045). Spearman correlations revealed a significant correlation between MAS and movement time (r = 0.33, p-adj = 0.038), maximum speed (r = -0.38, p-adj = 0.009) and the visually guided reaching task score (r = 0.34, p-adj = 0.028). Funding source: ORF-RE (SHS), the Federal Economic Development Agency for Southern Ontario – Technology Development Program (GM, SHS). Equipment and space have been funded withgrants from the Canada Foundation for Innovation,	1. EMG was not recorded 2. Proprioception was not measured. 3. Only one clinical scale was included. 4. Only part of the participants were assessed for elbow extensor spasticity. Extensor spasticity was not assessed in the No spasticity group.	Post-stroke individuals both with and without spasticity display deficits in movement kinematics and proprioception months to years after stroke. Those with spasticity have greater kinematic characterized by temporal features of movement and global measures. This study contributes to the body of literature pertaining to upper limb spasticity on motor control.

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			Clinical Assessments CMSA, MAS	Next the participant told the operator that the movement was completed, and the robot was prompted to move the limb to the other position in the workplace. The process was repeated until all four positions were attempted five times for the four-target version and six times for the nine-target version of the task. This task was only used for the less affected limb.	Ontario Innovation Trust,and the Ministry of Research and Innovation.		

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Montoya et al., 2022	Biomechanical Assessment of Post-Stroke Patients' Upper Limb before and after Rehabilitation Therapy Based on FES and VR	The purpose was to use motion capture systems to assess the kinematics of the upper limb in patients before and after rehabilitation with virtual reality (VR), exergaming, and functional electrical stimulation (FES) developed over two months.	**Individuals with stroke** N=13 Time Since Stroke: 2.08 +/- 1.28 years (4 wome, 9 men), 40-70, 56.61 +/- 14.16 years old 63-85 (74 +/- 10.48) kg, 1.60 - 1.75 (1.69-0.052) meters tall **Clinical Assessments** FMA	**Rehabilitation** A total of 16 therapy sessions were performed two days/per week, and 60 min/per session. Each session consisted of two activities. The first activity lasted 30 minutes and consisted of a multi-channel FES in the paretic upper limb, synchronized with an IMU sensor. The second activity consisted of exergaming with a VR headset and lasted 30 minutes. FES therapy was performed through active exercise assisted by a motorized upper limb cycle ergometer and a 6-channel functional electrical stimulator. **Max Forward Reach Test** Participants reached so that the extended arm made a 90-degree angles	**Max Forward Reach Test** There was a in the flexion, extension, adduction, and internal rotation of the shoulder after therapy ($P<0.05$). The increase was 16.25% for flexion, 27.65% extension, 17.45% abduction, and 63.50% internal rotation of the shoulder. For the range of motion of the paretic limb, there was a increase of 17.98% for flexion–extension and 18.12% for internal-external rotation of the shoulder ($P<0.05$). For execution time, there was no significant difference for the paretic limb after therapy. For angular velocities, there was a significant difference in the adduction–abduction (39.61%) and rotation (49.01%) ($P<0.05$). **Apley Scratching Test** For max joint angles, there was a significant increase in shoulder abduction 85.32% ($P<0.05$) For range of motion, there was a significant increase in shoulder adduction-abduction by 20.23% after therapy ($P<0.05$). For execution time, there was no significant difference after therapy ($P>0.05$).	1. Lack of conventional therapy groups to compare to.	The use of FES and virtual reality as complementary tools for post-stroke rehabilitation have the capacity to improve ROM, max angles, and angular velocity of the paretic arm when performing the Maximum Forward reach test and the Apley Sctartch test.

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				Apley Scratching Test ***Action One*** Subjects were instructed to touch the opposite shoulder with their hand. ***Action Two*** The subjects were instructed to raise their arm above their head and then bend the elbow and turn the arm out until it reached behind the head with the pal to play with the medial edge of the counter lateral scapula or reach the column by touching the vertebrae. ***Action Three*** The subject were instructed to hole the reach arm behind the back and bend their elbow and turn their arm in tiw their palm out to touch the lower hand of the contralateral scapula or reach the column, to touch the vertebrae as far as possible.	For angular joint velocity, there was a significant increase in shoulder adduction-abduction by 34.65% ($P<0.05$). Funding source: none.		

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Mullick et al., 2021	Obstacle Avoidance and Dual-Tasking During Reaching While Standing in Patients with Mild Chronic Stroke	The purpose was to identify whether and to what extent motor and cognitive demands in well-recovered people with stroke affect the ability to avoid obstacles when reaching with the more affected arm during standing	**Individuals with chronic stroke** N=13 Time since stroke: 19 +/- 8.3 months post stroke Age: 63.9 +/- 8.1 years 9 Right-handed **Clinical Assessments** Lesion Site/Type: FMA-UL FMA-LL CSI sWMFT MAL-QOM MAL-AOU CAHM Mini BEST MOCA TMT-A TMT-B **Healthy controls** N=11 Age: (63.7 +/- 10.9 years)	Participants performed a motor task, CT, and a dual task (motor and CT performed simultaneously) in one two-hour session. **Motor Task** Participants performed a reaching task in a 3D virtual environment. Individuals with stroke reached with their more affected arm, while the controls reached with their dominant or non-dominant depending on their corresponding stroke subject. Each participant stood with regular footwear in their preferred mediolateral stance and the foot position was marked and maintained throughout each session. The initial position included the treated arm alongside the body, the index fingertip rested on the lateral thigh support, the elbow in 30 degrees of flexion, and the forearm and hand in a neutral position between supination and	***Single Task Condition*** In both groups, successful trials were characterized by deviated endpoint trajectory paths (F1,20 = 29.69, P < .001, and d = 2.5). In both groups, qualitative observation indicate that endpoint trajectories were more variable in the stroke during the randomized blocks compared to the unobstructed blocks In unobstructed reaching, both groups used similar end point peak velocities, velocity profiles, trajectory lengths, and curvatures. Both groups had fewer movement units with a range of range: 1.09–1.11 peaks, with the number significantly greater in the individuals with stroke (F1,22 = 7.13, P = .014, and d = 1.14) The reaching peak velocities of both groups decreased when avoiding obstacles in the successful trials (F2,21 = 80.21, P <.001, and d = 3.83; stroke: by ~35.8%; controls: by ~39.4%) and unsuccessful trials (F2,21 = 3.64, P = .07, and d = .81; stroke: by ~28.0%; controls: by ~33.3%). Both groups took longer to reach peak endpoint velocity in obstructed compared to unobstructed trials	1. The results are limited to individuals with more severe or acute stroke. 2. Small sample size. 3. Lack of analysis of side, type of stroke, and hand dominance. 4. Failed to examine anticipatory postural adjustments and inter-joint coordination.	Individuals with a stroke that are considered to be recovered still have deficits compared to controls when performing a more complex motor task. Thus there is still a need to quantify the subtle motor, cognitive, and self-efficacy deficits to better tailor the rehabilitation approach for arm recovery.

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				pronation. The virtual environment included a grocery store aisle with shelves behind double sliding doors. Each participant was instructed to control the forearm and hand avatar to reach a 5cm diameter juice bottle on a shelf behind the door located arm length in the midsagittal plane aligned with the sternum. in 66% of the random trials, the reaching was obstructed by a transparent door. The door closed based on the time of the endpoint peak tangential velocity. **Cognitive Single Task** Participants performed an auditory-verbal working memory test which included sitting in a quiet room and listening to a sequence of 4 random numbers between 1000 and 9999. Each participant was required to repeat	(F2,21 = 16.75, P < .001, d = 1.75), and in successful compared to failed trials F1,22 = 31.32, P < .001, and d = 2.39). The endpoint trajectories were were longer (F2,21 = 9.75, P = .001, and d = 1.34) and more curved in the obstructed compared to unobstructed trials (F1.18,21 = 7.26, P =.009, and d = 1.15). The endpoint trajectories in the obstructed reaches were less smooth compared to those in the unobstructed trials and the successful trials had more movements units that unsuccessful trials in both groups (F2,21 = 37.74, P < .001, and d = 2.63). At the time of endpoint divergence, in the successfully avoided trials, the endpoint speed compared to the peak velocity of unobstructed trials was more reduced in the individuals with stroke (controls: 51.8 ± 14.4%; stroke: 39.6 ± 12.9%, t = 2.034, and p = .05). In addition, the individuals with stroke had more movement units that the controls in all conditions (F1,22 = 7.13, P = .01, and d = 1.14), and as varied by condition (F2,44 = 3.70, P = .03, and d = .79).		

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				the third number back. **Procedure** *Block One*: Unobstructed reaching *Block Two*: Randomly obstructed reaching *Block Three*: Unobstructed reaching while performing the cognitive task *Block 4*: randomly obstructed reaching while performing the cognitive task	For joint kinematics, there was no difference between groups or conditions except for shoulder adduction and trunk roll. The shoulder adduction was greater in the obstacle avoidance trials compared to the unobstructed trials in both groups ($F_{1.54,33.86}$ = 28.71, P < .001, and d = 1.59), and was greater in the successful compared to failed trials ($F_{1,22}$ = 12.91, P = .002, and d = 1.54). ***Dual Task Condition*** In both groups, success was characterized by earlier trajectory divergence ($F_{1,17}$ = 24.50, P < .001, and d = 2.21). Both groups maintained their unobstructed reaching peak velocity in the dual task condition using similar kinematic patterns for reaching and obstacle avoidance, where all subjects made slower movements when avoiding obstacles ($F_{2,18}$= 29.81, P < .001, and d = 2.44), and had longer time to peak arm velocity in obstructed compared to unobstructed trials ($F_{2,18}$ = 20.38, P < .001, and d = 2.02). The time to peak velocity was longer in the successful compared to failed trials ($F_{1,19}$ = 5.88, P = .025, and d = 1.08).		

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					The individuals with stroke took longer to reach peak velocity in successful trials (F1,19 = 8.47, P = .009, and d = 1.30) and had significantly lower endpoint velocity at the time of trajectory divergence (DP, controls: 58.9 ± 17.6%; stroke: 35.9 ± 13.2%; t = 2.96, P = .01). In both groups the endpoint trajectories were longer (F2,18 = 10.91, P = .001, and d = 1.48) and more curved in obstructed compared to unobstructed trials (F2,18 = 6.14, P = .008, and d = 1.11). The unobstructed trajectories were smoother than those in obstructed trials (F1,19 = 42.32, P < .001, and d = 2.78) and the successful trials had more movement units than unsuccessful trials (F1,19 = 7.6, P = .013, and d = 1.18). For joint kinematics, there was not difference between conditions or groups except for shoulder adduction which was greater in the obstructed compared to unobstructed trials for both groups (F1,19 = 54.44, P < .001, and d = 3.22) and was greater in the successful compared to failed trials (F1,19 = 32.31, P < .001, and d = 2.48).		

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					Funding source: Heart and Stroke Foundation of Canada. Melanie C. Baniña and Yosuke Tomita were funded by the Richard and Edith Strauss Doctoral Fellowship (McGill University).		

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Nibras et al., 2021	Dissociating Sensorimotor Recovery and Compensation During Exoskeleton Training Following Stroke	The purpose was to dissociate true recovery from compensations by analyzing both end-effector and joint kinematic data from a sub-group of participants who received 4 weeks of training with the Armeospring, with two sessions per day	**Stroke** N = 53 Time since stroke 56 ± 21 days (acute) Sex: 30 males, 19 females, 4 genders not available Age 59.3 ± 13.9 years old **Clinical Assessments** baseline UEFM 24.7 ± 9.1 final UEFM 37.2 ± 15.1 **Healthy non disabled controls** N=11 Gender: 4 females, Age: 23.5 ± 2.0 years old	**REM-AVC:** Individuals with stroke received training on their more affected arm via the AremoSpring twice /day, 5 days/week for 4 weeks, 30 minutes/session for a total of 40 sessions. Each session consisted of a variety of rehabilitative video games (therapist selected), and the ArmeoSpring vertical reaching test ("Ladybug" test). The ladybug test was performed before and after the video games session for a total of 80 tests. **Normative reaching performance:** the young control participants performed 10 video game training sessions for five days. The ladybug test was administered before and after each session for a total of 20 tests. **Lady Bug Test** The ladybug test is a two-dimensional	End-Effector Smoothness. The mean number of velocity peaks per trial improved for all participants post stroke, with a average decrease of 4.90 ± 2.41peaks, assessed by the model fit two-ample unequal variances t-test [$t(86) = 9.2$, $p < 0.0001$]. The slow component had a median time constant of 222 test [$t(86) = 9.2$, $p < 0.0001$], and the fast component had a median time constant of 5.7 test (IQR = 2.0, 11). **Nonlinear Mixed Effects Model for Joint Correlations** The models for z-transformed SE-forearm and SH-elbow correlations showed good fits to each participants joint. The RMSE was 0.13 (IQR = 0.12, 0.16) for the SE-Forearm correlation and 0.17 (IQR = 0.14, 0.19) for the SH-Elbow correlation. At the beginning of training there was atypical SH-elbow coupling in 38 participants, and atypical SE-forearm coupling, in all participants except for one. At the end of training there was atypical SH-elbow coupling in 44 participants, and atypical SE-Forearm coupling in 47 participants. **Sparse Principal Component Analysis of the Control Participants.** The SE-Forearm correlation was defined as the vertical synergy and	1. No motion capture system was used, only the exoskeleton for upper limb kinematic assessment. The exoskeleton counteracted the forces of gravity. 2. The difficulty level of the ladybug test was not constant 3. The cluster analysis would have benefitted from using motion capture of the whole arm 4. A young non-disabled control group was used instead of an age-matched group.	The participants with stroke recovered in task space, but only one-third relearned to move in joint space. Individuals obtain new compensatory movements by performing repetitive movements through robotic training without receiving joint level corrections. Individual differences in exploration in joint space may cause differences in learning compensatory movement patterns. This study could be used to inform exoskeleton

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				pointing task in the frontal plane. Participants are instructed to perform a fast and accurate pointing movement to catch the ladybug target that appears on the screen by moving a cursor. The position of the cursor is controlled by the Armed Spring end-effector in the vertical plane. The sequence of targets is fixed for each test. The participant has a total of 10 seconds to catch the ladybug before it disappears from the screen and a new ladybug appears at a different location. The test has four difficulty levels. If the participant is able to catch more than 90% of the ladybugs in two consecutive sessions, then the difficulty level is increased (via the therapist). Similarly, if the participant is unable to catch 90% of the ladybugs in two consecutive sessions,	the SH-elbow correlation was defined as the horizontal synergy. **Recoverers and Compensatory Clustering Analysis** A total of two clusters were identified, recoverers, and compensators. 19 participants were in the recoveree cluster as they showed improvements in both vertical and horizontal synergies. A total of 34 participants were classified as compensators and subcategorized into three subclusters. The first subcluster contained seven participants whose SH-elbow velocity correlation moved closer to the control mean during training, while the SE-forearm velocity correlation deviated further from the control mean, indicating improved horizontal synergy but worse vertical synergy. The second sub-cluster consisted of 18 participants whose SE-forearm velocity correlation moved closer to the control mean during training, and the SH-elbow velocity correlation deviated further from the control mean, indicating an improved vertical synergy and worse horizontal synergy. The third subcluster consisted of nine participants with both correlations deviated further from the healthy means while training indicating		robots on where and how to add torques during therapy to impact compensatory patterns.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
				the difficulty level is decreased.	worse horizontal and vertical synergies. Scatter plots of joint velocities for each synergy: The shoulder-elbow correlation were closer to 0. The SE forearm correlation was close to 1, indicating the two joints were strongly coupled. Funding source: National Institute of Neurological Disorders and Stroke of the National Institutes of Health under Award Number R56 NS100528. The REMAVC study was funded by the French ministry of health (STIC2010, number 08-13).		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Park et al, 2020	A comparison of the effects and usability of two exoskeletal robots with and without robotic actuation of upper extremity rehabilitation among patients with stroke: a single-blinded randomized controlled pilot study	The purpose was to explore whether there is a difference in clinical and kinematic outcomes between active-assistive and passive robots during robot-assisted upper extremity rehabilitation of patients with stroke showing a Medical Research Council (MRC) scale score of 3 or 4 for the paretic proximal upper limb.	A total of 19 individuals with stroke were randomly assigned to an Active-assistive robotic intervention group (ACT) or a Passive robotic intervention group (PSV) **ACT** N=10 Age: 54.9 +/- 10.7 years Time since stroke: 11.8 +/- 11 months stroke type; 5 Infarct, 5 haemorrhage Hemiplegic side: 6 R Sex: 8 Male **Clinical Assessments** FMA-prox, FMA-UE **PSV** n=9 Age: 53.9 +/- 16.7 years Time since stroke: 9.6 +/- 4.5 months stroke type; 4 Infarct, 5 hemorrhage Hemiplegic side: 5 R Sex: 8 Male	Participants were randomly assigned to an active-assistive robotic intervention or a passive robotic intervention. All participants completed 20 30-minute sessions, five days a week for four weeks. These sessions were conducted by an experienced research physical therapist in a research intervention room. **Active-assistive robotic intervention group** The intervention was administered using an Armeo Power (3D exoskeletal active-assistive robot used for upper extremity rehabilitation. The actuators actively assisted the affected arm movement to an established extent, on top of arm weight support offsetting the device weight. **Passive robotic intervention group**	There was a group times interaction with no significant effect on spectral arch length and the mean speed across the target button, but time had a significant effect on the spectral arch length of central target, (F=9.589, p=0.001), and the mean speed to the contralateral target (F=14.681, $p < 0.001$), and the mean speed of the ipsilateral target (F=7.323, p=0.003) The passive robotic intervention groups showed better improvement compared to the active assistive robotic intervention group with regard to the spectral arch length to the ipsilateral target from 2 to 8 weeks ($P<0.05$), and from 4 to 8 weeks ($P<0.05$), and with regard to the spectral arch length to the central target from 4 to 8 weeks ($P<0.05$). In addition, the active assistive robotic group showed better progression of the mean speed to the central target compared to the passive robotic intervention group from 0 to 4 weeks ($P<0.05$). Funding source: Grand (NRCTR-IN17002, NRCTR-IN18001) of the Translational Research Center for Rehabilitation Robots, Korea National	1. The passive robotic group exoskeleton also supported the limb with gravity. 2. The participants in the study may have not been representative of all patients with stroke. Individuals were included if they showed an MRC score of 3 r 4 for the proximal upper limb strength. In addition, the participants were only subacute and chronic patients (> 3 months since stroke). 3. Small sample size. 4. The length of the intervention was not sufficient to induce motor learning.	Active assistive robots do not offer a significantly higher advantage compared to passive robots in regard to improving impairment and activity. The active assistive robots might have a rather lower effect on participation, even though there were differences in kinematics. Lastly, passive robots can provide sufficient robotic rehabilitation for patients with stroke showing motor control of the upper extremities.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
			Clinical Assessments FMA-prox, FMA-UE	The intervention was administered using the Armeo Spring robot exoskeletal passive robot (3D exoskeletal passive robot) used for upper extremity rehabilitation. This exoskeleton provided gravity compensation that offset the upper extremity using a spring.	Rehabilitation Center, Ministry of Health & Welfare, Korea.		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Raj et al., 2020	Effects of Stroke on Joint Control during Reach-to-Grasp: A Preliminary Study	The purpose was to examine how interactive torque control is changed by stroke by computing IT, MT, and other torques with the use of inverse dynamics equations and compare these torques between individuals with stroke and healthy individuals.	**Stroke** N= 9 Time since stroke: 29.14 months Age: 62 (31-94) Years Weight: 84.7 (55.6-1113.2) Kg Sex: 6 Male, 3 Female Handedness: 6 R, 3, L FMUE Score: 57 (34-63) Lesion Location: 5 Cotrical Primary Motor Cortex, 4 Sub Cortical Dominant Hand: 6 R Affected Side: 4 R **Clinical Assessments** Modified Ashworth Scale (MAS) **Controls** N= (50-75) Age: 64 (50-75) Weight: 78.7 (57.3-103.4) Sex :5 Male, 5 Female Handedness: 10 R, 0 L	Participants sat on a backless bench with armrests. The initial position consisted of both arms in the parasagittal plane with the hands placed on the table. The lower arms rested on the armrests that were level with the table. The table and armrests were adjusted to allow participants to orient the upper arms vertically, keep the forearms on the horizontal armrests at a 90-degree elbow angle and the hands align horizontally with the forearms. The height of the bench was set, and the hip and knees were flexed at 90 degrees. Participants reached for a soda can placed on the table in the parasagittal plane at 55% of the subject's arm length from the xiphoid process on the chest. Arm length was the distance between the acromion process of	Both groups performed the reach to grasp movement by moving the arm primarily in the parasagittal plane with substantial shoulder flexion and elbow extension and small wrist ulnar deviation. The movement time was longer, and the peak hand velocity was lower in the individuals with stroke compared to the healthy controls. The hand covered a similar distance during movement in both groups. The mean amplitudes of the shoulder, elbow, and wrist angles calculated as the absolute differences of the initial and final joint angles were smaller in individuals with stroke, and the group difference was only significantly different at the shoulder (P<0.05). The shorter joint amplitudes suggest that the individuals with stroke utilized more trunk during the movement compared to the healthy controls. The linear displacement of the shoulder joint was significantly greater in the individuals with stroke compared with healthy controls, although it was relatively small in both groups. Lastly, the small mean lateral displacement of the elbow joint across the movement confirmed	1. Small sample size. 2. A convenience sample was used. The healthy controls were only age-matched, not gender or handedness. 3. Analysis did not take into account the inaccuracy of gravitational torque control.	Movements after stroke are characterized by an overcompensation of interactive torque. This deficiency can be the result of spasticity or a control compensation strategy. The latter has the advantage in that it accounts for multiple features of hemiparetic arm movements. Literature on this topic is lacking, thus emphasizing the need for additional research.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
			Clinical Assessments FMUE Score N/A Lesion Location: N/A	the shoulder joint to the tip of the middle finger when the arm was stretched. The can was positioned close enough to discourage movement of the upper body toward the target (limit trunk movement) Participants were instructed to reach toward the soda can at a comfortable pace, grasp the can, to eye level, put the can down, and return the hand to the starting position. Participants began the trial on the "go" command and performed 10 trials of the task.	that arm motion was performed approximately in the parasagittal plane in both groups. Funding source: University Honors College and the Department of Occupational Therapy at the University of Pittsburgh.		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Teremetz et al., 2022	Improving upper-limb and trunk kinematics by interactive gaming in individuals with chronic stroke: A single-blinded RCT	The primary aim was to evaluate the effect of supervised upper-limb therapy using a gaming system, the Nintendo Wii, on upper-limb recovery and compensation (elbow extension and forward trunk motion) and compare it with time-matched conventional upper-limb therapy. The secondary aim was to compare the effect of Wii and conventional therapy on the different dimensions of upper-limb function: (1) clinical tests of upper limb motor impairment and activity, pain and perceived effort and (2) kinematic parameters relating to hand transport during reach (velocity,	40 Individuals with stroke were allocated to Wii Therapy and a Conventional therapy group **Wii Therapy** N=21 Age: 55.8 (49.7-61.9) years Sex: 6 F Hemisphere: 13 R, 6 L Months Since Onset: 71.1 (43.5-98.7) **Clinical Assessments** FMA Barthel Index: AST Bedside Index: Bell's Neglect: Sensation: Spactiticy : Strength ARAT MAL Box and Block Test SIS **Conventional Therapy** N=22 Age: 56.2 (50.5-61.9) years Sex: 10 F Hemisphere: 15 R, 7	This was a single-blind, randomized controlled, single-center controlled trial. Participants with stroke completed both Wii therapy and conventional therapy. All participants completed 12, one-hour sessions, three times a week for four weeks. **Wii Therapy:** Participants performed three different games, tennis, golf, and boxing while sitting on a stool. These games were chosen as they all involved arm movements in different planes. **Conventional Therapy:** Participants performed a series of hand exercises individually selected by a physiotherapist.	The healthy controls had greater elbow extension and less forward movement of the trunk compared to those with stroke. There was no significant different between groups for the change in elbow extension (P>0.05), but elbow extension increased from pre to post intervention in both groups with no group by time interaction (P>0.05). There was no significant between group difference in change in trunk position (P>0.05). However, the trunk position was reduced from pre to post intervention in both groups with no group time interaction (P>0.05). There were no significant between group differences in peak hand velocity, curve index, number of peaks, or movement duration. Funding source: PHRIP grant from APHP.	1. The training dose was low. 2. Lack of follow-up assessment. 3. Higher than expected inter-individual variation in elbow extension.	Wii and conventional therapy increased elbow extension and reduced forward trunk motion. However, the differences were not significant and may be the result of a low training dose.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
		smoothness and curvature).	L Months Since Onset: 62.2 (37.7-86.7) **Clinical Assessments** Barthel Index: AST Bedside Index: Bell's Neglect: Sensation: Spactiticy : **Healthy controls** N=14 Age: 52 years (45.3 - 58.7) Sex: 43% females				

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Thrane et al,. 2020	Upper limb kinematics during the first year after stroke: the stroke arm longitudinal study at the University of Gothenburg (SALGOT)	The aim was to quantify longitudinal development in movement performance and quality during the first year after stroke using kinematic analysis of a drinking task, and to identify which metrics are comparable with healthy controls.	**Stroke**: N: 56 Age: 64 +/- 13.4 years Sex: 21 F Lesion Location: 30 R, 22 L, 3 Bilateral, 1 Cerebellar **Clinical Assessments** NIHSS FMA-UE **Healthy Controls**: N: 50 Sex: 27 females, 33 males Age: 63.4 +/- 12/6 years	Participants were enrolled in the Stroke Arm Longitudinal Study at the University of Gothenburg (SALGOT) and assessed at 3 days, 10 days, 4 weeks, 3 months, 6 months, and 12 months after stroke. Each testing session consisted of a standardized drinking task. Each participant was seated their back against a chair (adjusted so that there was a 90-degree angle between the knee and the hip joint), and a hard plastic glass (7cm in diameter and 9.5 cm in height) was placed on the table in the midline of their body (30 cm from the edge). The upper arm was positioned in an adducted position close to the body with a 90-degree angle in the elbow joint. The hand rested in a pronated position on the table with the wrist line close to the edge of the table.	The movement time of those with stroke significantly differed from the healthy controls at 3 and 10 days after stroke (P<0.05). At all other time points, the movement time of the individuals with stroke was comparable to healthy controls. The individuals with stroke had more movement units, and a lower peak hand velocity up to four weeks after stroke. In addition, the number of movement units differed between individuals with stroke and the healthy controls at 12 months. Peak elbow angular velocity, arm abduction during drinking and trunk displacement differed between healthy controls and individuals with stoke at every time point during the first year. The best performance of time to peak velocity was obtained at three months after stroke, while, movement time, movement units, peak hand velocity, time to peak velocity, peak elbow angular velocity, arm abduction, ad trunk displacement reached their best performance at six months after stroke. The movement time, number of movement units, peak elbow angular velocity, peak hand velocity, and trunk displacement showed the largest impairment three days after stroke. It remained significantly different from the six-month	1. The results are only generalizable to stroke patients that already have the ability to perform a full drinking task. 2. Participants were allowed to enter the study within 10 days post-stroke	The number of movement units, peak angular elbow velocity, trunk displacement and arm abduction were the most sensitive variables to identify movement deficits within the first-year post-stroke. Four kinematic variables (number of movement units, peak elbow angular velocity, and arm abduction) were best suited for individual analysis while the other variables were more appropriate for comparison to healthy controls. Most kinematic variables peaked at six

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				The drinking task consisted of 5 phases: reaching and grasping the glass, lifting the glass from the table to the mouth to take a drink, placing the glass back down behind a marked line on the table, and returning the arm to its initial position.	reference value during the first four weeks. The relative time to peak velocity was significantly different from six months to three days post-stroke. There was no significant change detected in the arm abduction. A slight non-significant decrease occurred in most kinematic variables between six and 12 months after stroke. Funding source: Swedish Research Council (VR 2012-70X-22122-01-3VR2017–00946) and the Health & Medical Care Committee of the Regional Executive Board, Region Västra Götaland, Swedish Heart and Lung Foundation, Swedish Brain Foundation, Norrbacka Eugenia Foundation, Foundation of the Swedish National Stroke Association, Hjalmar Svensson's Research Foundation, and the Promobilia Foundation, and grants from the Swedish state under the agreement between the Swedish government and the county councils, the ALF agreement (ALFGBG-718711, ALFGBG-775561 and ALFGBG-72060).		months and then slightly declined. The most recommended variables for the assessment of stroke recovery are peak angular velocity, arm abduction, and trunk displacement.

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Tomita et al., 2020	Stability of reaching during standing in stoke	The purpose was to investigate the effect of stroke on the organization of multiple degrees of freedom to maintain both endpoint and COM trajectories during reaching from standing compared to healthy controls.	**Stroke** N: 19 Sex: 6 F, 13 M Handed 19 right-handed Age: 62 +/- 8 years Time since stroke: 47 +/- 34.5 months Lesion Type: 8 Right, 3 Hem **Clinical Assessments** FMA CSI S-WMFT FRT **Healthy Controls** N: 11 Handed: 11 right-handed Age: 65 +/- 10 years	**Experimental Protocol** Each participant reached for a remembered object placed beyond the arm's reach with the eyes closed while leaning forward while flexing the hips. Each participant stood with their feet shoulder-width apart while wearing a safety harness. The target was placed at a 130% distance from the midsagittal at the level of the anterior superior iliac spine (ASIS) Subjects reached the remembered target with the eyes closed setting on. No metronome was used. Each participant completed 30 trials with 20-30s of rest	The synergy index in stroke subjects was greater than one for both endpoint and center of mass at the beginning of the movement. The synergy index at the end of the movement was maximally decreased when the endpoint was at its peak velocity and returned to baseline at the end of the movement. The peak endpoint velocity did not differ between subjects with stroke and healthy subjects. The synergy index at the end of movement decreased from baseline more in the stroke compared with healthy subjects during the movement (69.6% decrease in stroke vs. 51.7% in healthy, *P* =0.003). Changes in the synergy index of the center of mass in the individuals with stroke were similar to the healthy subjects throughout (8% decrease in stroke vs. 15% in healthy, *P*= 0.87) and at the end of reaching. The end range of the synergy index was significantly greater in the stroke compared with healthy subjects [95% CI: (0.52 0.09), *P* 0.009]. The end of the synergy index was significantly lower in the stroke subjects at 20–40% of the reaching movement compared with the healthy	1. Only a 2D kinematic model was used to compute the UCM. 2. Only community-dwelling individuals with stroke with independent ambulation were recruited. This prevents the findings to be applicable to other populations. 3. The location of the lesion and the integrity of the corticospinal tract were not addressed	The stability of the endpoint position was significantly reduced in individuals with stroke compared to healthy controls. In addition, there were no group differences in the COM position. The reduction in upper limb kinematic redundancy and prioritization of postural stability may hinder the stability of endpoint trajectories while reaching post-stroke.

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
					individuals [95% CI: (0.06 0.50), *P* 0.033]. Neither the range nor minimal values of the synergy index for the center of mass differed between groups. A significantly greater proportion of individuals with stroke had a minimal synergy index value of less than zero compared with the healthy group (6/19 in stroke vs. 0/11 in healthy, *P* 0.002). The proportion of subjects with a minimal synergy index of the center of mass that was less than zero was not different between groups (1/19 in stroke vs 0/11 in healthy). The max cross correlation coefficient between the synergy index at the end and endpoint velocity of -0.89 occurred at a lag of 6.0% of movement time. The max cross-correlation coefficient between the synergy index of the center of mass and the center of mass velocity was -0.44 at a time lag of -4.0% movement time. Both the maximal cross correlation coefficient and the time lag did not differ between groups The inter trial variability of the time-to-peak velocity was significantly greater in the stroke subjects (median QR: 6.4 2.2% movement time)		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
					compared with healthy controls (median QR: 4.0-3.5% movement time, (*P*= 0.042). The inter trial variability of the time to peak velocity was correlated with max VORT for endpoint position (*rs* = 0.647, *P*= 0.003), and not peak endpoint velocity (*rs* = 0.328, *P* = 0.170). In healthy subjects, the intertrial variability of time-to-peak velocity was not correlated with max VORT or peak endpoint velocity (P>0.05). Funding source: Grant-in-Aid for Young Scientists awarded by the Japan Society for the Promotion of Science. This study was supported by Canada Research Chairs (M.F.L).		

First Author and Publication Year	Title	Aim/Purpose	Participants	Methods/Design	Results	Limitations	Conclusions
Tomita et al., 2021	Association between self-perceived activity performance and upper limb functioning in subacute stroke	The primary objective was to examine the relationship among changes in UL motor impairment, compensation, and self-perception of UL activity performance in subacute stroke. The secondary objective was to examine the relationship among UL motor impairment, compensation, and self-perception of UL activity performance in each measurement period.	**Stroke** N: 24 Handed: 24 Right-handed Age: 65.4 +/- 10.8 years Subacute: <45 days since stroke Lesion Side: 16 R, 7 L Lesion Type: 10 Infarct, 13 Hemorrhage Time Since Stroke 33.9 +/- 5.2 days **Clinical Assessments** UL FMA Sensation RPSS STEF GDS COPM Performance COPM Satisfaction	Baseline measurements were taken within 45 days of stroke onset (M1) and the second measurement (m2) was taken 4 weeks after M1. Each participant received inpatient rehabilitation for 3 hours/day for 7 days/week. All participants was asked to reach, grasp, and lift the object from the table to the height of the sternum at a comfortable speed at M1 and at a matched speed to M1 at M2. Each participant sat in an upright position in a chair without leaning against the back support. The height of the chair was adjusted for each participant. The object was a cylinder-shaped target made of cork (dia: 6cm, height: 10cm, weight: 50g) and placed at a distance	Only the slope of the elbow-shoulder inter joint coordination significantly improved at M2 compared with M1 (M1: -0.74 +/- 0.25 vs. M2: -0.83 +/- 0.06, *p* = 0.016). Funding source: Takasaki University of Health and Welfare.	1. This study was a prospective observational study, and subjects were under different rehabilitation programs. 2. The reach-to-grasp task used to measure kinematic outcomes were not identified as meaningful by the participants. 3. The reach velocity was matched between M1 and M2, which may have limited changes observed in the kinematic measures. 4. The results are only generalizable to stroke patients with mild-to-moderate motor impairment. 5. The statistical analysis used parametric tests	Self-perceived performance is an important measure that should be integrated into future clinical research.

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				from the acromion to the ulnar head in the midsagittal lane (i,e, 75%-80% of the arms' length. The height of the table was adjusted to that the hand was placed on the table with a standardized arm configuration with 0 degrees of shoulder flexion/abduction and 90 degrees of elbow flexion.		for ordinal scales. Nonparametric analysis may have been better suited.	

Note. As each study performed a comprehensive statistical analysis which produced an innumerous amount of data, results related to kinematic measures of coordination and control in the spatial and temporal domain were recorded.

Table 5.

A summary table of the data extracted from each article with respect to each of the three purposes.

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
Carpinella et al., 2020	Control & Coordination	Inverse Kinematics	No Mention	Reaching	"Place and move Task" (Test Simulated the functional movement of transporting an object onto a shelf)	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L) **Task** Reaching **Environmental** Fixed trunk Seated eyes open Virtual Environment	Coordination and Control based measures	**Quantitative** Shoulder/Elbow Coordination Index (unitless)	**Joint Space (Spatial Domain)** ROM: Shoulder Flexion (deg) ROM: Elbow Extension (deg)
Cho and Song, 2019	Control	Forward Kinematics	No Mention	Reaching	Reaching towards a target in 3D space in 6 directions	**Individual** Sex Time post-stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location	Control based measures	N/A	**End Effector Space (Temporal Domain)** Mean Velocity during reaching

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
						Hand Dominance (R&L) Affected Limb (R&L) **Task** Reaching **Environmental** Trunk Fixation Eyes open Seated Virtual Environment			
Feingold-Polak et al., 2021	Control	Forward and Inverse Kinematics	No Mention	Reach to grasp	Participants were instructed to reach their hand to a self-selected speed towards a cup located on a table, then lift the cup and place it on top of a 5 cm high block positioned on the table **3 Heights** Low: 50cm above ground Medium: 75cm above ground High 86-104cm above ground	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L) **Task** Reach to grasp	Control based measures	N/A	**Joint Space (Spatial Domain)** *Maximum Joint Angles*: Elbow, Scapular Elevation, and rotation **Joint Space (Temporal Domain)** *Displacement Profiles*. Elbow angle, trunk displacement, scapular rotation, scapular elevation Movement Duration **End Effector Space (Temporal)** Mean Velocity Peak Velocity Time to peak velocity *Normalized Jerk*

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					2 Weights Empty Cup: 273g Filled with water: 443g	**Environmental** Sitting NO trunk support Real environment Eyes Open			(Trajectory Smoothness) *Index of curvature (IC) (Trajectory Straightness)*: the ratio between the length of the trajectory and the length of a straight line between the initial and final hand locations
Gomes et al., 2021	Control	Forward Kinematics	No Mention	Reach to grasp	2 tasks (T1, and T2) **T1** reach-pointing Participants were instructed to reach and touch 3 targets arranged in an "L" shape. **T2** Reach-hold-fit Participants were instructed to carry a glass of water between two distinct targets, 15cm apart	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location Hand Dominance (R&L) Affected Limb Functional: Attentional Focus **Task** Reach to grasp **Environmental** Sitting NO trunk support Real environment Eyes Open Back supported	Control based measures	N/A	**End Effector Space (Temporal Domain)** Movement Time Mean Velocity Peak Velocity Number of velocity peaks

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
Hasanbarani et al., 2021	Control & Coordination	Forward & Inverse Kinematics	Equilibrium Point Hypothesis	Reaching in an egocentric and exocentric frame of reference	**Task 1** Egocentric Reaching A 30cm rod was attached to e contralateral arm from the mid-forearm and extending beyond the forearm. The arm was held in a 90-degree elbow flexion in the horizontal plane in front of the body. The participants reached down the rod to the final target. **Task 2** Exocentric Reaching Two targets were placed 30 cm apart in the same direction and horizontal orientation as that of task 1 but in the external space. participants were asked to reach the targets without vision.	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb **Task** Reaching: egocentric and exocentic **Environmental** Sitting No Vision Armless chair Trunk constrained and unconstrained (via electromagnet)	Coordination and Control based measures	**Qualitative** *Angle-Angle diagrams:* Shoulder-flexion/elbow extension Shoulder-horizontal abduction/elbow-extension	**Joint Space (Spatial Domain)** *Joint Ranges of Motion:* Elbow flexion/extension angle Shoulder flexion/extension angle Shoulder-horizontal abduction/adduction angle **End Effector Space (Spatial Domain)** Movement Time Mean Velocity **End Effector Space (Temporal Domain)** Trajectory Length Index of Curvature

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					Both Tasks 1 and 2 were performed with and without a blocked trunk (via an electromagnet)				
Hejazi-Shirmard et al., 2020	Control	Forward Kinematics	No Mention	Reach to grasp	Participants sat in a straight-backed chair in front of a table with their trunks strapped to the back of the chair to minimize compensatory movements of the trunk. Participants reached a target under three conditions 1: Single task 2: Easy Dual Task 3: Difficult dual task **Dual-Task** Backward digit task. 50% difficulty for the easy dual-task condition.	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L) Functional: Anxiety **Task** Reach to grasp **Environmental** Sitting Trunk constrained Real Environment	Control Based Measures	N/A	**End Effector Space (Temporal Domain)** *Reach and Grasp Component:* Movement Time Peak Velocity *Transport and Reach Component:* Peak Velocity (PV) Percentage of movement time in which peak velocity occurred (PPV)

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Hussain et al., 2021	Control	Forward Kinematics	No mention	Pointing	Using a haptic stylus, participants were instructed to reach and point at round disc-shaped targets in virtual space.	**Individual** Sex Time post stroke (subacute) Type of stroke (Ischemic & Hemorrhagic) Lesion Location Hand Dominance (R&L) Affected Limb (R&L) **Task** Pointing **Environmental** Sitting: Height adjustable chair Vision: 3D shutter glasses Virtual Environment Pointing No mention of trunk constraint	Control based measures	N/A	**End Effector Space (Temporal Domain)** Movement time Mean Velocity Peak velocity Number of velocity peaks
Jayasinghe et al., 2020	Control	Forward Kinematics	No Mention	Reaching	Participants were seated in a height-adjustable chair with their chin resting on a horizontal mirrored screen, so their hands were not in their	**Individual** Sex Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R)	Control based measures	N/A	**End Effector Space (Spatial Domain)** *Hand Movement Performance Variables* *Constant Final Position Error:* The final position error is the distance between the target center and cursor position at the

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					field of view. Each participant completed a reaching task with their ipsilesional arm by moving a cursor from a starting circle (2 cm diameter) to a target circle (3.5 cm diameter) that appeared 17 cm away. The target appeared in one of three locations, vertical 90 degrees, 45 degrees clockwise, and 45 degrees counterclockwise.	Affected Limb **Task** Reaching **Environmental** Sitting Eyes open, looking at a monitor Virtual environment Reaching movement Trunk constrained (chin rest)			end of the trial. Higher final position errors signified poor control of postural stabilization mechanisms
Lencioni et al., 2021	Control & Coordination	Inverse Kinematics	Linked to the Uncontrolled Manifold Hypothesis.	Object Placing Forearm Pronation	**Object Placing Task** Each participant kept both hands in the middle of the thighs and was asked to move the virtual ball until it was placed inside the yellow cub (positioned at a forward vertical distance of 36 and	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L)	Control based measures		**Joint Space (Spatial Domain)** *Object Placing Task* *Range of Motion*: elbow extension Mean RMS of the angle of the trunk and shoulder joints *Forearm pronation Task* *Range of Motion*: wrist pronation Mean RMS of the angle

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					26 cm, respectively from the initial position) *Forearm pronation Task* Each participant kept the elbow angle at 90 degrees, the wrist fully supinated, and the shoulder laterally rotated so that the forearm was approximately 45 degrees relative to the thigh. The participant was then asked to move and rotate a virtual donut until it was placed inside a yellow cub (positioned at a medial and vertical distance of 52 cm and 12 cm, respectively, from the initial hand position)	**Task** Object Placing Forearm Pronation **Environmental** Sitting Eyes Open Virtual Environment Trunk unconstrained reaching			of the trunk and shoulder joints **Object placing and forearm pronation Task** Movement smoothness: Number of velocity peaks

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
Liao et al., 2020	Control	Forward kinematics	No mention	Reaching	**Unilateral Reaching Task** Participants were seated in front of a table with the seat height adjusted to 100% of the lower leg length. Each placed their hand in the starting position, so the elbow was in a 90-degree flexed position. Each participant was then instructed to reach and press a doorbell that was placed along the midsagittal plane (a distance of 1.25 timed the arm length).	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb **Task** Reaching **Environmental** Sitting Eyes open Reaching Real environment Unconstrained Trunk	Control Based Measures	N/A	**Joint Space (Temporal Domain)** Reaction time of the trunk Movement time of the trunk **End Effector Space (Spatial Domain)** *Normalized Total Displacement of the Hand:* Represents movement straightness **End Effector Space (Temporal Domain)** Movement time of the hand Reaction time of the hand
Mochizuki et al., 2019	Control	Forward Kinematics	No Mention	Reaching	**Visually Guided Reaching Task** Participants reached from a central target to one of four or eight randomized peripheral targets as quickly and accurately as possible. Each	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location Hand Dominance (R&L) Affected Limb (R&L)	Control based measures	N/A	**End Effector Space (Spatial Domain)** Path Length Ratio (PLR) **End Effector Space (Temporal Domain)** Number of Velocity Peaks: Speed Maxima Count (SMC) Movement Time (MT)

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					target was presented five times for the four-target version and eight times for the eight-target version of the reaching task.	**Task** Reaching Robotic exoskeleton **Environmental** Sitting Eyes Open Real environment Trunk Unconstrained			Maximum speed (MS)
Montoya et al., 2022	Control	Inverse Kinematics	No Mention	Maximum Forward Reach Test Apley Stretch Test	**Maximum Forward Reach Test** The participant reached a horizontal distance from the plane passing through the occipital, the scapula, and the glutes to the vertical axis that occurs in the hand with the fingers extended forward. The distance between the fingers' tip and the extended made a 90-degree angle. **Apley Scratching Test** 1. The participant	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location Hand Dominance (R&L) Affected Limb **Task** Max forward reach Apley Scratch **Environmental** *Max Forward Reach Test* Sitting Eyes open Real environment reaching Unconstrained trunk *Apley Scratch Test* Standing Eyes open	Control based measures	N/A	**Joint Space (Spatial Domain)** *Maximum Joint angles*: Shoulder, elbow, wrist, and forearm *Range of Motion*: Shoulder Elbow, wrist and forearm **Joint Space (Temporal Domain)** *Angular Velocity*: Shoulder, elbow, wrist, and forearm Execution Time

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					touched the opposite shoulder with their hand. 2. The participant was instructed to raise their arm above their head and then bend the elbow and turn the arm out until it reached behind the head with the palm to play with the medial edge of the counter lateral scapula or reach the column by touching the vertebrae 3. The participant was instructed to reach an arm behind the back, bend the elbow, and turn the arm in with the palm out to touch the lower angle of the contralateral scapula or reach the column, that is to the vertebrae as far as possible.	Real environment reaching Unconstrained trunk			

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
Mullick et al., 2021	Control	Inverse & Forward Kinematics	Linked to the Uncontrolled Manifold Hypothesis.	Reaching	Participants performed a reaching task in a 3D virtual environment using a head-mounted display. Each participant reached with their more affected arm, while the control used their dominant or non-dominant arm that corresponded to that of their paired stroke subject. Each participant wore regular footwear and stood with their feet in a preferred mediolateral stance width. The initial position consisted of the tested arm alongside the body, with the index fingertip resting on the lateral thigh support, the elbow in 30 degrees of flexion and the forearm and hand in a	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L) **Task** Reaching Constant speed **Environmental** Standing Eyes Open (VR Google) Environment: Virtual Reaching Unconstrained trunk Time constraint	Control based measures	N/A	**Joint Space (Spatial)** *Max Angles* *Wrist* flexion/extension and abduction/adduction *Elbow* flexion/extension *Shoulder* flexion/extension and horizontal abduction/adduction **End Effector Space (Spatial Domain)** Trajectory Length Index of curvature **End Effector Space (Temporal Domain)** Endpoint Peak velocity Time to peak velocity Number of velocity peaks Velocity Profiles

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					neutral position somewhere between supination and pronation. The 3D virtual environment consisted of a grocery store aisle with shelves behind a double sliding door. Each participant was instructed to control the forearm and hand the avatar to reach a 5 cm diameter juice bottle located on a shelve behind the door located at 90% arm length distance in the midsagittal plane aligned with the sternum. in 66% of the random trials, the reaching path was obstructed by a transparent door that slid across the scene in front of the shelf from the left to right				

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					side. When completely closed the door obstructed 30% of the bottle. The door closure time was so that corrective movement could only be made after the end of the initial arm movement				
Nibras et al., 2021	Control & Coordination	Inverse and Forward Kinematics	Linked to the Uncontrolled Manifold Hypothesis.	Reaching	The ladybug test is a 2D pointing task in the frontal plane using a ArmeoSrping exoskeleton. Participants were instructed to perform fast and accurate pointing movements to catch ladybug targets that appeared sequentially on the screen by moving a cursor to the target's locations. The user had to catch the ladybug	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location Hand Dominance (R&L) Affected Limb **Task** Reaching Time Constraint (<10s) Robotic exoskeleton **Environmental** Sitting Eyes Open Virtual Environment No mention of trunk constraint	Control and coordination-based measures	**Quantitative** *Correlations*: *Vertical Synergy*: Shoulder elevation angle and the Forearm *Horizontal Synergy*: Shoulder horizontal angle and the elbow	**Joint Space (Temporal Domain)** *Joint angular velocity Profiles:* Shoulder, elbow **End Effector Space (Temporal Domain)** Number of velocity Peaks

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					under a time constraint (<10s)				
Park et al, 2020	Control	Forward Kinematics	No mention	Reaching	Each participant sat in a chair in front of a table with the height adjusted so that the elbow was flexed at a 90-degree angle in the sagittal plane. Participants practiced reaching three times for familiarization with the setup. Buttons were positioned according to the participant's affected arm length. Three buttons were set on a vertical wooden plate in front of the participant at the height of thier xiphoid process and at a distance of 75% of the arm length and positioned in three different transverse plane	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location Hand Dominance (R&L) Affected Limb **Task** Reaching Robotic exoskeleton **Environmental** Sitting: height-adjusted table Eyes open Real environment trunk unconstrained	Control Based Measures	N/A	**End Effector Space (Spatial Domain)** Spectral Arch Length Mean Speed **End Effector Space (Temporal Domain)** Reaching Trajectories

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					positions (ipsilateral, central, and contralateral). The participant were instructed to reach from the base button to one of the three different target buttons and bring the upper limb back to the base button after each touch. Movements were repeated 9 times,3 for each button, with a one min rest between movements.				
Raj et al., 2020	Control & Coordination	Inverse Dynamics	Leading Joint	Reach To Grasp	Participants sat on a backless bench with armrests. The initial position consisted of both arms in the parasagittal plane with the hands placed on the table. The lower arms rested on the armrests that were level with the table. The table and	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location (R&L) Hand Dominance (R&L) Affected Limb (R&L) **Task** Reach to grasp	Control and torque	**Joint Space (Spatial Domain)** Movement Time Lateral displacement **Joint Space (Temporal Domain)** *Joint angles profiles*: of the hand Shoulder and elbow *Angular Velocity profiles*: of the hand, shoulder, and elbow **Torque Profiles:** Net torque Interaction Torque	

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					armrests were adjusted to allow participants to orient the upper arms vertically, keep the forearms on the horizontal armrests at a 90-degree elbow angle and the hands align horizontally with the forearms. The height of the bench was set, and the hip and knees were flexed at 90 degrees. Participants reached for a soda can placed on the table in the parasagittal plane at 55% of the subject's arm length from the xiphoid process on the chest. Arm length was the distance between the acromion process of the shoulder joint to the tip of the middle finger	**Environmental** Backless Chair Eyes open Real environment Unconstrained trunk		Muscular Torque Gravitational Torque	

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					when the arm was stretched. The can was positioned close enough to discourage movement of the upper body toward the target (limit trunk movement) Participants were instructed to reach towards the soda can at a comfortable pace, grasp the can, lift the can to eye level, put the can down, and return the hand to the starting position. Each participant began the trial on the "go" command and performed 10 trials of the task				
Teremetz et al., 2022	Control	Forward Kinematics	No Mention	Reaching	Participants sat at a table with their back against the back rest, hand in fist position on a cross marked on a table, upper arm	**Individual** Sex Time post stroke (Chronic) Type of stroke Lesion Location (R&L)	Control based measures	N/A	**Joint Space (Spatial Domain)** Elbow Angle Trunk Position **End Effector Space (Spatial Domain)**

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					vertical, elbow at 90 degrees, shoulder not abducted and forearm in a neutral pro-supination position. The target was a circle of red tape on a thin post positioned in 3 locations (short, long, and high range). Participants were instructed to touch the target with the knuckle of the hemiparetic hand at their self-selected speed and then return the hand to the starting position.	Hand Dominance (R&L) Affected Limb (R&L) **Task** Reaching **Environmental** Sitting: Back Against the backrest Unconstrained trunk Eyes open Real environment Reaching			Index of Curvature **End Effector Space (Temporal Domain)** Peak Hand velocity Number of velocity peaks Movement duration
Thrane et al,. 2020	Control	Forward Kinematics	No Mention	Drinking Task	Participants sat with their backs against the back of the chair without constraint. A hard plastic	**Individual** Sex Time post stroke (subacute) Type of stroke Lesion Location (R&L) Hand Dominance	Control based measures	N/A	**Joint Space (Spatial Domain)** Maximum Arm abduction angle (Max shoulder angle) **Joint Space (Temporal Domain)**

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					glass, 7cm in diameter, 9.5 cm in height was placed on a table in the body midline, 30cm from the edge of the table. The chair and table height were adjusted so the participant had a 90-degree angle in the knee and hip joints. The upper arm was adducted close to the body and the forearm horizontal with 90 degrees in the elbow joint. The hand was pronated and rested on the table with the wrist line close to the table's edge. This position was chosen as it allowed the participant to reach with our forward trunk displacement.	(R&L) Affected Limb **Task** Drinking **Environmental** Sitting Unconstrained Trunk Eyes Open Real Environment			Peak Elbow Angular Velocity **End Effector Space (Temporal Domain)** Movement Time Movement Units Peak Hand Velocity Time to Peak Velocity

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					The task consisted of 5 phases 1: Reaching and grasping the glass 2: Lifting the glass from the table and bringing it to the mouth 3: Taking one sip of water 4: Placing the glass back down behind a line marked on the table 5: Returning the arm to its initial position				
Tomita et al., 2020	Coordination	Forward & Inverse Kinematics	Uncontrolled Manifold	Reach to Grasp	Participants Stood with their feet shoulder-width apart and wore a ceiling-mounted harness to prevent falling. The target was placed at 130% arm length in the midsagittal plane at the anterior superior iliac spine level. Arm length was the	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location Hand Dominance (R&L) Affected Limb **Task** Reach to grasp	Coordination and Control based measures	**Quantitative** *Synergy Index* (SI): The proportion of VUCM and VORT Cross-correlation coefficient between SI and endpoint Velocity	**End Effector Space (Spatial Domain)** Variability of Endpoint position **End Effector Space (Temporal Domain)** Mean Endpoint velocity

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					distance from the acromion to the index finger. The endpoint position was the upper edge of the ipsilateral greater trochanter, with the shoulder extending to 15 degrees and the elbow flexing at 30 degrees. Participants reached a remembered target with their eyes closed after hearing the GO signal beep. Participants performed the reaching movement as fast and accurately as possible. No metronome was used. The movement was repeated 30 times with 20-30 seconds of rest between trials.	**Environmental** Standing Eyes Closed Harness to prevent falling Real environment			

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
Tomita et al., 2021	Control & Coordination	Inverse and Forward Kinematics	No Mention	Reach, grasp and lift	Each participant sat upright in a chair without leaning against the backrest. The Seat height was adjusted for each participant. A cylinder-shaped target made of cork (6cm diam, 10cm height, 50g weight) was placed at the distance from the acromion to the ulnar head in the midsagittal plane. The table height was adjusted such that the hand was on the table with a standardized arm configuration with 0 degrees shoulder flexion/abduction and 90 degrees elbow flexion. Participants were instructed to reach, grasp, and lift the object from the table to the height of the sternum at a	**Individual** Sex Time post stroke (Chronic) Type of stroke (Ischemic & Hemorrhagic) Lesion Location (R&L) Hand Dominance (R&L) Affected Limb Functional: self-perceived ability to perform meaningful activities **Task** Reach grap and lift Reaching Velocity was held constant. **Environmental** Sitting Eyes Open Unconstrained Back Rest	Coordination and Control based measures	**Qualitative** Angle-angle diagram of the elbow and shoulder **Quantitative** The slope of elbow-shoulder angle-angle diagram *Correlation* between COM displacement and FMA, RPSS, STEDD, and GDS (Clinical measures) *Correlation* between the COM displacement and the peak velocity, index of curvature, number of movement units, trunk displacement, trunk movement time, and final elbow angle.	**Joint Space (Spatial Domain)** Final elbow flexion angle **End Effector Space (Spatial Domain)** Index of Curvature **End Effector Space (Temporal Domain)** Peak Velocity Number of velocity peaks

Article	Conceptual Scope	Conceptual Framework	Motor Control Theory	Task	Task Description	Constraints	Methodological Aspects	Coordination Measures	Control Measures
					comfortable speed. The reach velocity was then matched between M1 and M2 to minimize the influence of reach velocity on kinematic features.				