MEASUREMENT OF BIMANUAL COORDINATION IN REHABILITATION FOR POST-STROKE INDIVIDUALS: A SYSTEMATIC REVIEW

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Abstract

A stroke can result in a decreased ability to coordinate the upper limbs, which leads to difficulty in performing the activities of daily living (ADLs). As a result, upper-extremity rehabilitation has been frequently implemented to improve impaired bimanual coordination. Many studies have examined the nature of bimanual coordination during two-handed discrete tasks such as reaching and grasping in many different populations. Over the past few decades, much research has been devoted to examining the nature of bimanual coordination. Foundational research examining bimanual coordination (i.e., inter-limb coordination) and control, has focused on how different constraints (e.g., task, individual) affect the degree and stability of spatial and temporal coupling between the end effectors or joints. This was done in the context of different philosophical paradigms, in the field of motor control and coordination, such as coordinative structures (Kugler et al., 1980), and synergies (Haken, 1983). However, in rehabilitation studies, the issue of bimanual coordination, along with the theoretical relevance of the emerging inferences have not been systematically addressed. Therefore, the first purpose of this project was to systematically review the methodological approaches used in the literature that examine changes in coordination and control in those who have had a stroke following upper-limb rehabilitation that aimed to improve bimanual function. Another objective was to classify these approaches in regards to their theoretical and conceptual basis. From this, suggestions were made as to how to potentially enhance the existing approaches to measuring inter-limb coordination during bimanual rehabilitation.

To address the first purpose, a literature search was conducted using CINAHL, PubMed, Web of Science, and PsycINFO to identify relevant studies. Two authors independently screened the full-text literature. The first author (Y.L.) extracted data, narratively analyzed the qualified studies, and undertook the assessment. The search identified 789 potentially relevant studies, with 20 articles fulfilling the established criteria. Overall, a variety of clinical scales were identified within many of the studies and only a small amount of literature implemented kinematic analyses both before and after interventions. Research implementing product measures for rehabilitation revealed that individuals following stroke exhibited improved temporal and spatial control where the reaching actions appeared to be faster, smoother, and less segmented. However, the investigation of control in joint space remained absent before and after rehabilitation. In regards to coordination, only one study investigated the emerging movement patterns at the quantitative level of measurement. Specifically, the lack of analysis of coordination between more distal anatomical structures like the wrist represents an important limitation of the existing work. Another notable issue for the generalizability of the data is the lack of measures that investigate stability and flexibility. Thus, the inferences about interlimb synergetic relations at a conceptual level remains unclear. In terms of the implementation of specific theories or models of motor control and coordination, none of the studies make any explicit inferences about the emerging spatiotemporal relations in the context of related theories.

Collectively, the reviewed literature showed that kinematic analysis and motor control theories or frameworks of bimanual coordination have not been systematically integrated into research examining arm rehabilitation. Data-driven research represents the primary motivation in this clinical field. This review makes suggestions to conduct more theory-driven research based on theoretical frameworks to describe the emerging actions from rehabilitation and to predict changes in movement organization that are induced by task constraints.

Keywords: stroke, upper-extremity, rehabilitation, systematic review, kinematics, bimanual coordination, control.

Acknowledgement

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List of Key Definitions

Constraints: A characteristic or factor of the individual, environment, or task that encourages some movements while discouraging others.

Continuous movement: A type of rhythmic movement that has no recognizable beginning and ending such as tapping with the index fingers of both hands for a certain period of time.

Control: The absolute magnitude of the limb or limb segment movement as it relates to measures of amplitude, velocity, acceleration, or force of the movement when performing an action.

Control parameter: A variable that when manipulated may induce changes in movement patterns.

Coordinative structures: A unit of different elements working together to produce movements that arise naturally in a well-developed motor system. In the human motor system, there is not an absolute difference between the definition of synergies and coordinative structures as they both represent functional movement units under a certain task requirement.

Coordination: The degree and stability of spatial and temporal relationships between two or more components in a system, leading to a functional movement pattern. Coordination can emerge between muscles, between joints (intra-limb coordination) or between limbs (inter-limb coordination).

Degree of freedom: The number of ways a system can vary, or the number of planes in which a joint can move.

Discrete movement: A type of movement that has a recognizable beginning and ending, such as reaching for a coffee cup with the right arm.

Dynamics: A status of a system that keeps changing instead of staying static. In the aspect of physics, dynamics is the equations of motion of collective variables in coordinated patterns.

Interlimb coordination: Temporal or spatial relationships between two limbs, such as two arms, or two legs. It can be contralateral interlimb coordination (i.e., two arms or two legs), or ipsilateral interlimb coordination (one leg and one arm on the same side of the body).

Intralimb coordination: Temporal or spatial relationships between joints within a limb, such as a relationship between the elbow and shoulder joint in an arm.

Intrinsic dynamics: The preferred coordination pattern that the performer tends to do spontaneously. It reflects tendencies towards certain patterns, under particular constraints.

Order parameter: A variable that identifies the qualitative changes in coordination patterns such as a phase transition. It can be seen as a dependent variable, which describes the changes in coordination. The features of order parameters are specific to biological functions and tasks.

Redundancy: In the area of motor control, redundancy refers to the fact that one task could be achieved in many different ways. This construct is often referred to as “motor equivalence”.

Self-organization: The spontaneous formation of spatial and temporal relationships in systems composed of few or many elements, in the face of different constraints.

Synergies: Stable, functional groups of structural elements (e.g., neurons, muscles, joints) that are temporarily organized to act as a single coherent unit in the domains of time and space. It is also considered the solution to the degrees of freedom problem.

Synergetics: Meaning “work together” in Greek. It is a research field that focuses on the spontaneous (i.e., self-organized) occurrence of changes in a dynamic system irrespective of the nature of the individual parts of that system.

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Introduction

Stroke

A stroke results from a lack of proper blood supply to the brain which is also known as a "brain attack" or a cerebrovascular accident (America Stroke Association [ASA], 2022). There are different causes of strokes. An ischemic stroke occurs when one or more vessel supplying blood to the brain get obstructed by clots. Ischemic stroke happens in 87% of all stroke cases (ASA, 2022). Once an ischemic stroke occurs, the brain cannot absorb enough nutrients and oxygen, due to a decrease in blood supply, which leads to the death of brain cells. A hemorrhagic stroke occurs when a weakened blood vessel ruptures (ASA, 2022). Finally, a transient ischemic attack is a brief episode of an ischemic stroke with clinical symptoms lasting less than one hour and without evidence of acute infarction (UK, National Guideline Centre, 2019). A transient ischemic attack is also called a mini-stroke because it is a warning sign that a more potent incident may occur in the near future (ASA, 2022).

Across the world, stroke has become the leading cause of death and the main cause of long-term adult disability and dysfunction (Feigin et al., 2017). More than 405,000 of these survivors are living with long-term disability that requires assistance with the performance of daily activities (Krueger et al., 2015). In Canada, more than 62,000 stroke cases are reported annually, and 741,800 people aged 20 and older are living with the consequences of a stroke (Canadian Institute for Health Information, 2021). According to the Ontario Stroke Network, a stroke occurs every 30 minutes in the province; additionally, there are approximately 25,500 new stroke cases each year (NWOstroke, 2021).

The prevalence of stroke is related to factors including age and sex. The incidence of stroke increases with age, with the number doubling for each decade after 55 years of age

(Boehme et al., 2017). Between the years 1990 and 2013 there have been increased cases of ischemic and hemorrhage strokes in individuals aged 20 to 64 years of age (Feigin et al., 2017). Specifically, the incidence of hemorrhagic stroke increases significantly after 45 years of age (Boehme et al., 2017). Sex is another factor that affects incidence of strokes, where females have an overall higher lifetime risk of stroke than males because of longer life expectancy (Seshadri et al., 2006). In the ages ranging from 55 to 75 years, 1 in 5 (20% to 21%) females had a stroke compared to 1 in 6 (14% to 17%) males in 4,897 participants of the Farmingham Study (Seshadri et al., 2006). However, the incidence rate of strokes between males and females in the older populations becomes similar with aging regardless of the higher incidence rate in women in early ages (Seshadri et al., 2006).

The genetics or family history of stroke is related to a higher risk of ischemic stroke (Seshadri et al., 2010). Heritability plays a larger role in strokes that occur in people who are younger than age 60, compared to older people who may also experience a stroke due to lifestyle choices (Schulz et al., 2004). In addition, the economic status of an individual or society can affect the prevalence of stroke. Developing countries have a higher proportion of stroke cases, death following a stroke or stroke related complications, and a higher level of long-term disability and handicap, compared to the high-income and middle-income countries (Cox et al., 2006).

Symptoms of stroke are heterogeneous in type and severity. The extent of the injury and the life-long effects after a stroke depend on the affected areas of the brain and the severity of the stroke. A stroke that affects large brain areas typically results in both motor and cognitive impairments, in which motor impairments are the most prevalent and widely identified consequences of a stroke (Virani et al., 2021).

Motor Impairments after Stroke

Motor deficits that are induced by stroke include partial loss of voluntary control over muscles on the contralateral side of the body from where the stroke occurred in the brain (Cauraugh & Kang, 2021). This condition is often referred to as hemiparesis, which is the most prevalent symptom of stroke, occurring in approximately 80-90% of all stroke survivors (Virani et al., 2021). Hemiparesis in the affected limb results in reduced muscle strength, slower movement speed, and overall difficulties in coordinating and controlling multi-joint actions (Roby-Brami et al., 2003). Although, sensorimotor deficits are usually more evident on the contralateral side to the brain damage, in the meantime, the ipsilateral side of the body could also be affected (Pandian & Arya, 2013). In addition, stroke can also result in the occurrence of poorly controlled reflexes causing muscle contractions and spasms (i.e., spasticity), which in turn exacerbates coordination during tasks such as reaching and grasping (Roby-Brami et al., 2003).

Stroke survivors often struggle to incorporate the more affected upper limb in activities of daily living (ADLs). ADLs include tasks that people undertake every day to maintain a necessary quality of care including feeding, dressing, and mobilizing (Legg et al., 2007). Due to the asymmetry of deficits after unilateral stroke, bimanual activities are also compromised. As a result, the stroke contributes to the inability to coordinate the two arms as well as decreases the quality of performance in carrying out ADLs and other domestic activities (Mercier et al., 2001).

The common functional deficits in bimanual coordination that occur in the upper limbs as a result of stroke, are learned non-use, learned bad-use, and forgetting (Raghavan, 2015). The "non-use" means that individuals may not use their affected arm after a stroke at all. This limited "use" is due to weakness, paralysis, and sensory loss, and with time it may become habitual (Raghavan, 2015). Eventually over time, the impaired limb may not be incorporated into functional movements, which is then referred to as learned “non-use”. Due to spasticity, abnormal motor synergies, and resulting pain, individuals with stroke are often unable to carry out typical movements. Instead, the individuals are constrained to implement compensatory strategies to complete the task (McCrea et al. 2005). Thus, the learned “bad use” occurs due to the lack of accurate feedback and correction of the abnormal behavior in compensatory movements (Raghavan, 2015). Lastly, “forgetting” takes place when participants are unable to perform the task that they were guided to learn in previous training sessions (Krakauer, 2006). As a result, the learning processes associated with the acquirement of previously learned movements are longer in individuals with stroke compared to healthy individuals (Kitago et al. 2013).

Although hemiparesis and other functional deficits are usually only evident in one side of the body, ADLs largely rely on the cooperation between two arms, which requires bimanual coordination. After stroke, hemiparesis could deteriorate the capability of coordinating two arms in bimanual actions. Bimanual coordination describes how two or more limbs generate and maintain a temporal and spatial relationship to each other to achieve a functional goal (Sparrow, 1992). However, traditional post-stroke rehabilitation programs usually focus on improving and evaluating the motor function of the paretic arm only (Waller & Whitall, 2008). From the practical perspective and conceptual standpoint, the re-gaining of bimanual coordination involves the relearning of old patterns or coordinating two arms in new adaptive actions. This process is of particular importance to physical rehabilitation, given that performance on ADLs is better predicted by the degree to which stroke patients use both arms to complete tasks, rather than by the function of either arm alone (Haaland et al., 2012).

Rehabilitation Approaches to Bimanual Coordination

Stroke rehabilitation is defined as a dynamic, progressive, goal-oriented process aimed at enabling a person with impairment to reach their optimal physical level (Dawson, et al., 2013). Less than 15% of survivors of stroke regained full recovery of the upper limb, despite intensive rehabilitation (Hendricks et al., 2002). Thus, due to deficits in motor coordination and control observed after stroke, the need to recover the capability of coordinating the arms together has been emphasized (Kantak et al., 2016). Considering the prevalence of stroke and its deteriorative effect to bimanual coordination, rehabilitation approaches that facilitate bimanual coordination, have been widely applied to clinical settings. Three representative examples, bilateral arm training, robot-assisted training, as well as constraint-induced training, will be discussed in this section as common rehabilitative approaches to bimanual coordination.

Bilateral Arm Training

Bilateral arm training is a type of arm rehabilitation that requires simultaneous use of both the upper limbs under various task conditions. Participants are trained to perform a "default mode" of bimanual coupling with either symmetric (e.g., arms moving together in the same direction) or asymmetric (e.g., one arm pushes away while the other is pulling towards) patterns to stimulate informational exchanges between both hemispheres, and then to improve the motor function of the paretic arm (Mudie & Matyas, 1996). From this perspective, practicing bimanual movements is expected to evoke the bilateral neural networks, which is presumably absent in unilateral arm movement (Waller & Whitwall, 2008). With time, this type of training is expected to restore neural networks that are involved in the organization of bimanual coordination.

The underlying rationale of bilateral arm training is that, by practicing bimanual movements, the patients can either exploit the persistent or restore the weakened or lost coupling between two arms (Sleimen-Malkoun et al., 2010). Bilateral arm training has been implemented in different circumstances in clinical settings. For example, in bilateral arm training with rhythmic auditory cueing, bilateral movements are practiced with music or a metronome that guides the arms by specifying the required relative phasing between arms. This approach, from the motor control perspective, corresponds to the use of behavioral information that can stabilize the intrinsic coordination pattern (Zanone & Kelso, 1992). In some cases, bilateral arm training is also coupled with active electromyography-triggered neuromuscular stimulation of the more affected arm where the intact arm assists the impaired arm during bimanual tasks (Cauraugh, 2004).

Robot-Assisted Training

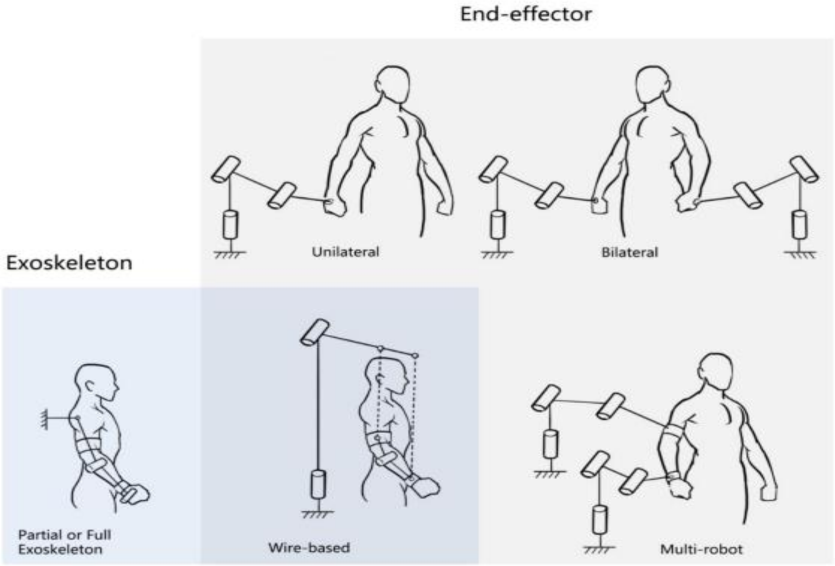
Another rehabilitation approach that has been frequently implemented involves the use of robots. The logic is that the introduction of robotic devices can automate and mechanize the training sessions. Compared to traditional therapy that is directed and measured by therapists, rehabilitation robots can provide long-term intensive and accurate rehabilitation continuously, which avoids fatigue of the therapists (Sheng et al., 2016).

In general, robots used in rehabilitation programs can be classified as end-effector and exoskeleton robots (Figure 1). With either type, the arm that is affected by stroke can be guided by the less impaired arm to perform synchronous exercises (Sheng et al., 2016). A basic mode of all types of robots is the passive mode, in which the impaired arm is passively driven to be moved by the robot. As evident in the figure below, an end-effector robot is attached to a patient by a single distal point on the hand so that it can apply mechanical forces to the attached arm segment (Veerbeek et al., 2017). This type of robot is simple and can be easily adjusted to different sizes of patient’s arm because only the most distal part of the limb is guided.

Another type of robot, the exoskeleton is an external structural device. An exoskeleton is aligned with the anatomical axes of the human body (Veerbeek et al., 2017). An exoskeleton robot encloses the arm into the bionic structure to control movement. Exoskeleton devices can fully control the posture of the arm and determine the torques that should be applied to each joint separately, which could help train a certain muscle more precisely (Sheng et al., 2016). Exoskeleton robots allow researchers to accurately determine the kinematic configurations of joints, while end-effector robots exert forces only in the most distal part of the arm.

Figure 1

Two types of robots in robot-assisted training



Note: Two main categories of upper-limb rehabilitation robots (Sheng et al., 2016).

Robot-assisted training has another advantage as the robotic device can measure quantitative data efficiently by assessing motor performance at frequent time intervals (Sheng et al., 2016). For example, two popular movement velocity measures used in robotic-assisted training are the mean and maximum end-effector velocity (Balasubramanian et al., 2012). This methodological approach can provide information about the temporal nature of motor control and the underlying tendencies in the process of “trajectory formation”. As for the recovery of bimanual coordination, given the advantage of robot-assisted training, which provides outcome measurements, Veerbeek et al., (2017) suggest that robot-assisted training should be integrated into other interventions such as bilateral arm training in order to optimize the training results.

Constraint-Induced Movement Training (CIMT)

Constraint-induced movement training (CIMT) is a specialized task-oriented training approach. CIMT requires functional training of the affected arm with gradually increased difficulty levels and the immobilization of the non-affected arm (Hatem et al., 2016). The original form of constraint-induced movement training consisted of three components: 1) immobilization of the non-paretic arm during 90% of the waking hours, 2) repetitive task-oriented training for 6 hours per day, and 3) practice of skills achieved in the clinical setting to be translated to the patient’s daily life (Hatem et al., 2016). Modified CIMT is applied with less intensity ranging from 0.5 to 6 hours per day (Kwakkel et al., 2015).

The conceptual basis of CIMT is based on the idea that learned non-use of the affected arm is common after traditional rehabilitation. The pain, slowness, and difficult attempts to use the impaired arm, let the patients tend to rely on the unaffected arm (Hatem et al., 2016). Thus, the forced use of the paretic arm is emphasized in CIMT. The neural mechanism underlying CIMT is to induce motor learning (i.e., practice specificity) and neuroplasticity with intensive blocks of training (Hatem et al., 2016). It has been suggested that motor recovery after CIMT may occur due to the exploitation of the existing less active motor pathways (Schaechter, 2004). The activation of the undamaged hemisphere contra-lateral to the lesion(s) can counteract adverse brain functions and enhance neuroplastic modifications relating to motor recovery (Hatem et al., 2016). As a result, CIMT can induce the restoration of motor function from neuroplasticity. The implicit assumption of CIMT, for improving bimanual coordination function, is that as soon as the basic aspects of unimanual control are relearned, they can be more easily integrated into more complex bimanual movement patterns. Additionally, some research also used kinematic analysis to investigate the effectiveness of CIMT, such as reaction time and movement time, as well as movement units (Wu et al., 2007; Shi et al., 2011).

Although effective, these rehabilitation approaches often do not tap into different aspects of bimanual coordination which are intimately related to the measurement of temporal and spatial relations between and within the affected and unaffected limb. In the context of bimanual coordination, the measures of spatial and temporal aspects of the movements will be discussed in the literature review.

Literature Review

In order to record the motor improvements induced by rehabilitation, a variety of measures are conducted in clinical studies to compare the difference in performance between pre and post treatment (e.g., clinical scales). Accurate measures of motor performance are of vital importance to infer the effectiveness of different rehabilitation programs designed to regain bimanual coordination. In clinical research, as related to rehabilitation of bimanual actions in stroke, different clinical scales are used to capture the outcomes of rehabilitation programs (e.g., FMA-UL, ARAT, & MAL). In addition, improvements in motor behaviour can also be examined by kinematics, in which two different broad categories of measures are incorporated, namely movement product and movement process measures (Derrick & Thomas, 2004).

Clinical Scales

Some clinical scales widely used in evaluating motor performance of the upper extremity are the Fugl-Meyer Assessment-Upper Limb (FMA-UL) (Fugl-Meyer et al., 1975), the Action Research Arm Test (ARAT) (Lyle, 1981), and the Motor Activity Log (MAL) (Wolf et al., 2006). The FMA-UL consists of 33 items that examine the motor function of proximal and distal parts of the arm. The score of each item ranges from 0 to 2, so the total score ranges from 0 (no function) to 66 (normal function) (Fugl-Meyer et al, 1975). The FMA-UL is the most frequently used scale to evaluate arm motor function (Raghavan, 2015). The other clinical scale frequently used in this kind of research is the Action Research Arm Test (ARAT) designed to measure arm disability by evaluating 4 basic movements: primary grasp, grip, pinch, and gross movements of flexion and extension at the elbow and shoulder (Lyle, 1981). Task performance is rated on a 4-point scale, ranging from 0 (no movement) to 3 (movement performed normally) (Lyle, 1981). The ARAT motor score was also strongly correlated with FMA-UL (r=0.93, Platz et al., 2005).

Another measure used in this kind of research is MAL. This tool allows the user to infer the quality of movement and the amount of use, which is evaluated based on two five-point scales. The MAL provides inferences about how well and how much the paretic arm is used spontaneously to accomplish ADLs outside of the laboratory (Wolf et al., 2006). The MAL has been proved to have good consistency, reliability, and validity in stroke patients (Wu et al., 2011). Scales introduced above can evaluate a wide range of motor performance, ranging from motor deficits (e.g., flexion or extension of elbows) to motor functional capacities (e.g., grasping a cup) based on the examiner's observation.

Kinematic Analysis: Movement Product Measures

Kinematic analysis focuses on the description of the emerging movements of joints, end effectors, or body segments, without making inferences about underlying causes of the action. In kinematic analysis, the distinction between product and process measures can also be made. Movement product measures are usually regarded as the quantitative measurement of the performance outcome expressed in terms of distance, time, or amount of error. Movement product measures can be further divided into those which pertain to the spatial aspect of the organization, as well as those that capture the temporal aspect of the movement. Spatial kinematics involves the measures of displacement of joints or segments of the body, in both linear and angular domains. Temporal kinematics measures implicitly capture the nature of movement timing. In addition to product measures, kinematic analysis provides a vast number of variables that allow the researcher to capture the nature or quality of the movement patterns and coordination. The temporal and spatial movement product kinematics will be introduced in this section.

Spatial Kinematics

Linear Displacement

In the context of manual actions, unilateral or bilateral, the linear displacement of the end effector is a common variable of interest. The hand is described in the Cartesian coordinates to capture the nature of the trajectory of the hand in the x, y, or z-axis of movement. However, reaching movement trajectories of hand are likely captured in the horizontal plane of motion. Kinematics of end-effectors are usually obtained by markers attached to the dorsum of the hands or wrist joints (Lin et al., 2010; Mazzoleni et al., 2014). In this case, the movement is described in terms of the performance of end effectors of the arm, such as the linear displacement of the hand.

Linear displacement is defined as the shortest distance in the specific direction from the initial to the final position of a movement. On the other hand, the hand path is usually measured by the total distances traveled during the trajectory. In a desired reaching task with a target, the hand path would allow researchers to evaluate the quality and straightness of movements based on linear displacement measures. For example, the hand path ratio is measured by the comparison between the actual hand trajectory from onset to offset and the straight-line distance (Otaka et al., 2015). Thus, a value of a hand path ratio close to 1 is representative of a straight hand path. A hand path ratio higher than 1 indicates a larger divergence from the straight path, resulting in a more curvilinear trajectory. Other studies also referred to the hand path ratio as "index of curvature" (Cacho et al., 2011; Jaspers et al., 2011; Tomita et al., 2017). The measurement of hand paths has been applied to tasks such as pointing (Cacho et al., 2011; Jaspers et al., 2011) and reaching (Merlo et al., 2013; Wagner et al., 2008).

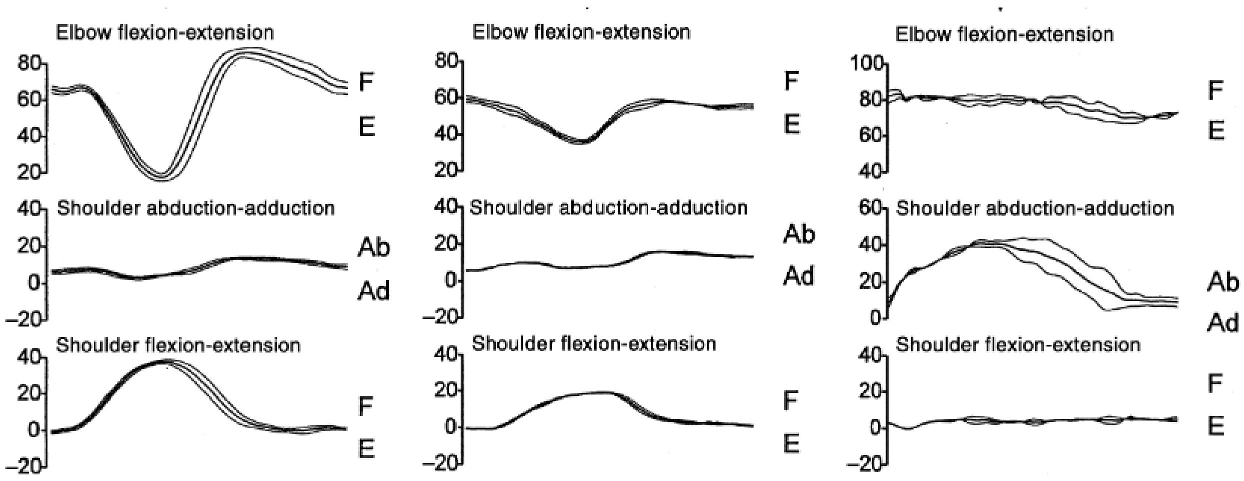
Angular Displacement

Angular displacement is a measure of the change in joint space. Angular kinematics measure the action that is planned and described around the coordinate of a joint instead of the Cartesian coordinates. For example, a reaching movement can be planned to move the shoulder, elbow, and wrist joints to arrive at the target so that the movement is performed around a set of intrinsic coordinates of the body, expressed in terms of joint angles. Angular displacements in arm movements are computed from the position data for elbow flexion or extension, shoulder flexion or extension in the sagittal plane, and adduction or abduction in the frontal plane, as well as wrist flexion or extension.

The measure of angular displacement involves the quantification of the range of motion of a joint (de los Reyes-Guzmán et al., 2014). A typical reaching movement is usually composed of elbow extension and shoulder flexion, with slight shoulder abduction, as well as wrist pronation or supination. As evident in Figure 2A, elbow extension and shoulder flexion movements are more segmented in individuals with hemiparesis, compared to those made by healthy individuals (Figure 2B and 2C). Additionally, in individuals with severe hemiparesis, the elbow angular displacement is small and irregular, while shoulder joint movement mainly consists of a large shoulder abduction with little flexion (Figure 2C). Thus, the measurement of angular displacement allows for the visualization of changes in trajectories of arm movement in individuals with stroke. Although this example is a unimanual action, the meaning of angular displacement in bimanual movements would be the same.

Figure 2

Angular displacements of respective planes in a reaching movement in healthy and stroke individuals


A. Healthy *B. Mild hemiparesis* *C. Severe hemiparesis*

Note: Time course of the angular displacements in reaching. (A) a healthy individual (left column); (B) a stroke patient with mild hemiparesis (middle column); (C) a stroke patient with severe hemiparesis (right column). Direction of the angular displacements: F, flexion; E, extension, Ab, abduction; Ad, adduction. (Roby-Brami et al., 2003).

Temporal Kinematics

Linear Velocity

Linear velocity provides information about the temporal motor control. Variables that are derived from a linear velocity profile are movement time, peak velocity, time to peak velocity, and the portion of time spent in acceleration and negative acceleration. Movement time is a measure of time required to perform a functional task successfully which is the interval between movement onset and offset (de los Reyes-Guzmán et al., 2014). Movement time also indicates the temporal efficiency of the movement since it incorporates the distance. This variable reflects the overall speed of the action, as a faster movement would result in a shorter movement time. Velocity not only shows the speed of a moving subject, but also the direction and distance of the movement. Peak velocity is the highest instantaneous velocity during the movement, as the point of shift from the acceleration to deceleration phase when the hand is moving in the same direction. Peak velocity is regarded as being correlated with the force generation of a movement (Chang et al., 2007). The location of peak velocity in the velocity profile is one indication of the control strategy used. For a normal preplanned movement, peak velocity is located at 33% to 50% of the velocity profile (Chang et al., 2007). A left shift of the peak velocity indicates increasing dependence on a visually guided strategy during reaching (Chang et al., 2007). The length of the ballistic component can be inferred from the percentage of time to peak velocity, in which small values indicate that the movement relies on online corrections instead of pre-planned control (Chang et al., 2007; Woodworth, 1899; Wu et al., 2007; Wu et al., 2011).

In unimanual actions, the metric of movement time has been widely used in discrete actions such as reaching tasks (Balasubramanian et al., 2012; Chang et al., 2005; Fasoli et al., 2002; Jaspers et al., 2011; Lin et al., 2010; Wagner, et al., 2008; Volman et al, 2002). In bimanual tasks, temporal control of end-effectors has been examined in catching (Tayler & Davids, 1997), aiming (Rose & Winstein, 2013), and reach-to-grasp tasks (Bingham et al., 2008, Mason & Bruyn, 2009). In the context of bimanual coordination, movement time has been measured in reaching movements with different task requirements (Kelso et al., 1979, 1983; Taylor & Davids, 1997). To summarize, literature on discrete unimanual and bimanual actions has frequently examined temporal parameters so that temporal control of both arms was investigated.

Linear Acceleration

As another temporal measure, linear acceleration is the rate of change in linear velocity which is the third time derivative of the displacement. Acceleration could be positive, negative, or zero, depending on the direction of change in velocity. Acceleration can provide information on the control strategy used in a movement. It is generally considered that the acceleration phase in the velocity profile corresponds to a preplanned and ballistic mode of control, while the negative acceleration phase represents the online corrective component (Lin et al., 2010). One movement unit consists of 1 acceleration and 1 deceleration phase, which can be used to characterize movement smoothness. A more preplanned motor control would have a longer acceleration phase and a shorter deceleration phase, with a smooth single-peaked velocity (Balasubramanian et al., 2012). In contrast, online-controlled movements would have a discontinuous, multiple-peaked velocity trace with multiple movement units (Balasubramanian et al., 2012). The length of the acceleration phase can be referred to as an indication of the motor recovery and control strategy, in which a longer acceleration phase is related to a better pre planned motor movement (Lin et al., 2010).

Variables like the jerk profile and the number of zero-crossings in the acceleration profile indicate the temporal aspect of control as well as the movement smoothness. Jerk is the rate of change of acceleration over time (Mazzoleni et al., 2014; Tropea et al., 2013). Lower jerk values are indicative of smooth and more efficient actions, which are required (during development) or reacquired (during rehabilitation). In contrast, higher jerk magnitude indicates the presence of tremor and inefficient underlying control (e.g., individuals recovering from stroke) (Balasubramanian et al., 2012). A jerk metric characterizes the average rate of change of acceleration, which is calculated by dividing the mean jerk magnitude by the peak velocity

(Balasubramanian et al., 2012). Additionally, the number of zero-crossings in the acceleration profile represents changes in directions of acceleration, indicating the existence of functional sub-movements (Lambercy et al., 2010).

Angular Velocity/Acceleration

Compared to linear velocity and acceleration, angular temporal measures can provide additional information on underlying rotating movements of an individual joint. A joint can be stationary without any linear velocity but exhibit angular temporal adaptations**.** Angular velocity is the rate of changes in angular displacement as a function of time. In other words, angular velocity indicates how fast the angular position or orientation of a joint changes with time. Angular acceleration is the rate of change of angular velocity divided by time. In upper limb movements, the wrist, elbow, or shoulder joint are typically measured **(**Asmussen et al., 2014).

Angular velocity and acceleration have been computed in unimanual studies as the evaluation of single-arm control (Asmussen et al., 2014; Flanagan et al., 1993). The time to elbow peak velocity has been referred to the control strategy in a reaching movement, in which a well-controlled reaching movement would have a longer time to elbow peak angular velocity with less dependence on online feedback for corrections (Chang et al., 2005).

Bimanual discrete actions are usually multi-joint movements, which indicates that the rotation of more than a single joint is involved in the movement (Asmussen et al., 2014). Generating a smooth and straight endpoint trajectory in reaching movements requires a subject to coordinate rotations of both shoulder and elbow joints, typically characterized by a roughly constant ratio of joint angular velocities (McCrea et al., 2002). On the other hand, deviations from straight hand paths can be caused by reduced coordination of the shoulder and elbow joint movements. Thus, the measure of angular velocity of multiple joints can identify the bimanual control strategy of placing the hands accurately in the desired position.

In both unimanual and bimanual actions, kinematic variables have been adopted differently depending on the task characteristics. Regardless of kinematic variables that are being measured, if they describe the nature of spatial or temporal organization, they can usually be referred to as the measures of “control”. Control refers to the absolute magnitude of the movement of a limb, such as parameters like time, amplitude, velocity, acceleration, and force of movement that indicate the level of control (Sparrow, 1992). However, if kinematic variables are only used as product measures, changes in the value of variables still represent the control of the movement because they do not directly describe the pattern of the movement (Sparrow, 1992). Thus, it is not adequate to only refer to product measures of motor control when bimanual coordination is examined. In order to derive valid inferences about the spatial as well as temporal coordination in bimanual actions, process measures also need to be integrated.

Kinematic Analysis: Movement Process Measures

Bernstein defined the coordination of human movements as the process of mastering redundant degrees of freedom (Bernstein, 1967). This definition implies that coordination is a process rather than a product or consequence of the movement. Spatial and temporal product measures in bimanual movements, such as the linear velocity (temporal) or movement straightness (spatial) of both hands, are also emerging features of coordination. Because of the kinematic redundancy, the same movement product can be achieved by many different combinations of degrees of freedom. In addition, bimanual coordination is not the simple sum of the control of two arms during bimanual actions. Instead, functional groups of structural elements such as muscles and joints are temporarily constrained as a unit to achieve the task, which is referred to as coordinative structures (Kugler et al., 1980). Bimanual coordination describes how two or more limbs generate and maintain a temporal and spatial relationship to each other to achieve a functional goal (Sparrow, 1992). In the domain of research examining bimanual actions, the measures of movement process, hence the coordination can be further divided into those which are more of quantitative in nature (i.e., Pearson's correlation) and those which are purely qualitative (i.e., angle-angle plots).

Quantitative Process Measures

Pearson's Correlation

The Pearson Product-Moment correlation, which is usually referred to as Pearson's correlation, allows one to infer the covariance or the magnitude of the relationship between two continuous variables (Derrick & Thomas, 2004). In the context of biomechanical analysis of goal-directed actions, such as bimanual movements, correlations are used to investigate the spatiotemporal relationship between two joints at the intralimb, or end-effectors at the inter-limb level over the course of the movement. To measure bimanual coordination, the coefficient value (r) has been considered as an index of coupling strength between two arms. Generally speaking, the absolute value of correlation coefficients close to 1 indicate a strong or "tight" coupling between two variables such as the velocities of two hands in which the changes in one variable are synchronized with the changes of another variable (Bewick et al., 2003). Lower absolute values represent more independent changes in spatial or temporal relations between the respective components (Przysucha & Maraj, 2013). A near-zero value indicates independent relations between the segments, joints, or end-effectors analyzed. In bimanual actions, the nature of coupling and synchrony, is often inferred from the velocity profiles of both end effectors, in the Cartesian frame of reference.

Correlations in end-effector space. In the context of bimanual actions, research studies have examined the temporal synchronization and spatial symmetry in Cartesian coordinates. In this approach, the relationship is inferred from the velocity or displacement profiles of the left and right hand, more specifically, the wrist joint of both arms (McCrea et al., 2002). In a bimanual reach-to-grasp task, temporal coupling was examined by correlation coefficients in the wrist velocity data of left and right arms (Mason et al., 2013). They investigated temporal coupling by manipulating the object distance in which the task was to reach two cylinders located at the same distance (i.e., both near or both far). While the asymmetric task in this study was reaching at different distances, the results showed that the highest coefficient occurred in the symmetric task with far targets. The lowest coefficient occurred when the non-dominant hand reached to the far target and the dominant hand reached to the near target (Mason et al., 2013). The authors suggested that temporal coupling could be affected by both the task and individual where it is difficult to couple two hands when the non-dominant hand needs to perform a more challenging movement (i.e., when the object located farther).

Other than goal-directed actions, the approach of correlations has also been incorporated in other bimanual movements under external time demands such as ball catching. In the study of bimanual ball-catching (Przysucha & Maraj, 2014), the degree of temporal synchrony between two hands was captured by the Pearson's correlation coefficient. This evaluation of temporal coordination was derived from the magnitude of covariation between the linear velocity of each wrist (Przysucha & Maraj, 2014). Thus, correlation coefficients infer the degree of the temporal relations in bimanual movements.

Linear displacements of two end-effectors in both arms has also been correlated as an indication of spatial coupling. For example, in a reach-to-grasp bimanual task conducted by healthy individuals, correlation coefficients were calculated from the hand displacements for every trial (Dohle et al., 2000). The study implemented different task constraints into the grasp phase, in which participants were required to reach the same distance to the targets and grasp two cylinders with different or similar sizes. To assess the coupling of the hands during reaching phase, the displacements of hand markers in the anterior direction were correlated. An evaluation of coupling between the grasping components was based on the magnitude of correlation between the absolute values of the grip aperture of two hands (Dohle et al., 2000). Their results showed that regardless of the object sizes, coupling of the hands during the reaching component was significantly stronger than the coupling of the grasp component. Additionally, manipulation of object sizes led to a significant reduction of coupling in grasping, while the strength of coupling in reaching was not affected (Dohle et al., 2000). These results showed that the grasp component was constrained by the task requirements, while the reaching phase was stable as the location of the target was identical across the trials (Dohle et al., 2000). These results have been supported by another study in which the similar task constraints were implemented, which was reaching to objects with different sizes (Mason & Bruyn, 2009). They found that displacements of two hands was more tightly coupled in the reaching phase than the grasp phase.

Regardless of spatial or temporal coupling that is measured, it is important to note that not all calculations of correlations between two kinematic variables can be referred to as process measures. For example, in a study of a bimanual reach-to-grasp task, temporal correlations between two hands at movement initiation and termination have been examined in both healthy and stroke subjects (Wu et al., 2008). The temporal relationship was determined by correlating the reaction time for one hand with that for the other hand and by correlating the time to finish the task between two hands (Wu et al., 2008). Left-right synchronization, measured at the onset of the movement and at its completion, as well as compared between the groups (the preceding sentence is unclear or fragmented). This method was also used by some other studies of bimanual movements (Kantak et al., 2016; Perrig et al., 1999; Weiss et al., 2000; Wiesendanger et al., 1994). In addition, other temporal variables have also been correlated between two hands in bilateral reach-to-grasp actions, such as peak velocity, the time to peak velocity, and peak acceleration (Castiello et al., 1993). Although, these measures could not be categorized as process measures, since the correlated kinematic variables do not represent the entire movement, they still provide valuable insight into the degree of synchrony in bimanual actions. More specifically, they allow for inferences to be made about the degree of synchrony at some critical points during the action, such as movement onset, transition from ballistic (acceleration) to the homing (deceleration) part of the action (i.e., time to peak velocity), and at the moment the task is completed.

Correlations in joint space. Determining the correlations between the displacements of adjacent joints is a method used to describe kinematic linkage at the intra-limb level of organization (Newell & van Emmerik, 1989). Particularly, spatial coupling between two joints has been widely documented in the investigation of intralimb and interlimb coupling. The degree of spatial coupling is calculated by correlating angular displacement of two joint angles over an entire movement. If the two joints start and end rotation synchronously, and maintain a fixed ratio of angular displacements, the absolute value of the correlation coefficient (*r*) will be close to 1. This value would indicate a tight coupling between the two components. As the ratio of angular displacements varies over the course of the movement, the absolute coefficient will be substantially less than 1 (Levin, 1996; Lum et al., 2009; Murphy et al., 2006).

The degree of spatial coupling has been examined by the magnitude of Pearson's correlation in a ball-catching task (Przysucha & Maraj, 2013) and a writing task (Newell & van Emmerik, 1989). In the ball-catching task performed by children with and without developmental coordination disorder, the degree of spatial symmetry was captured by the magnitude of correlation coefficients between shoulder-elbow and elbow-wrist joint pairs in both arms, respectively. To infer the degree of bimanual synchronization, the authors compared the coefficients of each joint pair across the arm, and there was no statistical significance (Przysucha & Maraj, 2013). Thus, there was no difference between left-right coupling, which indicated that the spatial relation of a joint pair was comparable across the arms. This technique allowed for the inference of how angular displacements of each joint pair across both body sides evolved over time against one another (Przysucha & Maraj, 2013).

To summarize, correlations have been used to infer the temporal and spatial relations between two hands in bimanual tasks, at the end-effector level as well as in joint space. Tight coupling is indicated by a higher correlation coefficient value, whereas lower values indicate that the two arms are organized independently. Ultimately, the nature of the task performed (e.g., symmetrical versus asymmetrical) must be considered when inferring if the actions and corresponding coupling are functional or require treatment.

In bimanual movements, correlations between end-effectors and association between angular displacing in joint space have been used to infer the degree of temporal and/or spatial coupling. Many details can be gleaned from quantitative measures of movement where variability and change, within participants or between participants, can be quantified with central tendencies and standard deviation.

Qualitative Process Measure: Angle-Angle Plots

Correlations capture quantitatively the magnitude of coupling, hence coordination in temporal or spatial variables between joints or end effectors. One limitation of these approaches is that they do not explicitly reveal the actual relationships between the joints, particularly in the spatial domain. This limitation also relates to the issue of motor equivalence because participants can produce the same trajectory using different joint configurations (Bernstein, 1967). In other words, an infinite number of joint configurations or redundant degrees of freedom can accomplish a reaching movement, described by endpoint trajectories. When a stroke occurs, deficits in single-joint control may also influence coordination by disruptions of the linkages required for the formation of a synergy (Steenbergen et al., 2000). Since the angle-angle plot qualitatively describes the angular movement of each joint, changes in the control of joint rotation and the kinematic linkage in the action can be revealed graphically. As a result, angle-angle plots can be used to infer the degree of spatial coupling regarding relationships between the motions of one joint with respect to another (Lacquaniti & Soechting, 1982).

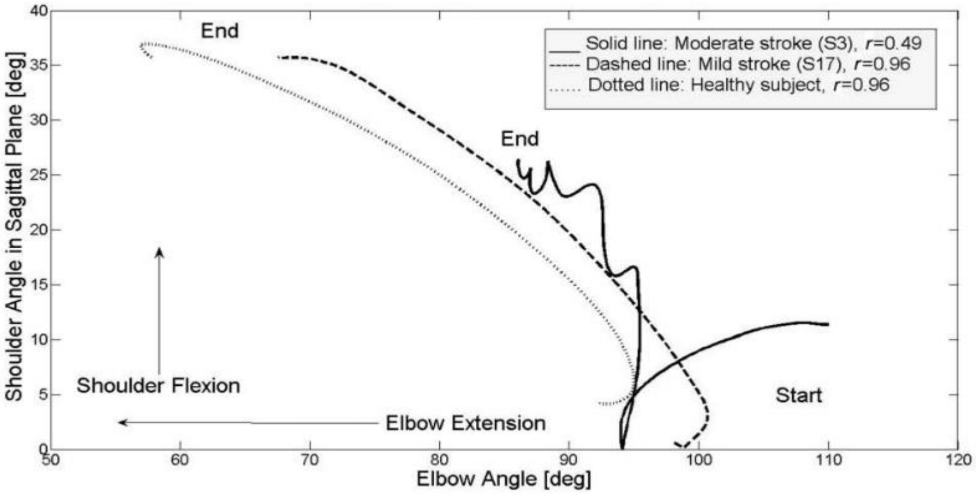
Angle-Angle Plots in Intralimb Coupling

Angle-angle plots have been used in the evaluation of intralimb coordination for analyzing the coupling in shoulder-elbow, elbow-wrist, and shoulder-wrist joint pairs (Tomita et al., 2017). In upper-extremity actions, angle-angle plots have been implemented in various tasks, such as single-arm reaching (Murphy et al., 2006, 2011), bimanual reaching (Steenbergen et al., 2000), and the performance of each arm in a bimanual ball-catching (Przysucha & Maraj, 2014). Angle-angle plots for each joint pair in upper extremity actions in the context of different task constraints and populations will be discussed below.

Shoulder-elbow coupling. The relationship between proximal joint pairs (shoulder-elbow) of the arm has been widely examined in arm movements, especially in individuals with stroke. For instance, a study by Murphy et al. (2011) documented a reaching movement in healthy individuals and stroke participants with a mild to moderate arm impairment (Figure 3). This study measured angular joint displacements for elbow flexion or extension and shoulder flexion or extension in the sagittal plane. As shown in the Figure 3, in healthy individuals the angle-angle trajectory is smooth and continuous, generating an almost straight line. This relationship shows a high degree of spatial coupling between two joints, with corresponding and consistent changes from both joints. However, individuals with stroke showed a decoupled and more segmented line, which indicated an interrupted intralimb coordination (Murphy et al., 2011). The segmented line of individuals with moderate stroke individuals indicated less coupled shoulder and elbow angular displacements in a reaching movement. As evident in Figure 3, both joints are involved in the action, but the nature of their spatial relationship was different. At the start of the action, the elbow started to flex, while the shoulder was slightly "frozen" with only around 5 degrees of angular displacement. The angular movements of the shoulder were suddenly initiated when the elbow started to be "frozen" out. After this point, there was little to no change to the angular displacement of the elbow, while the shoulder continued to extend and slightly flex throughout the main part of the remaining action. Therefore, compared to neurologically intact individuals, the coordination patterns exhibited by individuals with moderate stroke are demonstrated in a segmented way, as seen on the qualitative angle-angle plot.

Figure 3

An angle-angle plot of shoulder and elbow joints in both healthy individuals and individuals with stroke

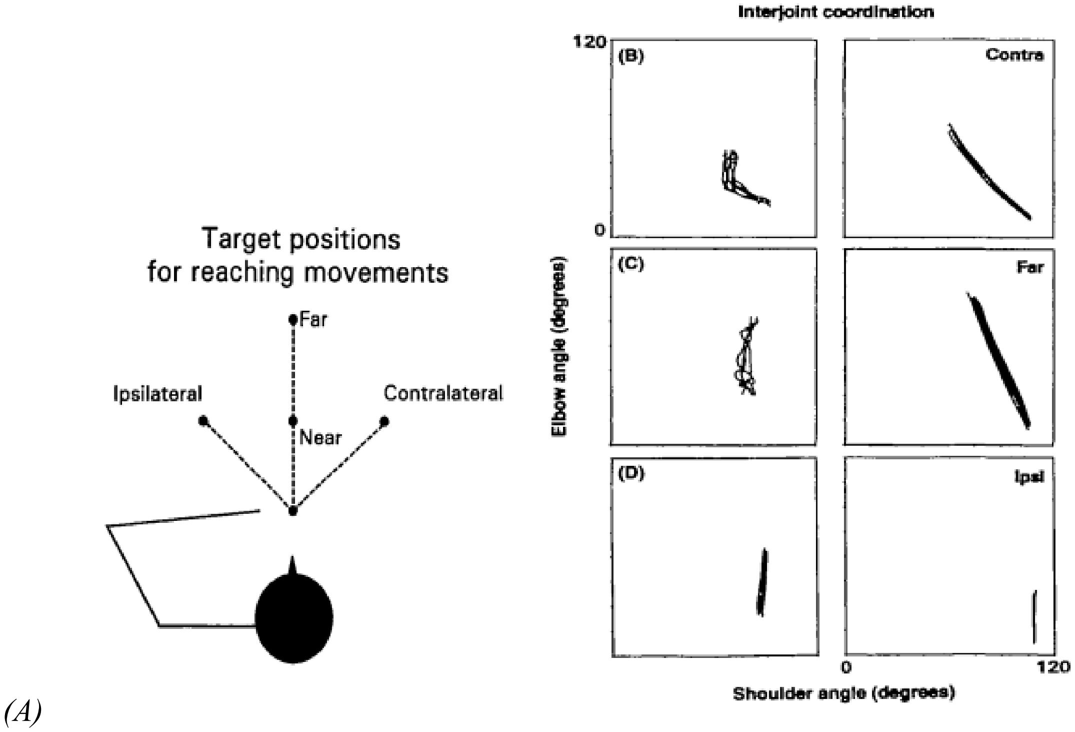


Note: An angle-angle diagram describing the spatial relationship between two joints within a single arm. (Murphy et al., 2011).

Levin (1996) also investigated intralimb coupling of the paretic and non-paretic arm in stroke subjects, in which they were asked to reach for a target that was located either ipsilateral, near or far, or contralateral to them (Figure 4A). Movements towards the ipsilateral target required a combination of horizontal shoulder abduction (extension) with elbow extension if the subject intended to produce a straight-line trajectory or a single-joint elbow movement if a curved trajectory was produced (Levin, 1996).

Figure 4

Angle-angle plots for elbow-shoulder with different target positions



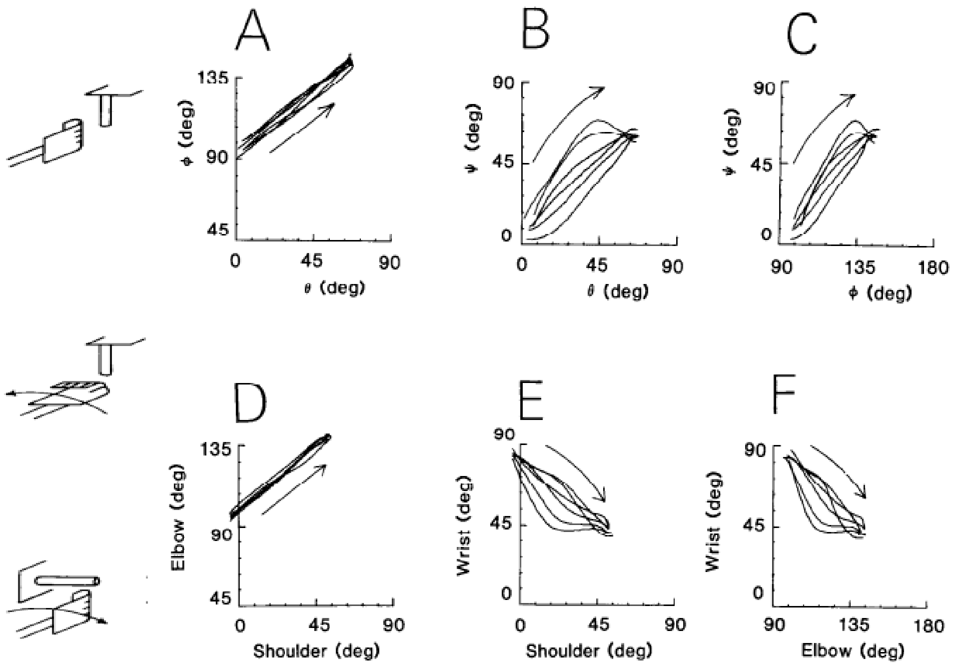
Note: (A) Target positions for a single-arm reaching movement. (B-D) Intralimb coordination in angular coordinates for the affected (left column) and non-affected arm (right column) for a hemiparetic subject with severe spasticity. Angular diagrams for the near target (not shown) were similar to those for the far target shown in (C) (Levin, 1996).

As evident in Figure 4B-D, intralimb coupling of the non-paretic arm was smooth, which was illustrated by the almost linear relationship between elbow and shoulder joint excursions. For different targets, the degree of movement in the shoulder joint varied from maximal for the contralateral target (Figure 4B, right column) to no involvement in this subject for the ipsilateral target (Figure 4D, right column). This difference was accounted for by the task requirements (different target locations) in which each joint needed to generate different angles to complete the task. In contrast, for the more affected arm, the subject could not produce a smooth coupling between shoulder and elbow movement for the contralateral and far targets (Figure 4, left column), demonstrated by segmentation of the angle-angle diagrams. This segmentation was the most obvious for the movement to the contralateral target (Figure 4B, left column), in which a combined elbow/shoulder movement was followed by an isolated elbow extension. Movements to the far and ipsilateral targets were achieved mainly by the elbow joint. However, for the far movement, there was not systematic involvement of the shoulder joint (Figure 4C, left column). Although for the ipsilateral target, the shoulder movement was small, there was a strictly linear relationship between elbow and shoulder movement (Figure 4D, left column) in contrast to the non-affected arm in which the shoulder joint was stationary.

Wrist-shoulder/elbow coupling. Compared to shoulder-elbow coupling, the coupling between wrist and proximal joints (i.e., shoulder or elbow) has been relatively less investigated in descriptive studies. This could be because the shoulder-elbow relationship represents a more essential and invariant relationship in the coordination of goal-directed actions as compared with the coupling of more distal components (e.g., the elbow-wrist) (Soechting, 1989). A well-known study has examined the coupling in each joint pair of the arm (Lacquaniti & Soechting, 1982). The task was forward projection of the hand in order to reach for and grasp an object at different orientations, in which the forearm rotation was required in the task (Figure 5, left panel). The reaching action included shoulder flexion, elbow extension, and wrist pronation or supination, and participants were asked to vary their speed from trial to trial (Lacquaniti & Soechting, 1982). The relationship between shoulder-elbow, elbow-wrist, and shoulder-wrist was described in angle-angle plots in which the wrist needed to pronate (Figure 5A-C) and supinate (Figure 5D-F) in six representative trials respectively. The maximum angular velocity at the shoulder was different from each trial, in order to detect the variability with various movement speeds (Lacquaniti & Soechting, 1982).

Figure 5

Angle diagrams for shoulder-elbow, shoulder-wrist and elbow-wrist in reaching with rotations of forearm



Note: The left panel shows the initial position of the hand and the orientation of the target to be grasped. (A-C): intralimb coupling when the target is vertically oriented, and the forearm needs to pronate and grasp; (D-F): when the target is horizontally placed, and the forearms need to supinate and grasp (Lacquaniti & Soechting, 1982).

As evident in Figure 5A and D, there is small variability in the coupling between shoulder and elbow among trials despite different speeds of movement execution (Lacquaniti & Soechting, 1982). This indicated that tight coupling was preserved in a stable linkage at the shoulder and elbow joints. On the contrary, when the wrist angles were plotted versus shoulder angle (Figure 5B and E) or elbow angle (Figure 5C and F), there was considerable coupling variability. These representative trials showed that no invariant relationship existed between changes in wrist excursions and changes in shoulder or elbow excursions (Lacquaniti & Soechting, 1982). In addition to the information from angle diagrams, the authors reported that the timing and duration of wrist movement were extremely variable from trial to trial, and the variability of wrist excursions did not decrease with practice. The fact that wrist movement was uncoupled with the proximal joints compared to the functional coupling of shoulder-elbow could not be ascribed to external constraints introduced by tasks, since these constraints were the same for the actions at all joints and existed in the initial and final angular positions (Lacquaniti & Soechting, 1982). The authors concluded that this difference might result from the nature of internal constraints acting on the movements at the two proximal joints and wrist (Lacquaniti & Soechting, 1982).

In conclusion, angle-angle plots represent the relationship between the two joints of interest, in which the excursions of the joint are recorded. Angle-angle plots qualitatively measure the spatial coupling at the intralimb level, as one of the solutions to the motor equivalence problem.

Conceptual Basis of the Nature of Bimanual Coordination

In the past several decades, great effort has been put towards the topic of understanding bimanual coordination since the control of single-arm action can not simply infer the laws of coordination when both arms are involved simultaneously. The nature of bimanual coordinative tendencies in human movements has been derived from the issue of the degree of freedom problem (Bernstein, 1967). To solve this problem, the spatiotemporal characteristics of upper-limb bimanual actions has been investigated as evidence for the development of the concepts and theories related to coordinative structures (Kugler et al., 1980) and synergies (Bernstein, 1967).

The coordinative principles of continuous bimanual actions have evolved from the theories around the dynamic system approach, which is the theoretical framework for analyzing the space-time features of discrete bimanual behavior.

The Degree of Freedom Problem

As described above, the human motor system is composed of multiple joints and an even greater number of muscles. Due to this complexity in the muscular-skeletal system, many degrees of freedom need to be simultaneously controlled in order to perform a simple motor action. In general, the number of degrees of freedom can be defined as the number of individual components in a system and the number of ways in which each component can act or move. In the context of the kinematic level of organization, the degrees of freedom refer to the number of planes of motion in which a joint can move (Sporns & Edelman, 1993). For example, since the shoulder joint can move freely in three planes to circumduction, including abduction, adduction, or flexion and extension, then the shoulder has three degrees of freedom. In a reaching movement, not only the shoulder joint, but the elbow, wrist, as well as finger joints, are also involved in the task and each have their own number of degrees of freedom that need to be controlled. The presence of these abundant degrees of freedom, from many joints, results in a fact that the same task can be accomplished with almost an infinite number of movement patterns.

Bernstein observed that an unequivocal relationship between neural signals and motor behaviour cannot be expected (Sprons & Edelman, 1993). This outcome is mainly because motor actions are defined by the initial position of the limbs and the varying interactions of motor impulses and external forces on the moving parts of the body. The degrees of freedom of the motor system needs to be reduced and reorganized to achieve a coordinated movement.

Bernstein (1967) defined coordination as a problem of mastering redundant degrees of freedom involved in a movement. For instance, in a bimanual action, to coordinate two arms when they are moving simultaneously, the redundant possibilities of joint configurations need to be organized. This organization indicates that the entire number of degrees of freedom from which a movement can be created is more than the number of degrees of freedom that are minimally needed to finish a task. In general, this number of the possible degrees of freedom is far greater than the dimension of their workspace such as the planes in which a joint can move. In motor control, this phenomenon is referred to as motor equivalence.

From the kinematic standpoint, motor equivalence results from the fact that the same endpoint trajectory can be accomplished by an infinite number of joint configurations (degrees of freedom). The issue of motor equivalence could occur at two domains of coordination such as intralimb and interlimb. Intralimb coordination defines the topology of a single arm's movement, while interlimb coordination describes how two or more limbs generate and maintain a temporal and spatial relationship to each other to achieve a functional goal (Sparrow, 1992). Although conceptually both levels of organization share common principals, and are affected by the same or similar constraints, there are some important differences in regards to how such processes are understood. One way for the central nervous system to handle the redundancy of the system is to organize the degrees of freedom into functional units, often referred to as "synergies" (Bernstein, 1967) or "coordinative structures" (Kugler et al., 1980).

Coupling in Coordinative Structures/Synergies

At the kinematic level, the investigation of the characteristics of arm movements regarding space and time has started from unimanual tasks, such as the speed-accuracy trade off in Fitts' law (Fitts, 1954). To examine the application of Fitts' law in bimanual actions, Kelso and his colleagues (1979) has further explored the principles of spatiotemporal relationship between two arms. The study of Kelso et al. (1979), along with other similar studies that analyzed the kinematic features of discrete bimanual actions, have been regarded as the experimental support for the notion of coordinative structures (Kugler et al., 1980) and synergies (Bernstein, 1967).

Fitts' Law in Unimanual Actions

The investigation of spatiotemporal kinematics in the upper limb has started from the work of Woodworth (1899), and a well-known study with the manipulation of a speed-accuracy task (Fitts, 1954). Fitts (1954) formulated a relationship between movement duration, movement amplitude, and target size in unilateral arm movements, which is referred to as Fitts' law. In the equation of Fitts' law, the movement time = $a + b* \log_2$-$(2A/W)$, in which a is the intercept and b is the slope of the regression equation that uses the log function. A is the amplitude of movement, and W is the width of the target (Fitts, 1954). The key aspect of this formula is that movement time depends on the ratio of movement amplitude to movement precision. Thus, the movement time for a 5 cm movement distance to a 0.5 cm target width is practically identical to a 10 cm movement distance to a 1 cm target width. According to Fitts' law, in a one-handed movement, when the target is large and the amplitude is short, it is an easy task for the arm; when the target is small and the amplitude is long, it is a hard task. The movement time of an easy task will be shorter.

Fitts' Law in Bimanual Actions

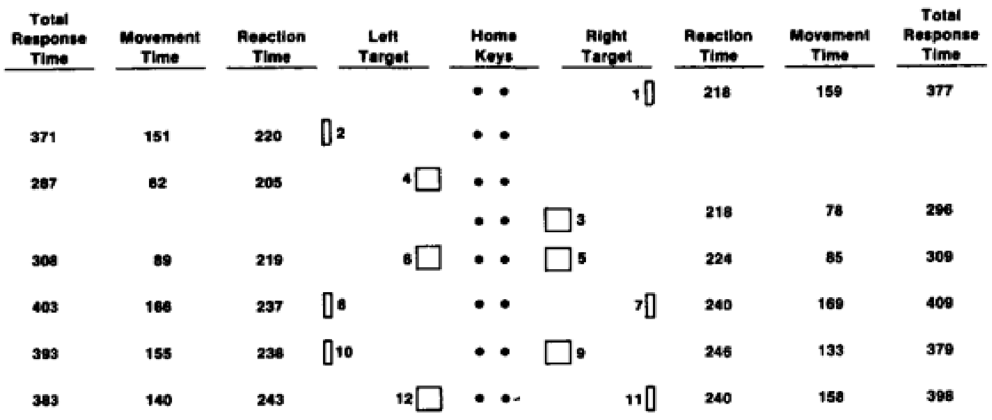
Since Fitts' law applies to one-handed actions, Kelso and his colleagues (1979) wanted to examine if the same "cognitive" explanation would apply to bimanual actions. In other words, they investigated if bimanual actions, as well as the degrees of freedom problem associated with it, were “solved” by the (generalized) motor program. Their research questions focused on if Fitts’ law was applicable to bimanual movements and if movements of one hand could influence movements of the other hand.

To examine whether bimanual actions are controlled via a motor program, or some alternative “solution”, Kelso et al. (1979) conducted a series of three experiments. They investigated bimanual aiming movements over different amplitudes (6 cm and 24 cm) and different target sizes (7.2 cm and 3.6 cm width; Figure 6). Tasks were designed to be hard (i.e., reaching the 3.6 cm width target with 24 cm distance) and easy (i.e., reaching the 7.2 cm width target with 6 cm distance) according to Fitts’ law.

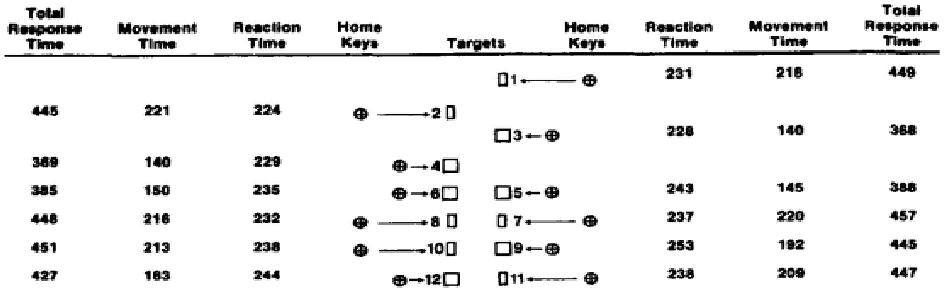
Figure 6

Experimental setups of the study from Kelso et al. (1979).

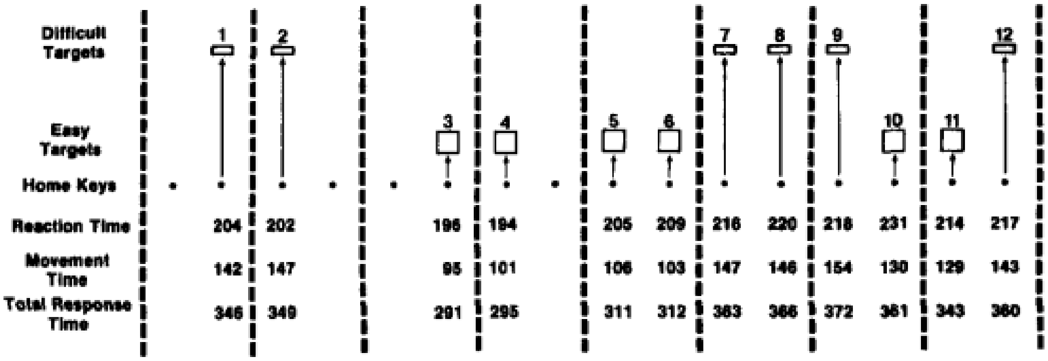
a. *Settings for experiment 1.*



b. *Settings for experimen*



c. *Setting for experiment 3.*



Note. The setups for the three experiments in the study of Kelso et al. (1979).

All three experiments from Kelso et al. (1979) reported a clear difference in movement times in one-handed movements that were consistent with Fitts' law, in which the easy task was significantly faster than the difficult task. In bimanual movements, when two hands had the same tasks, the movement time of the easy task was also shorter than the movement time of the hard task. This showed that Fitts' law was also applicable to bimanual movements in which two hands have identical movements. On the other hand, when two hands performed different tasks together, the authors found that participants initiated two arms almost at the same time, in which the largest interlimb difference in reaction time was 8 ms in experiment 1 and 15 ms in experiment 2 (Kelso et al., 1979). A strong interlimb temporal coupling and the simultaneity of movement initiation were found in three experiments regardless of task demands because the within-subject correlations for reaction time between left hand and right hand were high in experiment 1 (r=.95-.97), experiment 2 (r=.74-.98), and experiment 3 (r=.82-.98) (Kelso et al., 1979). When two arms were moving together to an easy hard target individually, the discrepancy in movement time detected in the single-handed movement was eliminated significantly. Additionally, the authors noticed that the total response time, which was the sum of reaction time and movement time, showed a non-significant difference between the hard target and the easy target (Kelso et al., 1979). To summarize, their results revealed that at the beginning and the ending of the movement both hands were temporally coupled regardless of if the hands were performing movements with the same or different spatial demands. Also, another main finding of this study was that, even when the participant was asked to move different distances of each arm to targets, time to peak velocity and time to peak acceleration for each limb showed a synchronous pattern, although both arms traveled at completely different speeds. This also suggested a strong interaction between two arms, and it was not consistent with the idea that two arms were programmed independently. They concluded that control is simplified by task-dependent “functional groups of muscles” (Kelso et al., 1979). Additionally, this study has also been interpreted as the support for a theoretical concept that bimanual movements are controlled via coordinative structures or synergies.

In conclusion, this study suggested that Fitts’ law did not apply to bimanual actions, as temporal characteristics of the trajectories of each end-effector (e.g., movement onset and offset, movement time, time to peak velocity) were coupled despite the fact that each arm performed actions under different spatial difficulty. The velocity profiles also indicated that two hands had similar temporal patterns, where the hands tend to accelerate and decelerate simultaneously. Even though the results were contrary to Fitts’ law, bimanual movements appeared to be constrained to the same temporal mechanism. The hypothesis that each arm would be controlled by a different motor program was rejected. The temporal entrapment of the second limb to the more difficult limb’s trajectory has been posited to be caused by a common neural pattern being transmitted across the corpus collosum, down the lateral corticospinal tract, and rubrospinal tract.

Coordinative Structures/Synergies in Bimanual Movements

Bimanual movements appear to be controlled by the cortex using functional groups of muscles that are formed across the arms, instead of controlled by individual muscles (Kugler et al., 1980). Those functional groups of muscles are defined as coordinative structures that are the essential units of movements, which has been proposed as a solution to the degree of freedom problem in the human motor system (Kugler et al., 1980).

The idea that functional groups of muscles are constrained to act as a single unit is also termed as synergy or a functional synergy, a concept proposed by Bernstein (1967). To be specific, functional synergies are collections of muscles, all of which share a common pool of afferent or efferent information that are deployed as a unit in a task (Kelso et al., 1983). In complex systems like human motor system, elements are organized into synergies defined as functional groupings of structural elements (e.g., neurons, muscles, joints) that are temporarily constrained to act as a single coherent unit (Kelso, 1983). Other following studies of bimanual reaching also indicated that movements of one hand are influenced by movements of the other hand as the evidence of coordinative structures (Kantak et al., 2016a; Marteniuk et al., 1984; Perrig et al., 1999; Steenbergen et al., 2000). It is worth mentioning that there is no clear difference between the concept of coordinative structures and synergies, since they both represent the emerging functional movement units under a certain task requirement.

In discrete bimanual actions, the concept of synergy or coordinative structure has been applied to tasks such as bimanual reaching (Kelso et al., 1979, 1983) and catching (Taylor & Davids, 1997). The study of Taylor and Davids (1997) investigated whether the notion of synergies, as solutions to bimanual actions, was also applicable to tasks other than those which are self-paced like reaching. Participants were asked to catch the ball with both hands when the ball was projected to the right shoulder area, left shoulder area, and the center of the chest area (Taylor & Davids, 1997). Thus, two arms needed to move different amplitudes to catch the ball. The authors reported high values of correlations in the temporal profile (e.g., movement initiation, time to peak velocity, and time to peak acceleration) between the arms, showing a strong temporal coupling even though the movement distances of two arms are slightly different (Taylor & Davids, 1997). Additionally, when the arms needed to move different distances, the arm traveling the greater distance moved at a faster speed to catch up with the other arm so that they could touch the ball together (Taylor & Davids, 1997). This study supported the concept that two arms were coupled as a functional unit even though the two arms were not performing identical movements.

Other studies that revealed assimilation effects between two arms in both temporal (Rose & Winstein, 2013) and spatial (Franz et al., 1991) domains also supported the existence of synergies. In reaching movements performed by healthy individuals, the time to peak velocity and peak velocity of both end effectors are nearly the same with the execution of both equal and different distances, indicating the existence of a synergy between the two hands (Kelso et al. 1979; Mason et al., 2013; van Dokkum et al., 2014).

In conclusion, to decrease the redundancy of the motor system, interlimb coordination is achieved by organizing the motor apparatus to synergies specifically oriented to the task goal (Kugler et al., 1980, 1983). Interlimb coupling, especially temporal coupling was evident in bimanual reaching and catching movements regardless of the movements of two arms not being identical. This observation suggests that synergies or coordinative structures are the self-organized formations of coordinated movement patterns. The notion of self-organization in coordinated movements has been developed from the synergetic model and dynamic system approach, which will be discussed in the next section.

Dynamic System Approach to Bimanual Coordination

In the past, efforts have been devoted to investigating the stability, flexibility, and variability of coordination in bimanual movements. The synergetic model (Haken, 1977) and the model of rhythmic bimanual coordination introduced by Haken, and his colleagues called the Haken-Kelso-Bunz (HKB) model have revealed some elementary rules that underlie the organization of stable and flexible motor synergies, which emerged from the dynamic system approach (Haken et al.,1985). Additionally, the concepts introduced by the synergetic model and HKB model also provided more information about coordination in discrete bimanual actions.

Stability and Variability in Human Behaviour

In a complex and functional motor system, coordinated behaviour generated by the motor system is stable yet flexible (Kelso, 1984). The characteristics of bimanual coordination have been described in the dynamic system approach, which introduced the concepts of stability and variability in the non-linear human motor system (Kelso & Schöner, 1988). An increased amount of variability indicates less cooperative behaviour among the elements of the system, which eventually leads to new attractor states or behaviorally stable solutions (Kelso & Schöner, 1988). Thus, the human motor system is a non-linear system since the input does not lead to a linear change in output. Instead, input changes the variability of the system, which could drive the occurrence of a new behaviour (Harbourne & Stergiou, 2009). Generally speaking, under the same task demands, small amounts of variability indicate a highly stable behaviour.

The stability of coordination patterns in the HKB model could keep behaviour in a specific state or attractor and maintain its structure despite small perturbations (Kelso, 1984). On the other hand, the loss of stability, and the transition between existing patterns, as observed in the HKB model, are compatible with the dynamic system approach, in which increased variability in the system reveals growing instability and leads to a shift to a new attractor, or new behaviour. A necessary amount of variability is required to adapt substantial changes to task and environmental demands (Kelso, 1984). Therefore, the HKB model along with the dynamic system approach, advances the description of phase transitions between coordination states or patterns, in which variability is considered not as an error but rather as behavioral changes and adaptations (Harbourne & Stergiou, 2009).

The Synergetic Model

In Greek, synergetic means “working together” (Haken, 1983). In the field of motor control, synergetics is an area of study which focuses on the spontaneous formation of patterns or new changes in open systems (Haken, 1983). In a dynamic system composed of many elements, patterns occur in a self-organized fashion according to the spontaneous formation of temporal and spatial relations under different constraints. The stability of a self-organized pattern is influenced by control parameters, which are the variables that the collective behaviour of a system that is sensitive to and induces changes in a system through collective states (Haken, 1983). More specifically, in bimanual discrete movements, control parameters could generally be referred to as task constraints that may influence the coupling strength between two upper extremities. Thus, a control parameter does not “control” the behaviour in the system but rather acts as a catalyst for reorganizing behavior across the movement landscape.

Self-organization only occurs in nonlinear systems, in which the nonlinear dynamics can be defined in the matter of low dimensional attractor states (Kelso & Schöner, 1988). An attractor or an attractor state is the highly stable state of a dynamic system that leads the behaviour into routinized patterns. A low-dimensional attractor, such as the in-phase mode in a finger tapping movement, is usually described by order parameters that are derived from the behaviour of a high-dimensional system like the human motor system (Kelso & Schöner, 1988). The existence of attractors indicates that there is a significant reduction of complexity in the system, concerning the number of degrees of freedom in the system; on the other hand, low dimensional attractors have a noticeable characteristic that is the generation of a considerable degree of behavioral variations (Kelso & Schöner, 1988). In line with the characteristics of attractors, in bimanual symmetric movements, a low dimensional attractor could be observed by a high level of interlimb temporal and/or spatial coupling. Thus, the set of attractors or stable states that exhibit under certain values of a control parameter represents self-organized coordination patterns, known as "coordinative tendencies" or "spontaneous patterns" (Kelso, 1995). These spontaneous coordinative tendencies were also called as "intrinsic dynamics" (Haken et al, 1985).

Within the synergetic model, an important issue that researchers are investigating is identifying what is called an "order parameter" (Kelso & Schöner, 1988). An order parameter is a collective variable that can define the overall behaviour of the system and enable coordinated movements that can be reproduced and distinguished from other patterns. Therefore, an order parameter can describe the qualitative changes in coordination patterns, such as the relative phase between two hands in a continuous finger-tapping movement (Haken et al., 1985). In other words, the emergence of a coordination pattern is captured by the dynamics of order parameters. When a control parameter is altered, such as the speed is increased from slow to fast, an order parameter may remain stable or change its characteristics of the stable state, depending on if the control parameter reaches a critical value requiring change (Haken et al., 1985). As a result, order parameters can be referred to as dependent variables that describe the spatiotemporal pattern when the transition of a coordination patterns takes place due to the introduction of a new task or demand. The issue of parameters that has been specifically investigated in bimanual continuous movements, along with applications in bimanual discrete movements, will be discussed in the next section.

The HKB Model as Applied to Discrete Actions

At the behavioral level, the dynamic system approach has been inferred from the investigation of the degree of coupling between two hands, such as the Haken-Kelso-Bunz

(HKB) model which was derived from rhythmical tasks (Haken et al., 1985). The HKB model described behavioral features of intrinsic dynamics in bimanual coordination. When participants were asked to rhythmically flex and extend their index fingers in anti-phase (i.e., one finger extends while the other flexes), they were able to maintain this anti-phase mode for low frequencies only. When the oscillating frequency of fingers increased, and reached a critical level, participants switched abruptly and spontaneously to an in-phase mode in which homologous muscles were activated simultaneously (Haken et al., 1985; Kelso, 1984). Additionally, even when the movement frequency goes back to a lower level, the in-phase mode is not disturbed. In line with the synergetic model, if the right and left hand are described in terms of two oscillators, rhythmical movements can be characterized by their relative phase relationship. Thus, coupling between the hands can be modeled as a non-linear interaction between these oscillators and describe the system's intrinsic dynamics (Haken et al., 1985; Pepper et al., 1995).

Although these models capture the main features of rhythmical behavior, it is difficult to extend this model to discrete movements (Schöner, 1990), since the coupling between the hands is modeled as a potential function of the relative phase, which does not exist in discrete actions. However, the principles of coordination and control in rhythmic tasks are important for understanding the control issues in discrete tasks. Thus, researchers identified that the coupling strength could be the alternative order parameter (collective variable) that was applicable to bimanual discrete actions (Schöner, 1990). At the kinematic level, the properties of coordination dynamics are due to a nonlinear coupling between the homologous elements (e.g., two arms) which specifies their positions and velocities relative to each other (Temprado et al., 1999). Therefore, the coupling strength between two body segments such as joint angles or trajectories of end effectors in the temporal or spatial domains could act as an order parameter within a dynamic system (Steenbergen et al., 2000; Temprado et al., 1997).

Summary and Purpose

Stroke represents a neurological deficit that can result in a plethora of motor issues. These problems may affect gait, balance, as well as fine motor skills. However, one of the most prevalent motor issues that emerge due to stroke is a less than optimal ability to perform bimanual actions (Virani et al., 2021). These problems may be reflected in the inability to perform even the most rudimentary skills that involve both arms, in symmetrical or asymmetrical actions (Roby-Brami et al., 2003). Collectively, there have been numerous studies that examined these issues and attempted to delineate the most effective rehabilitative protocols. There have also been many systematic reviews that provided a meaningful and exhaustive summary of these investigations and the effectiveness of various types of rehabilitation. However, one of the aspects that has not been examined in detail is how the emerging spatial and temporal coupling, between the two effectors (hands/arms), are investigated or measured in stroke rehabilitation.

Examining the change in motor function of stroke patients in a reliable and valid way is one of the key issues in rehabilitation. In the context of this research, the emphasis is focused on making inferences about changes in coordination. There are several different methodological approaches to examine such issues, in terms of the degree and stability of spatiotemporal coupling. However, they have not been reviewed systematically this far in the literature on upper extremity rehabilitation. As a result, the primary purpose of this research is to review the different methodological approaches that make qualitative and quantitative inferences about the synergistic relations between the arms as a result of stroke rehabilitation. Specifically, interlimb coupling in spatial and temporal domains that are described by kinematics will be investigated.

The secondary purpose is to classify these approaches in relation to their conceptual basis that withstand from the existing theories/models of coordination. The third purpose is to provide suggestions for the future research in regards to how the issue of bimanual coordination could be examined in individuals with stroke, especially when they are enrolled in arm rehabilitation programs.

Method

A systematic review of the literature was performed to identify all relevant research studies that satisfied the eligibility criteria. Studies that focused on improving bimanual function after stroke were collected and used to determine and evaluate which methodological approaches were incorporated to measure bimanual coordination.

Searching Strategy

Electronic databases searching was conducted with several search engines including Cumulative Index within Nursing and Allied Health Literature (CINAHL), PubMed, PsycINFO, and Web of Science. Google Scholar was used as a secondary search tool as this search platform was more informally used to locate articles that were not found in the above four databases. A search string was used in all selected databases to include the key text words “stroke”, “bimanual”, “coordination”, and “intervention”, along with their synonyms, such as “cerebrovascular accident”, “brain infarction”, “transient ischemic attack”, “brain hemorrhage”, “brain ischemia”, “interlimb”, “bilateral”, “coupled”, “rehabilitation”, “therapy”, “functional training”, “neurorehabilitation”, and “training”, to retrieve the appropriate articles. The search terms listed in Appendix A were used in each database, which were consistent with the main topics of this paper. “Stroke” was used to locate the targeted population. “Bimanual” describes the movements that were analyzed in studies, in which both arms were involved in the intervention protocol. “Coordination” represented the organization of two hands and related body segments in a complex movement to allow them to work together effectively and functionally. “Intervention” was the setting of the experiment taking place, which needed to follow a certain protocol that aims to facilitate the recovery of bimanual coordination of arm function, by training one arm or two arms.

Study Selection Criteria

Inclusion Criteria

Characteristics of participants

The eligible studies for review included participants that were both adult males and females, over 19 years of age who have experienced a stroke (Sawyer et al., 2018). The review included research studies with participants who have had a diagnosis of either ischemic, hemorrhagic, or transient ischemic stroke (TIA). Regardless of the type of stroke experienced, the participants had to be involved in arm movement rehabilitation or other similar training programs such as bimanual arm training and robot-assisted training. The article was included in the review if participants were characterized as being in any of the subcategories including acute stroke (0-1 month post-stroke), subacute stroke (1-6 months post-stroke), or chronic stroke (longer than 6 months post-stroke).

Types of interventions

Stroke rehabilitation studies that aimed to improve bimanual coordination were targeted in this review. In this context, “stroke rehabilitation” was defined as a dynamic, progressive, goal-oriented process aimed at enabling a person with impairment to reach their optimal physical level (Dawson, et al., 2013). Interventions that represented the rehabilitation approaches in the field which were related to bimanual coordination of the hands were primarily included. The combination of bilateral movement training and supplementary assistive protocols such as auditory or rhythmic cues and active neuromuscular stimulation were accepted since the article met other inclusion criteria outlined previously. From the internal validity perspective, the studies involving randomized controlled trials (RCTs) was primarily considered. However, other types of study such as pilot studies and cohort studies were also included if they met the inclusion criteria. If the study design was not specified, the inclusion would depend on the satisfaction of other eligibility criteria. In addition, only peer-reviewed articles were included in order to retrieve high-quality articles. No limitation on the publication year was applied.

Exclusion Criteria

Studies that were single-case reports without empirical data were excluded. All commentaries were excluded. Other systematic reviews and meta-analyses were excluded. Studies that were not published in English were excluded. Studies with non-human being subject were excluded. Articles in dissertations, books, or as conference abstracts without access to full-texts were excluded.

Based on the eligibility criteria, some filters were applied to each database in order to rule out irrelevant results. The filter of “English” was applied to all databases. The filter of “Human(s)” was used in CINAHL, PubMed and PsycINFO. As for the age group, applicable filters indicating adult subjects were implemented. Based on the definition of adult (>18 years old) (Sawyer et al., 2018), the filters were “adult: >=19 years old” in CINAHL and PubMed and “adult: >=18 years old” in PsycINFO. The search engine Web of Science did not have a limit of subject age, so no filter was applied. A filter of “peer-reviewed” was applied to CINAHL and PsycINFO in order to extract articles that were peer reviewed. Since there was not a limitation of “peer-reviewed” articles in Web of Science and PubMed, no extra filter was applied.

Data Extraction and Analysis

Selection and Characteristics of Studies

One reviewer (Y.L.) independently read the titles and abstracts of identified publications from the initial search to eliminate irrelevant studies. The full-text for the studies that were to be reviewed was obtained. To reduce the selection bias and information bias, two reviewers (Y.L.

and T.K.) independently examined potentially relevant full-text studies based on the predetermined criteria and decided which articles to be included based on those most relevant to the purposes. The evidence has shown that an additional 6.6% to 11.9% of eligible studies could be identified when the full texts of articles were screened by two reviewers (Stoll et al, 2019). Any disagreements on the selection of studies were resolved through discussion between the two reviewers. General information of the studies was extracted including study design, purposes, sample size, participant characteristics, intervention characteristics, intervention outcomes, and the measurements used to assess bimanual coordination.

The procedure of reporting of this review followed the PRISMA 2020 Checklist (Page et al., 2021; Appendix B) as it included what was generally used to assess the accuracy of the process related to a systematic review. This checklist guided the review to improve transparency which covered all aspects of the manuscript, including the title, abstract, introduction, methods, results, discussion (Page et al., 2021). Since this review was not a meta-analysis, the items that were associated with the reporting of a meta-analysis were marked as not applicable (N/A).

To ensure accuracy and reproducibility in the review approach, a Preferred Reporting Items for Systematic and Meta-Analysis (PRISMA) flowchart was used (Page et al., 2021). This flowchart depicted the flow of information through the different stages of this review. It was used to map out the number of records identified, included, and excluded, as well as the reasons for exclusions. The flowchart was modified in this review. First, the number of articles that were retrieved from each database were listed, instead of a total number from all databases. In order to retrieve high-quality articles with reliable and peer-reviewed content, the search was limited to the databases only. Information from other sources such as registers, websites, organizations, citation searching that are in the original chart were not included.

Examining Methodological Approaches to Bimanual Coordination

In addition to the general characteristics of studies, the key issue to be examined in this review was the methodologies used in measuring the nature of bimanual coordination and control. Appropriate aspects of extraction included task characteristics (i.e., symmetrical or asymmetrical, discrete or continuous), the use of kinematic measures including product measures, and the use process measures (i.e., correlations and angle-angle plots). This procedure was necessary since it guided the data synthesis and improved the quality of reporting.

The specific dependent variables used to examine the nature of bimanual coordination and control was further categorized and examined. Given the methodologies commonly used in the broad field of studies that examined bimanual coordination in discrete actions, the measures were divided into product and process measures. Based on the scope of this review, clinical measures were also summarized as part of the product measure since it demonstrated the current use of various types of scales. Further categories were made for kinematic analysis, as the temporal and spatial domains of coordination and control were of importance to investigate. Inferences about stability and flexibility of spatiotemporal relations between two arms were also investigated.

Examining Theoretical Foundations in Bimanual Coordination Interventions

This study also examined if related theoretical frameworks or motor control theories were applied to the study design, outcomes, or interpretations. Any theoretical framework or motor control theory that related to bimanual coordination, such as theory of coordinative structure, the HKB model, and the dynamic system approach were included and reviewed.

A Checklist of Methodological Approaches and Theoretical Foundations

The research questions of this review were specified and summarized into a checklist (Table 1). This checklist has been tailored to be consistent with the purposes, in order to classify the methodologies for investigating bimanual coordination and control in stroke interventions. Articles were evaluated by this checklist and the results of the evaluation were presented in the tables in Appendices E and F.

There were two parts of this checklist assessment tool that examined the methodologies and theoretical basis. The items in Part A focused on the methodological aspect of the research in post stroke rehabilitation which trained or facilitated bimanual function. Questions 1 checked if bimanual discrete movements were examined in the outcome measure. Question 2 examined if kinematic analysis was utilized before and after the intervention in order to detect changes in arm function. Questions 3 and 4 identified if either correlations or angle-angle plots was used to measure interlimb coupling. Question 5 checked if temporal and spatial control was also measured.

The items in Part B examined if related theoretical frameworks or motor control theories were applied to study, indicating that the article was theory-driven. Thus, questions 6-8 checked if a theoretical framework of motor control was applied to the intervention protocols, the outcome measurements, results, or interpretation of the results in the conclusion and discussion.

Table 1

Checklist for methodological approach to bimanual coordination

CHECKLIST FOR METHODOLOGICAL APPROACH			
	Part A. The Methodological Aspect of Research	***Yes***	***No***
1	Were bimanual discrete movements performed by the participants when intervention outcomes were evaluated? If not, what types of tasks were implemented?		
2	Was kinematic analysis conducted in outcome measures to examine bimanual coordination and control of stroke participants after rehabilitation?		
3	Were correlations used to measure the temporal and spatial coupling in outcome measure?		
4	Were angle-angle plots created to describe the spatial coupling in joint pairs across two arms?		
5	Were the temporal and spatial control measured via kinematic analysis in both arms?		
	Part B: The Theoretical Aspect of Research		
6	Was any theoretical framework of bimanual coordination referred to by the study to create intervention protocols?		
7	Was any theoretical framework referred to by the study to guide the measurement of interlimb coupling, but not limited to the theories and models mentioned in the literature review?		
8	Was any theoretical framework referred by the study to support the results and the discussion/conclusion of the study?		

Quality Assessment

Quality Assessment for Selected Studies

A quality assessment was carried out using the Downs and Black tool (Downs & Black, 1998; see Appendix C). This assessment tool was designed to examine the quality of study reporting, external validity, internal validity, as well as statistical power. The Downs & Black scale has been ranked in the top six quality assessment scales that are suitable for use in systematic reviews (Samoocha et al., 2010). As has been done in other reviews using the Downs and Black Scale, the tool was slightly modified for use in this review. The scoring of question 27 dealing with statistical power was simplified to a choice of awarding either 1 or 0 points depending on whether there is sufficient power to detect a clinically important effect (Samoocha et al., 2010). Thus, this question was adapted by the author in terms of whether the authors of the study provided any information concerning a sample size calculation, or whether they expressed any information concerning alpha and beta error and provided information about the effect they regarded as important to be detected. The maximum score of item 5 was changed from a maximum score of 2 to a score of either 1 or 0. Downs and Black score ranges were grouped into good (>19), fair (15-19), and poor (<15).

Quality Assessment for This Review

A quality assessment tool for checking the quality of the current review was included. The tool was the upgraded version of the "A MeaSurement Tool to Assess systematic Reviews (AMSTAR) scale (AMSTAR-2, see Appendix D) (Shea et al., 2017). AMSTAR-2 was a 16-item assessment tool that evaluated systematic reviews of both randomized and non-randomized studies of healthcare interventions (Shea et al., 2017). AMSTAR-2 has been reported as an effective tool for assessing the quality of systematic reviews and its reliability and validity have been verified (Perry et al., 2021). The use of AMSTAR-2 ensured the methodological quality of this review according to self-evaluation. According to the authors of AMSTAR-2, it is not intended to generate an overall score (Shea et al., 2017).

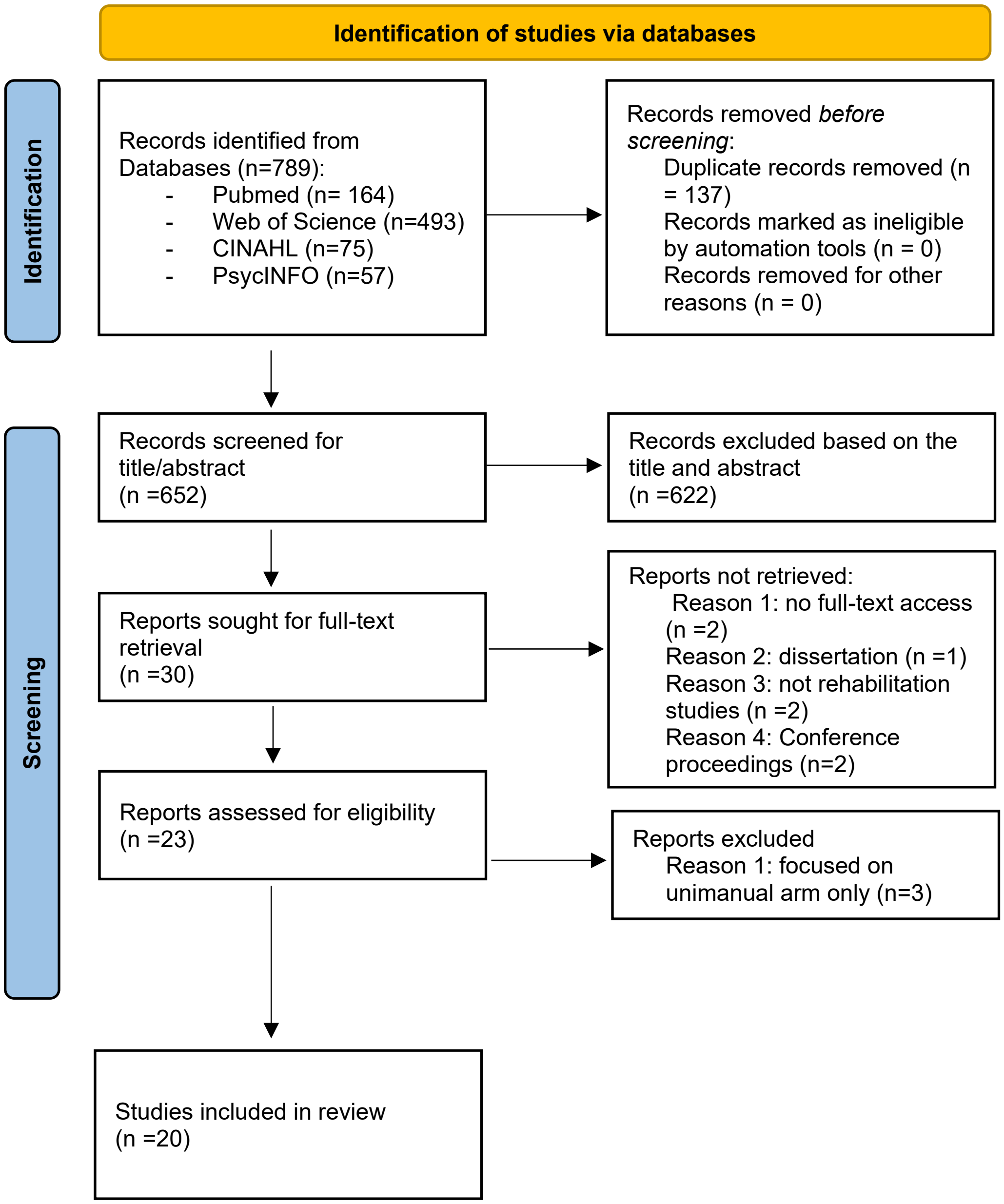
Results

Search Results

The search yielded 789 titles/abstracts across the four databases. After the elimination of duplicates, 652 titles/abstracts remained for analysis. These abstracts were obtained, and the author (Y.L.) assessed them based on the inclusion criteria. Among the 652 abstracts, 622 records were excluded. After the initial screening, 30 possibly relevant abstracts were retrieved for full-text screening. Two reviewers (Y.L.) and (T.K.) independently screened the full text of 30 articles. As a result of this review, seven additional studies were excluded. Two abstracts did not have full-text access, two articles were not rehabilitation studies, one article was a dissertation, and two articles were conference proceedings. Based on the inclusion criteria "stroke interventions that aimed to facilitate bimanual coordination," three more articles were excluded since they only focused on the motor function of the paretic arm (Finley et al., 2005; MacClellan et al., 2005; Masiero et al., 2011). At the end of the screening, 20 eligible articles were included in this review for further analysis. Among them, there were 15 randomized controlled trials (RCTs), four pilot studies (Ambreen et al., 2021; Jung et al., 2013; Pandian et al., 2015; Whitall et al., 2000), and one cohort study (Change et al., 2007). The years of publication ranged between 2000 and 2022. The screening and selection process is presented in a PRISMA flowchart (Figure 7). For the summary of descriptive information of all included studies, please see Appendix E.

Figure 7

PRISMA 2020-2022 flowchart for the systematic review



Quality Assessment

The quality of each study was assessed by the Downs & Black Scale (Downs & Black, 1998). Out of the 20 studies examined, seven studies were of good quality, scoring between 19-21 points (Arya et al., 2019; Burgar et al., 2011; Kale et al., 2019; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Whitall et al., 2011). Eight studies were considered as fair quality, scoring 15-18 points (Ambreen et al., 2021; Chang et al., 2007; Gerardin et al., 2022; Kim & Park, 2019; Liao et al., 2011; Waller et al., 2008; Wu et al., 2007; Wu et al., 2011), and five studies were classified as poor quality, scoring from 11-14 points (Cauraugh & Kim, 2002; Cauraugh et al., 2009; Doost et al., 2021; Jung et al., 2013; Whitall et al., 2000). The score of each study is listed in Appendix E.

The quality of the current review was evaluated by the first author using the AMSTAR-2 (Appendix D). The quality of the review was moderate quality by rating overall confidence (Shea et al., 2017). This indicates that this review has more than one weakness, no critical flaws, and may provide an accurate summary of the results in the included studies.

Characteristics of Design and Samples

In regards to the sampling approaches, 14 studies combined purposive and convenience sampling (Ambreen et al., 2021; Burgar et al., 2011; Change et al., 2007; Doost et al., 2021; Gerardin et al., 2022; Jung et al., 2013; Kale et al., 2019; Liao et al., 2011; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2007), whereas the rest implemented purposive sampling alone.

In all studies reviewed, 18 recruited post-stroke participants exclusively, while two included both stroke and healthy participants (Doost et al., 2021; Gerardin et al., 2022). The lowest reported mean age of stroke participants was 43.1 years old (Pandian et al., 2015), and the highest mean age was 67.2 years old (Cauraugh et al., 2009). In terms of gender, except for one study that did not report the relative data (Burgar et al., 2011), the rest of the studies involved mix samples of both males and females. The age as well as gender factors were not manipulated in any of the studies reviewed.

Regarding the time since stroke, the majority of the studies included participants who had a stroke more than six months prior, thus they were at the chronic stage of stroke. Participants included in the study by Burgar et al. (2011) were at the earliest stage of stroke recovery, which was 9-20 days post-stroke. One study included participants at the sub-acute stage of recovery, in which the mean time after stroke was 9.4 weeks (Van Delden et al., 2015). Three studies included both subacute and chronic stages of stroke participants (Ambreen et al., 2021; Kale et al., 2019; Pandian et al., 2015). The rest of the studies included chronic stroke patients only. In terms of the research design, time since stroke was not an independent variable in any of the studies examined.

In regards to the stroke type, participants with ischemic stroke were exclusively included in three studies (Ambreen et al., 2021; Burgar et al., 2011; Waller et al., 2008), while six studies recruited participants with hemorrhagic and ischemic stroke (Arya et al., 2019; Doost et al., 2021; Jung et al., 2013; Kim & Park, 2019; Lin et al., 2015; Pandian et al., 2015). The remaining 11 studies did not identify the types of stroke that the participants were diagnosed with (Cauraugh & Kim, 2002; Cauraugh et al., 2009; Chang et al., 2007; Gerardin et al., 2022; Kale et al., 2019; Liao et al., 2011; Van Delden et al., 2015; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2007; Wu et al., 2011). In terms of the sample sizes, they ranged from 14 participants (Whitall et al., 2000) to 111 participants (Whitall et al., 2011). However, only three studies included more than 50 participants (Burgar et al., 2011; Whitall et al., 2011; Wu et al., 2011). In regards to power analysis, seven studies incorporated the calculation (Cauraugh et al., 2009; Kim & Park, 2019; Liao et al., 2011; Lin et al., 2015; Van Delden et al., 2015; Wu et al., 2007; Wu et al., 2011), and 11 studies did not explicitly state if a power analysis was conducted (Ambreen et al., 2021; Burgar et al., 2011; Cauraugh & Kim, 2002; Chang et al., 2007; Gerardin et al., 2022; Jung et al., 2013; Kale et al., 2019; Pandian et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011). In addition, two studies explicitly stated that no power analysis was conducted (Arya et al., 2020; Doost et al., 2021).

Rehabilitation Approaches

This review also identified three types or categories of interventions, including bimanual movement training implemented in 14 studies (Ambreen et al., 2021; Arya et al., 2019; Cauraugh & Kim, 2002; Cauraugh et al., 2009; Jung et al., 2013; Kale et al., 2019; Kim & Park, 2019; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2011), bimanual robot-assisted training used in five studies (Burgar et al., 2011; Chang et al., 2007; Doost et al., 2021; Gerardin et al., 2022; Liao et al., 2011), and constraint-induced movement training implemented in four investigations (Kale et al., 2019; Van Delden et al., 2015; Wu et al., 2007; Wu et al., 2011). Also, in the 14 studies that examined bimanual movement training, six studies combined supplementary protocols, including bimanual training and an EMG-triggered neuromuscular stimulation approach (Cauraugh & Kim, 2002; Cauraugh et al., 2009) and bilateral arm training with rhythmic auditory cueing (Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011).

Of the 20 eligible studies, three types of research designs were identified. They included randomized controlled trials (Arya et al., 2019; Burgar et al., 2011; Cauraugh & Kim et al., 2002;

Cauraugh et al., 2009; Doost et al., 2021; Gerardin et al., 2022; Kale et al., 2019; Kim & Park, 2019; Liao et al., 2011; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2011; Wu et al., 2007; Wu et al., 2011), quasi-experimental studies (Ambreen et al., 2021; Jung et al., 2013; Whitall et al., 2000), and a longitudinal study (Chang et al., 2007). The effectiveness of different approaches, namely bimanual training and constraint-induced training was addressed in three studies (Kale et al., 2019; Van Delden et al., 2015; Wu et al., 2011). In addition, eight RCTs compared the impact of rehabilitation protocols with conventional therapy (Arya et al., 2019; Burgar et al., 2011; Liao et al., 2011; Lin et al., 2015; Pandian et al., 2015; Waller et al., 2008; Whitall et al., 2011; Wu et al., 2007). Furthermore, the effectiveness of bimanual robot-assisted training between stroke participants and healthy subjects as a control group was compared in two RCTs (Doost et al., 2021; Gerardin et al., 2022). The longitudinal study recruited a cohort of stroke patients and implemented a training program that combined robot-assisted bimanual training and conventional therapy (Chang et al., 2007).

In terms of the internal validity of the designs, six studies implemented a retention test (Burgar et al., 2011; Chang et al., 2007; Doost et al., 2021; Van Delden et al., 2015; Whitall et al., 2000; Whitall et al., 2011), and one study implemented a transfer task (Gerardin et al., 2022). The rest of the studies included a simple repeated measures (pre vs post) design.

In regards to the ecological validity of the tasks/activities implemented in the protocols, the studies could be classified as those involving highly controlled laboratory-based tasks (Burgar et al., 2011; Cauraugh & Kim, 2002; Cauraugh et al., 2009; Chang et al., 2007; Doost et al., 2021; Gerardin et al., 2022; Liao et al., 2011; Lin et al., 2015; Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011) and functional ADLs (Ambeen et al., 2021; Ambeen et al., 2019; Jung et al., 2013; Kale et al., 2019; Kim & Park, 2019; Liao et al., 2011; Pandian et al., 2015; Wu et al., 2007; Wu et al., 2011).

Methodological Aspect of Research

Task Constraints

Two types of bimanual tasks were utilized to assess the changes in arm motor function. One type of task can be broadly classified as discrete movements. These were incorporated into five studies (Burgar et al., 2011; Jung et al., 2013; Waller et al., 2008; Wu et al., 2007; Wu et al., 2011). More specifically, bimanual symmetrical reaching was implemented in three studies (Burgar et al., 2011; Jung et al., 2013; Waller et al., 2008) where the participants were asked to move two arms simultaneously in the forward direction from the side of the table to a target in these tasks. An asymmetrical bimanual task, which involved opening a drawer with the affected arm and retrieving an object with the unaffected arm, was used in two studies (Wu et al., 2007; Wu et al., 2011).

In addition to bimanual discrete tasks, three studies implemented bimanual continuous tasks (Doost et al., 2021; Gerarhin et al., 2022; Van Delden et al., 2015). The rest of the included studies (12 out of 20) did not measure any bimanual discrete or continuous tasks before or after the intervention (Ambreen et al., 2021; Arya et al., 2019; Cauraugh & Kim, 2002; Cauraugh et al., 2009; Chang et al., 2007; Kale et al., 2019; Kim & Park, 2019; Liao et al., 2011; Lin et al., 2015; Pandian et al., 2015; Whitall et al., 2000; Whitall et al., 2011). In one study, participants needed to rotate two handles of robotic devices by circular mirror bilateral movements in order to lift a tray on the screen (Doost et al., 2021). In another task the participant was asked to control a cursor on the screen via two robotic handles, in which each hand moved in a single axis via either right-left or front-back motions (Gerardin et al., 2022). In addition, bimanual rhythmic wrist flexions and extensions in in-phase and anti-phase patterns were incorporated in one study (Van Delden et al., 2015). In the in-phase pattern, participants were instructed to flex both wrists with auditory beeps that were a part of a rhythmic auditory signal. For the anti-phase pattern, peak flexion of one hand and peak extension of the other hand needed to coincide with the auditory signal (Van Delden et al., 2015). None of these studies, however, examined the stability and flexibility of interlimb coupling as the respective control parameters (e.g., frequency of oscillation) were not manipulated.

Dependent Variables

Clinical Scales

A variety of clinical scales were identified as the measure of functional gains before and after interventions. Except for Van Delden et al. (2015), who only implemented kinematic analysis, 19 studies utilized at least one clinical scale in the baseline and post-intervention assessment. Within these studies, nine implemented clinical scales as the only outcome measure of interest (Ambreen et al., 2021; Arya et al., 2019; Cauraugh & Kim, 2002; Cauraugh et al., 2009; Kale et al., 2019; Kim & Park, 2019; Liao et al., 2011; Lin et al., 2015; Pandian et al., 2015). The remaining studies implemented clinical scales as well as kinematic analysis. Among the studies which used clinically-derived outcomes measured with a scale, 20 different scales were identified. They were categorized into those that evaluated the overall motor function, fine or gross motor function, motor-cognitive function, and the performance of ADL. In addition, they were further classified as performance-based, clinician-reported, and self-reported scales.

The overall motor function in upper extremity was examined in seven scales, which can be further subdivided as clinician-reported and performance-based measures. The clinician-reported scales included the Ashworth scale (Burgar et al., 2011; Chang et al., 2007), Brunnstrom Recovery Stages (Pandian et al., 2015), and the Fugl-Meyer Assessment-Upper Limb (Ambreen et al., 2021; Arya et al., 2019; Burgar et al., 2011; Chang et al., 2007; Gerardin et al., 2022; Liao et al., 2011; Lin et al., 2013; Pandian et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011). Furthermore, the Action Research Arm Test (Kale et al., 2019; Kim & Park, 2019), Motor Assessment Scale (Lin et al., 2015), and Wolf Motor Function Test (Ambreen et al., 2021; Burgar et al., 2011; Lin et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2011) were based on the performance of a set of movements or tasks.

Gross motor function was investigated via performance-based scale, Box and Block Test (Cauraugh & Kim, 2002; Cauraugh et al., 2009; Doost et al., 2021; Gerardin et al., 2022), and two clinician-reported measures included Manual Muscle Testing (Pandian et al., 2015) and Minnesota Manual Dexterity Test (Pandian et al., 2015). In regards to the fine motor function, the Nine Hole Peg Test specifically measured finger dexterity (Kale et al., 2019). In addition, the Purdue Pegboard Test evaluated gross motor function of the arms, hands, and fingers as well as fine fingertip dexterity according to the performance of a pin-placing test (Lin et al., 2015).

In terms of motor-cognitive function, the performance-based Function Independent Measure (Burgar et al., 2011; Liao et al., 2011; Wu et al., 2007), and self-reported Stroke Impact Scale (Gerardin et al., 2022; Kim & Park, 2019; Whitall et al., 2011) evaluated both motor and cognitive aspects of recovery in individuals with stroke. The Montreal Cognitive Assessment, a clinician-reported assessment, specifically evaluated cognitive function in order to determine if cognitive impairment was present (Gerardin et al., 2022).

The scales that assessed the quality of performing ADLs consisted of ABILHAND (Gerardin et al., 2022; Liao et al., 2011), Barthel Index (Lin et al., 2015), Canadian Occupational

Performance Measure (Jung et al., 2013; Kim & Park, 2019), Frenchay Arm Test (Chang et al., 2007), modified Rankin Scale (Arya et al., 2019), and Motor Activity Log (Jung et al., 2013; Liao et al., 2011; Wu et al., 2007; Wu et al., 2011). Among these scales, Frenchay Arm Test was performance-based scale and modified Rankin Scale was clinician-reported, while the others were all self-reported assessments.

Kinematic Analysis

In addition to the clinical scales that were utilized as outcome measures, eight studies implemented kinematic analysis (Chang et al., 2007; Jung et al., 2013; Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2007; Wu et al., 2011). However, only two studies evaluated the nature of movement organization between the arms via product (Waller et al., 2008) and process measures (Van Delden et al., 2015). The rest of the studies examined the paretic arm only in either unimanual tasks (Chang et al., 2007; Jung et al., 2013; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2007; Wu et al., 2011) or bimanual tasks (Jung et al., 2013; Wu et al., 2007; Wu et al., 2011).

Product Measures: Spatial Control

Spatial control was investigated in 6 out of 20 studies (Jung et al., 2013; Van Delden et al., 2015; Waller et al., 2008; Whitall et al., 2000; Whitall et al., 2011; Wu et al., 2007). Only Waller et al. (2008) measured the spatial control for both arms, while the other four studies measured the paretic arm only. In terms of end-effector space, two studies examined movement straightness of the paretic arm (Jung et al., 2013) and both arms (Waller et al, 2008) as inferred from the endpoint trajectory ratio. The total displacement of the paretic hand path in 3-dimensional space was examined in a bimanual asymmetrical task and a unimanual pointing task in one study (Wu et al., 2007). In terms of joint space analysis, the measure of spatial control consisted of two dependent variables, the mean amplitude and range of motion. The mean amplitude, which was the distance between peak extension and peak flexion divided by 2, was measured to assess the range of motion of the wrist joint on the affected side of the body (Van Delden et al., 2015). Two studies measured the range of motion of the shoulder, elbow, wrist, and thumb on the paretic side of the body (Whitall et al., 2000; Whitall et al., 2011).

Product Measures: Temporal Control

Temporal control was measured in 5 out of 20 studies (Chang et al., 2007; Jung et al., 2013; Waller et al., 2008; Wu et al., 2007; Wu et al., 2011). One study examined both arms before and after the intervention (Waller et al., 2008), while the other four studies evaluated the temporal control of the paretic arm only (Chang et al., 2007; Jung et al., 2013; Wu et al., 2007; Wu et al., 2011).

The dependent variables that examined temporal control can be further grouped into measures of velocity and measures of movement smoothness. Regarding the velocity measures, kinematic derivatives examined the issues of temporal control in end effector space included movement time (Chang et al., 2007; Waller et al., 2008; Wu et al., 2007; Wu et al., 2011), peak velocity (Chang et al., 2007; Jung et al., 2013; Waller et al., 2008), the percentage of time to peak velocity (Chang et al., 2007; Wu et al., 2007; Wu et al., 2011), mean velocity (Jung et al., 2013) and peak acceleration (Waller et al., 2008). Movement smoothness, representing the discontinuity and segmentation of the movements, was evaluated by the jerk score (Chang et al., 2007) and the number of movement units (Waller et al., 2008; Wu et al., 2011). None of the studies examined the issues of temporal control in joint space.

Process Measure of Bimanual Coupling

The coordinative relations between two arms can be measured qualitatively and quantitatively, in order to investigate the nature of interlimb coupling in emerging movements.

Qualitative Measures. None of the studies examined in this review implemented angle-angle plots in order to infer the qualitative nature of bimanual coupling.

Quantitative Measures. Only one study calculated the cross-correlation coefficient as the measure of the strength of temporal coupling between two arms (Van Delden et al., 2015). In this study, the bimanual task involved rhythmic wrist extension and flexion and the independent variable was the amplitude of two wrists. A positive correlation coefficient between both hands indicated an in-phase pattern, whereas a negative value indicated an antiphase pattern (Van Delden et al., 2015). A positive lag of the highest absolute value of the cross-correlation coefficient represented that the non-paretic hand was leading the paretic hand in time, whereas a negative lag was for a reverse situation. On the other hand, in terms of the interlimb coupling in bimanual discrete movements, none of the studies calculated a correlation coefficient.

Theoretical Aspect of Research

The degree to which the studies implemented theories of motor control was generally low since none of the studies were identified as theory-driven research. One study explicitly framed its training protocol within the dynamic system approach (Cauraugh & Kim, 2002). In the training sessions, participants performed in-phase wrist-finger extensions in order to improve bimanual coordination. In line with the prediction of the HKB model, in-phase movement pattern would keep stable in which two wrists executed the same movement simultaneously (Cauraugh & Kim, 2002). However, the methodology of this study was not aligned with the dynamic system approach since the order parameter (relative phase) and interlimb coupling were not examined. Thus, this study was not classified as theory-driven research.

In addition, some studies implicitly referred to motor control concepts such as interlimb coupling (Arya et al., 2019; Cauraugh et al., 2009; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Wu et al., 2011), coordinative structures (Cauraugh & Kim, 2002; Pandian et al., 2015; Whitall et al., 2000; Whitall et al., 2011) and Fitts' law as applied to bimanual discrete actions (Waller et al., 2008). However, the methodological considerations and results of these studies were not explicitly discussed in the context of the related theory. The rest of the studies were data-driven research, in which the authors did not explicitly or implicitly mention any related theoretical frameworks or concepts of motor control (Ambreen et al., 2021; Burgar et al., 2011; Chang et al., 2007; Jung et al., 2013; Kale et al., 2019; Kim & Park, 2019; Liao et al., 2011; Wu et al., 2007).

Discussion

This systematic review aimed to investigate the methodologies and related theoretical frameworks in studies that focused on improving bimanual coordination in individuals with stroke. Overall, the review included 20 studies based on the eligibility criteria. Suggestions were made, in terms of methodological and theoretical considerations, to enhance future research in this domain.

Sample Characteristics

In terms of the sampling approaches implemented, 14 studies utilized both purposive and convenient sampling, and the rest implemented purposive sampling alone. Purposive sampling can enhance internal validity as specific inclusion/exclusion criteria assures homogeneity of the sample. This is particularly relevant in rehabilitation research in order to avoid a person x treatment interaction, where the program affects some but not all participants. Due to the fact that such an effect is often difficult to delineate in factorial designs, assuring the homogeneity of the sample represents an important methodological criterion.

In terms of the age of the participants, this factor was not considered as an independent variable in the design of any of the reviewed studies. This is an important issue as often the age of the participants spanned more than 20 years, on average. Considering that the prevalence of the stroke is rising among younger adults, the effects of different rehabilitation approaches may be age specific. In a similar context, sex of the participants was also not included in the designs as an independent variable. Stroke could have a greater impact on females than males since women have poorer functional recovery and lower quality of life after stroke (Rexrode et al., 2022). Again, this could jeopardize the internal validity of the inferences, as it is likely that both males and females, even when exhibiting similar post-stroke symptoms and limitations, may have different recovery trajectories.

In regards to the stage of post-stroke recovery, 15 studies recruited individuals who were characterized as chronic, while three studies included stroke patients who were classified as both chronic and sub-acute. In another two studies, acute and sub-acute stroke participants were recruited. From the motor functioning standpoint, the perceptual-motor status of chronic stroke patients was relatively stable. Versus, when an individual is considered to be in the acute or subacute stage of recovery, the motor performance may be more variable (Hatem et al., 2016). Kim and Kang (2020) reported that a greater time since stroke onset was associated with more bimanual coordination impairments, thus suggesting that the nature of gains resulting from a rehabilitation may also vary.

In terms of the sample sizes, only three studies included more than 50 participants. In addition, a power analysis was only conducted in seven studies. From the practical standpoint, smaller sample sizes are to be expected, as often it is difficult to find participants who are willing to engage in frequent and often extensive rehabilitation programs, even if it should enhance their well-being. On the other hand, the lack of statistical power analysis prior to the commencement of the study, represents an important issue in hypothesis testing for both parametric and non-parametric analyses. The possibility of Type 2 error, or the risk of a false negative, represents a critical concern because a particular treatment could have a positive impact, yet its effect cannot be shown statistically. An alternative approach, which unfortunately is rarely incorporated, is to examine the effects of the program at the individual level. In this case, rather than relying on the probabilistic statements emerging from the inferential analysis, the effectiveness of the program can be documented at the level of a “person”, rather than the mean of the group. This approach could be particularly useful when the study involves a relatively small number of participants. Implementation of the effect size measures in simple (d-statistics), factorial (eta-squared) or correlational studies (coefficient of determination) may represent an alternative approach in order to delineate if the observed effects are meaningful statistically as well as clinically.

Methodological Aspects of Rehabilitation Studies

An important constraint that affects the nature of the emerging behaviour, and in this case the outcomes of a rehabilitative approaches, is related to the tasks incorporated in a particular training protocol. Also, the nature of the dependent variables capturing the emerging outcomes and coinciding movement process are important. Both of these areas will be considered and discussed in the following sections.

Tasks

Ecological Validity

As part of the training protocols, tasks in the rehabilitation programs could be classified according to their ecological validity, or representation of how performance predicts behaviour in real-world settings (Schmuckler, 2001). Among the studies included in this review, nine of them used functional ADLs as the training protocol. These activities were related to the ability of the person to carry out tasks in real-life settings. The rest of the tasks were laboratory-based thus it remains unclear if the gains achieved in those tasks are transferable to the performance of actions involved in daily routines. In motor learning studies the issue of generalizability is often addressed by incorporating transfer tasks. However, none of the present studies reviewed implemented such an approach.

Symmetrical and Asymmetrical Tasks

An important constraint on the nature of the emerging coordination as well as control is the degree of symmetry implemented in the tasks being measured or practiced. This is true for continuous actions, and even more so in discrete tasks which are the main focus of the following discussion. In bimanual discrete actions, the notion of coupling is of essential importance. The ability to modulate relations between moving limbs is dependent on individual constraints, and maybe even more importantly, the goal of the task itself. Depending on the task constraints, the degree of interlimb coupling is varied. In symmetrical actions, tight interlimb coupling, in both the spatial and temporal domains, is an indication of effective coordination whereas in asymmetrical actions, the coupling strength between two arms is expected to vary. When asymmetrical tasks are examined, it is difficult to hypothesize what degree of coupling, or decoupling, should be viewed as effective, thus often measures of stability or the functionality of the resulting outcomes are used to infer the effectiveness of the emerging action.

In three of the studies included, a bimanual symmetrical task was used as the outcome measure. In such a task, the participants were required to reach forward with two arms simultaneously (Burgar et al., 2011; Jung et al., 2013; Waller et al., 2008). Control of bimanual reaching was examined in the paretic arm (Burgar et al., 2011; Jung et al., 2013), resulting in shorter movement time, less movement units, and higher peak acceleration of the affected side. When both arms were involved, a straighter, more symmetrical trajectory ratio were reported as a result of training (Waller et al., 2008). Unfortunately, bimanual coordination was only examined in only one study via process measures (Waller et al., 2008). Thus, inferences about the strength of interlimb coupling in symmetrical tasks were insufficiently investigated before and after stroke rehabilitation.

In two studies, bimanual asymmetrical tasks were implemented where the participants needed to open a drawer with the affected arm and retrieve an object with the unaffected arm (Wu et al., 2007; Wu et al., 2011). Compared to symmetrical reaching, this asymmetrical task requires the participants to decouple two arms since the affected arm needs to reach and pull the drawer, while the unaffected arm is reaching, grasping, and transporting an object. Similar to the studies involving symmetrical actions, only performance of the paretic arm was examined. The results revealed that the velocity as well as percentage of time to peak velocity, and peak velocity were enhanced after training (Wu et al., 2007, 2011). Collectively, the studies involving bimanual symmetrical and asymmetrical tasks failed to examine the nature of inter-limb coordination but confirmed that the involvement of a paretic arm in a bimanual context had a positive impact on its spatial and temporal control.

Kinematic Measures

Kinematic analysis can detect even subtle changes in coordination and control. Thus, such approaches have an important role in the rehabilitation process in order to detect statistical and clinical change (Murphy & Häger, 2015). Among the reviewed studies, less than half implemented kinematic analysis as the primary measures of interests. When kinematic measurements were used, broadly speaking they were used to examine the nature of movement product as well as process.

Product Measures

Conceptually speaking, kinematics descriptors of product allow making inferences about movement control relative to an underlying theory, in both the spatial and temporal domains. In order to examine spatial control, linear displacement or distance of the end-effector can be quantified, as well as the angular displacement of the individual’s joints. Among the reviewed studies, five investigated the issue of spatial control. The analysis of trajectory ratio provided contradictory results as one study confirmed improvements in the hand trajectory of the paretic arm (Waller et al., 2008), whereas the other analysis failed to confirm such an effect (Jung et al., 2013). In regards to task constraints, these two studies implemented a unimanual reaching (Jung et al., 2013) and a bimanual reaching (Waller et al., 2008) task respectively, which could account for the difference in the trajectory ratio of the paretic arm.

Kinematic changes in the temporal domain represent another important aspect of motor performance in the context of manual self-paced tasks such as reaching and grasping. The relevant measures are derived from velocity profiles, such as peak velocity, time to peak velocity, and peak acceleration. In this review, five studies investigated the issue of temporal control mechanisms via measures of velocity and movement smoothness such as jerk scores and the number of movement units. Across all the intervention programs implemented, significant improvements were found in the smoothness measures of the paretic arm after rehabilitation. These findings were robust as they emerged across stroke participants who were involved in different rehabilitation programs (e.g., BAT, BATRAC, and CIMT) and performed different tasks (e.g., bimanual symmetrical and asymmetrical reaching).

Process Measures

Process measures allow making inferences about the nature of the spatial and temporal coupling between the arms as via qualitative (angle-angle plots) and quantitative (correlations) methodological approaches. In regard to correlations, only one study implemented this approach in the pre- and post- design, while the angle-angle plots were not used in any of the reviewed studies. This fact indicates that although implicitly the studies aimed at examining the nature of the emerging coordination tendencies, the methodologies implemented failed to address these issues explicitly.

In the study that included correlations, the authors examined interlimb coupling in bimanual continuous actions (Van Delden et al., 2015). Individuals with stroke were assigned to three experimental groups, including BATRAC, CIMT, and dose-matched control treatment, and all subjects were required to perform rhythmic wrist extensions and flexions. Cross-correlations were calculated for both the in-phase and anti-phase modes, before and after the interventions. As expected, results showed that interlimb coupling was significantly stronger during the in-phase mode than during the anti-phase mode across all measurements (Van Delden et al., 2015). This is consistent with the predictions of the HKB model (Kelso, 1984). In the pre- and post-assessments, improvements of the in-phase coupling strength were significant only in the control group and bimanual arm training group. In addition, the coupling of the anti-phase mode was not improved significantly in any groups. These results indicated that the therapeutic effects of bimanual arm training were limited. Furthermore, the improvement in the coupling strength did not necessarily result from the bimanual arm training.

Theoretical Approaches to the Design of Bimanual Rehabilitation after Stroke

In the field of motor control, theories are essential as they afford researchers to postulate the mechanisms underlying the emerging behavior. Also, theoretical models allow researchers to delineate the constraints under which motor behaviour changes, as well as allow predictions of the relationship between different constraints and emerging motor behavior (e.g., reaching and grasping). In rehabilitation research, theory can provide a framework to understand the relationship between intervention inputs, how the intervention is designed and implemented, and the corresponding outcomes (Davis et al., 2015).

Based on the current review, none of the studies were classified as theory driven as they were not explicitly linked to any explicit conceptual frameworks. One study designed the training protocol in the context of the dynamic system approach, but the methodologies and results were not explicitly discussed within the implications of the HKB model and dynamic systems approach (Cauraugh & Kim, 2002). In addition, the nature (degree and stability) of interlimb coupling was not examined and control parameters were not manipulated to make inferences about the stability or flexibility in the emerging temporal adaptations.

Several studies included well known motor control constructs as related to study of coordination or control, such as bimanual coupling (Arya et al., 2019; Cauraugh et al., 2009; Lin et al., 2015; Pandian et al., 2015; Van Delden et al., 2015; Wu et al., 2011), coordinative structures (Cauraugh & Kim, 2002; Pandian et al., 2015; Whitall et al., 2000; Whitall et al., 2011), and Fitts' law in bimanual discrete actions (Waller et al., 2008). However, these concepts were only referred to as a justification for implementing bimanual arm training, and the corresponding conceptual and methodological assumptions were not implemented. As a result, the applied field of stroke rehabilitation did not sufficiently incorporate fundamental motor control theories into the purpose and hypothesis of these studies. From a philosophical standpoint, conducting studies for the collection of data or knowledge is not meaningful unless the result is synthesized within related theories for better understanding. In essence, collecting or creating data without a theoretical framework or the intention of conducting deductive research defeats the purpose of the study (Fischman, 2011; Forscher, 1963). Without underlying theories, empirical investigations contribute little to the current understanding of bimanual coordination in stroke rehabilitation.

Strength and Limitation of Current Review

This systematic review aimed to explore studies related to post-stroke arm rehabilitation and bimanual coordination in individuals who had stroke. The methodological and theoretical approaches were investigated in this review. The eligibility criteria ensured a detailed analysis of methodological and theoretical considerations in studies of upper-extremity rehabilitation. Having multiple reviewers in the study selection procedure was also a strength, where the risk of bias was reduced by having more than one author choose and review potential articles for inclusion.

Another strength of this review is that the quality was examined by the AMSTAR-2 checklist. The results of this checklist suggested that the quality of the current review was moderate. This indicates that the current review has more than one weakness, but no critical flaws, and could provide an accurate summary of the results of available studies. The rating of moderate may have likely emerged as no meta-analysis was done in this review.

A few limitations have also been identified in this review. The search was only conducted on English-language articles thus it is possible that there would be studies published in other languages that would have met the search criteria generally. Another limitation was that the literature search generated a small number of studies compared to other systematic reviews. However, the primary goal of this review was to examine research studies of stroke rehabilitation, where both arms were involved in the intervention. Thus, the number of studies that qualified for the criteria could be impacted.

In terms of the purpose and scope, the current review only focused on kinematic analysis that investigated the nature of coordinative synergies emerging at the inter-limb level of organization in reaching tasks. However, other types of measures of motor performance, such as kinetic analysis and EMG measurement, could also provide information on coordination and control at intra- and inter-limb level of movement planning and production.

Recommendations and Future Directions

Stroke can result in significant and chronic functional deficits of upper-extremity function, especially bimanual coordination, even after several months of rehabilitation (Tomita et al., 2017). Thus, bimanual interventions that are implemented should be clinically effective, as well as theoretically sound and methodologically reliable. This review showed that, among many issues, the measures implemented in the investigations examining the rehabilitation of bimanual coordination and control were limited. Thus, a number of considerations have been suggested for practitioners and researchers to take into account when devising rehabilitation programs and assessing their effectiveness.

Potential Methodological Approaches to Examine Bimanual Coordination

From a clinical perspective, kinematic analysis is a useful tool to measure the nature of motor performance involving upper extremity in individuals with stroke. It is a reliable way to capture subtle changes or differences in movement control as well more pronounced qualitative differences in movement coordination. Thus, kinematic analysis can provide more accurate, real-time indicators of the recovery of the patient as compared to the sole use of clinical scores (Van Dokkum et al., 2014). In addition to clinical scales, such variables would provide more insight into the degree and stability of interlimb coupling before and after interventions.

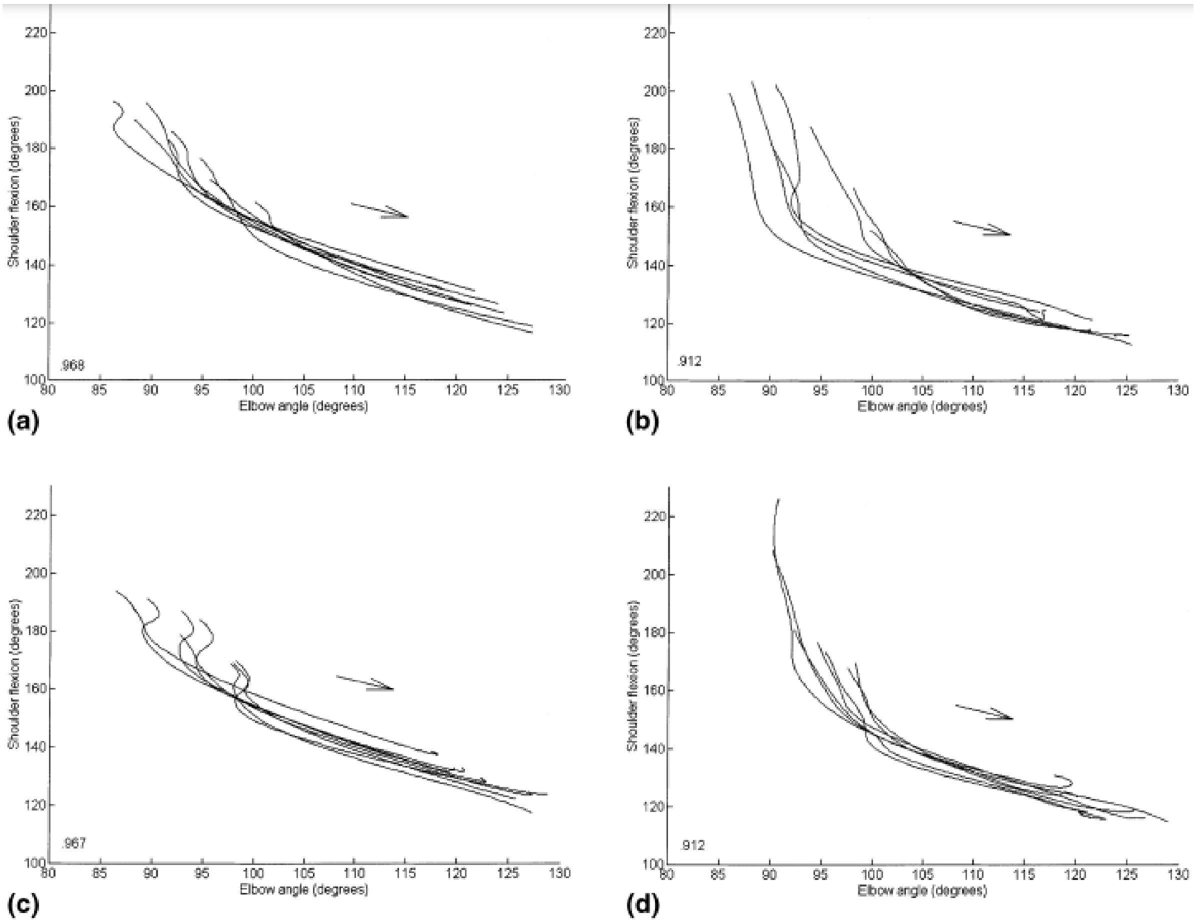
One of the most frequent ways of examining spatial coupling, at intra- and inter-limb level of organization, is via angle-angle plots (Tomita et al., 2017). However, the present analysis revealed that this methodological approach was not used in any of the studies reviewed. In motor control research, angle-angle plots, which capture the spatial coupling between the joints of interest, allow researchers to derive inferences about the nature or degree of coupling as well as intra-individual stability of the emerging coordination. Hence, coupling that is qualitatively different (e.g., between a person with and without stroke), yet stable and functional across attempts may be viewed as adaptive rather than deficient. At the interlimb level, spatial symmetry between the arms can be qualitatively inferred as the similarity of the coordination patterns between the same joint pair (e.g., left and right shoulder). At the intralimb level of organization, the angle-angle plot can reveal the tendency of both joints (e.g., shoulder-elbow) to either tightly couple or decouple. The former implies that changes in one joint correspond to proportional changes in the other joint, as both move through their range of motion, whereas the latter indicates that one joint maybe moving while the other one remains “frozen”. The nature of the emerging relations is context specific, hence in bimanual symmetrical actions, tight coupling would be expected at the interlimb level, while the degree of intralimb coupling is likely joint specific. In actions that are asymmetrical, the nature of the emerging coordination is more difficult to predict as both arms are expected to perform two independent actions that are functionally linked. Hence, the effectiveness of coordinative relations, emerging from angle-angle plots, should be taken into the account in the context of the emerging outcome.

The approach of angle-angle plots has been implemented in past studies examining uni-manual reaching performed by stroke patients (Beer et al., 2000; Hasanbrani et al., 2021; Levin, 1996; Murphy et al., 2011; Tomita et al., 2017), as well as in few studies involving bi-manual tasks (e.g., Steenbergen et al., 2000). Also, in regards to other descript bimanual actions, spatial coordination was also examined in ball-catching in children with developmental coordination disorder (e.g., Przysucha & Maraj, 2013). However, only the study of Przysucha and Maraj (2013) examined the coupling of wrist-elbow, while other studies investigated shoulder and elbow only. The instantaneous spatial relations between elbow and shoulder angles are usually similar and consistent from trial to trial in typical forward reaching, independent of the overall speed (Lacquaniti & Soechting, 1982). On the contrary, the wrist displacement is highly variable and flexible, meaning that wrist motion is more likely to be uncoupled from elbow and shoulder (Lacquaniti & Soechting, 1982). This difference may result from the nature of internal constraints acting on the actions of two proximal joints and wrists. Therefore, a potential gap in spatial coupling is examining the coupling between joints other than shoulder and elbow. Future studies should devote more attention to the spatial coupling involving the distal joint (wrist), due to the fact that the control of the wrist highly depends on task demands and has larger variability (Lacquaniti & Soechting, 1982).

In terms of spatial coupling at the interlimb level, Steenbergen et al (2000) used angle-angle plots to examine the degree and stability of spatial coupling in individuals with hemiparesis in reaching. The results showed that the performance of the unimpaired arm had a tight degree of coupling in shoulder flexion-elbow extension, in which the patterns of both unimanual (Figure 8a) and bimanual (Figure 8c) reaching exhibited a fairly straight line. Thus, the unimpaired arm exhibited a high degree of coupling between the joints, representing an effective and potentially efficient coordinative tendency. In contrast, at the beginning of the movement in unimanual (Figure 8b) and bimanual (Figure 8d) conditions, the elbow of the impaired arm has been “frozen” since there was no little to no change to the angular displacement of the elbow. The angular changes to the elbow were initiated only when the shoulder already finished half of its movement. Thus, the impaired arm exhibited a segmented type of movement where the elbow and shoulder were decoupled. In the context of the solution to the degrees of freedom, two arms exhibited different synergetic relations while preforming a bimanual reaching movement. Also, as evident from the diagram, in terms of stability, the unimpaired arm had consistent spatial relations between the shoulder and elbow in all the attempts, while the coordination pattern of the impaired arm was more variable. On the other hand, the coupling between the two shoulders, elbows or wrists was not explicitly examined in bimanual tasks. As evident from this study, angle-angle plots represent a valid approach to reveal the degree and stability of spatial coupling in bimanual actions. Due to the fact that they are relatively easy to analyze, angle-angle plots represent a useful methodological approach which could aid researchers and practitioners in examining the nature of the emerging coordinative tendencies before, during, and after rehabilitation.

Figure 8

Angle-angle plots in both bimanual and unimanual reaching in an individual with stroke



Note: Elbow-shoulder flexion angle plots of a stroke patient reaching with unimpaired arm (left column) and impaired arm (right column) under both unimanual (upper row) and bimanual (bottom row) conditions (Steenbergen et al., 2000).

Correlation coefficients, derived from angular or linear spatial or temporal parameters, represents another dependent variable that can be used to infer the nature of the emerging coupling at both the intra- and inter-limb level of organization, in bimanual actions. Despite this fact, this approach was only implemented in one study (Van Delden et al., 2015). Compared to angle-angle plots, correlations allow researchers to deploy statistical analysis in order to examine the differences between groups, times, or both at the inferential level. One of the advantages associated with correlations is that they can reveal aspects of coordination that may not be apparent in other approaches, such as the lag between two variables in the temporal domain. The time lag has been used as an indication of the degree of synchrony between the arms, where a shorter time lag (close to zero) indicated stronger temporal synchrony (Kantak et al., 2016a). Cross-correlations, with zero time-lag, which are similar in the nature of Pearson's correlations, can also be used to capture the degree of interlimb coupling.

In the past research, which was not reviewed for the purpose of the current analysis, bimanual temporal coupling was measured in individuals with hemiparesis, by cross-correlating the velocity profiles of both end effectors (wrists) at zero lag in symmetric pointing and reach-to-grasp tasks (Steenbergen et al., 2000). In another study, temporal and spatial coupling were examined via correlations in a symmetrical pushing task, where the linear displacement and velocity of two hands were examined (Akremi et al., 2022). Both studies showed that stroke subjects had stable coordinative tendencies and a high degree of interlimb coupling in the temporal or spatial domains. The nature of temporal coupling in individuals with stroke and healthy subjects were also examined by cross-correlation coefficients and the magnitude of the time lag between the velocities of two hands (Kantak et al., 2016) in bimanual symmetrical and asymmetrical reaching. In the asymmetrical task, two hands needed to reach forward and backward respectively. In all bimanual movements, as expected, people with stroke had significantly lower cross-correlation coefficients and significantly longer time lags compared to age-matched controls (Kantak et al., 2016a). These results confirmed that individuals with stroke had a relatively lower degree of temporal coupling in both symmetrical and asymmetrical tasks, confirming that the intrinsic coordinative tendencies were affected by stroke.

Thus, the magnitude of (cross) correlation coefficients, along with the time lag, allows for inferences to be made about the degree (stability) of coupling and synchrony between the arms under different task constraints. In rehabilitation studies, it appears that bimanual coupling and its nature (degree and stability) under different task demands should be further studied quantitatively at the interlimb level of organization. Due to the fact that the past studies in this field did not use enough process measures as mentioned above, future research should integrate this method to the rehabilitation process. Before rehabilitation, correlations and angle-angle plots should be implemented in different bimanual tasks, in which the stability of interlimb coupling needs to be examined. During rehabilitation, examining the performance of certain tasks at the individual level is necessary since the motor function of stroke patients could change over time. After rehabilitation, the same set of tasks and measures should be implemented again to compare the behavioral changes at the intra-individual and intra-group level. More specifically, angle-angle plots could show the stability and degree of spatial coupling between the joints, while correlations could reveal the magnitude of temporal coupling between end effectors or joints.

Potential Methodological Approaches to Examine Movement Control

A well-developed spatial and temporal control of arm movements ensures effective and efficient organization by producing a smooth end-point trajectory, with a bell-shaped velocity profile. These variables can be derived from the kinematic analysis of end effectors and represent a reliable and valid evaluation of movement patterns affected by sensorimotor or neurological impairments (Nowak et al., 2008; Subramanian et al., 2010). From the clinical perspective, such information appears to be critical as it informs the practitioners whether the emerging issues, caused by stroke, are emerging in the spatial or temporal domains, or both (Murphy & Häger, 2015).

Spatial Control

In self-paced actions spatial control represents an important variable that the central nervous system (CNS) has to parametrize in order for the hand to reach the target via a straight and smooth trajectory. In this context the measures of straightness, derived from linear displacement of the end effector, can provide insight into the nature of the emerging issues. Based on past research, in goal directed reaching, the hand path of typically developed individuals exhibits a nearly straight line between the starting point and the target location (Cacho et al., 2011; de los Reyes-Guzmán et al., 2014; Jaspers et al., 2011; Merlo et al., 2013). In contrast, the more affected arm of individuals with stroke usually exhibits a more curved and discontinuous trajectory, resulting in a longer hand path (Coderre et al., 2010). In the current review, only one study examined the hand paths qualitatively in a symmetric reaching task (Waller et al., 2008). After rehabilitation, both hands exhibited straighter hand paths compared to the baseline test, where the trajectory of the more affected hand improved drastically from an “S” shape to almost a straight line. Interestingly, the improvements were also exhibited in the less affected hand indicating that the symmetry between the two arms was also enhanced after the program.

Aside from the subjective “eye-balling” of the emerging paths, researchers have also used straightness of endpoint trajectory. This approach is generally examined by kinematic variables such as trajectory ratio and the index of curvature, which is a more objective and reliable measure. However, in line with the scenario emerging from the studies using qualitative analysis, this approach was also seldomly incorporated in the studies reviewed here. In fact, only two studies incorporated this methodological approach (Jung et al., 2013; Waller et al., 2008), both providing contradictory results. The trajectory ratio was improved after training in one investigation (Waller et al., 2008), but the researchers failed to find such effect in another work (Jung et al., 2013). This lack of consistency likely is due to differences in task constraints (unimanual versus bimanual reaching), training protocols (i.e., with or without auditory cueing), and the length of rehabilitation, rather than the reliability of the measures themselves. In fact, this observation supports the sensitivity of such a methodological approach as it detects even subtle changes or differences in the emerging movement patterns when those changes are expected.

In addition to the endpoint kinematics, which are examined in the Cartesian coordinates, the spatial control can also be measured in terms of the intrinsic coordinates within the joint space. This measure is necessary since a joint can make substantial rotating movements in the joint space without any linear displacement. For example, typical developed individuals tend to freeze the wrist joint under a pointing task in order to keep a straight end-effector trajectory (Morraso, 1981), while they tend to free the wrist when a unimanual catching task is performed (Mazyn et al., 2006). Also, in the context of stroke, changes or differences in angular displacement of the respective joint can allow the researchers to know whether the joints are overlay “laxed” or “restricted”. Although the contribution of each joint to the emerging pattern cannot be pre-determined in the normative sense, comparisons between those with and without stroke can provide an important insight into which joints are more or less affected. Shoulder and elbow joints are generally responsible for the transport phase of the reaching action, whereas the differences at the wrist are generally associated with the spatial fine-tuning of the “homing” phase of the movement.

Despite the obvious clinical application of such measures, in the current review only two studies examined the nature of the emerging actions in joint space, both involving the same research group (Whitall et al., 2000; Whitall et al., 2011). The studies inferred the range of motion using goniometers rather than kinematics, in addition to the fact that only uni-manual tasks were implemented. Thus, collectively the reviewed works failed to address this important motor control issue altogether.

Temporal Control

In the present review, kinematics related to temporal control of end effectors were examined in unimanual and bimanual reaching, as well as bimanual asymmetric reach-to-grasp actions. Across the five studies which implemented this approach, the inferences regarding the emerging temporal parameters were derived from measures of movement smoothness and velocity. However, compared to velocity measures like peak velocity or time to peak velocity, variables of smoothness such as jerk profile and movement units were less used in rehabilitation studies. The temporal organization of end effectors, especially the movement smoothness is usually affected by stroke. In addition to studies included in this review, previous descriptive research showed that the temporal control of the paretic arm was less smooth and more segmented in reaching tasks (Mazzoleni et al., 2014; Tomita et al., 2017). After bimanual arm training, fewer sub-movements and longer acceleration phases of the paretic arm were reported, regardless of task constraints and rehabilitation types (Chang et al., 2007; Waller et al., 2008; Wu et al., 2007). This indicated that the control strategy of the paretic arm was improved, which leads to a more coordinated bimanual movement. Therefore, both arms were controlled as a coordinative structure instead of being controlled individually, suggesting the improvement of temporal organization in bimanual actions. Thus, these findings suggest that these temporal measures of end effectors before and after rehabilitation can capture expected changes in motor control at the interlimb level, which should be incorporated into future studies.

In addition to quantitative inferences made from kinematic variables mentioned above, the movement smoothness can also be examined by the qualitative analysis of velocity profiles of end-effectors. In typically functioning individuals, a reaching movement has only one velocity peak occurring approximately halfway between the start and endpoints, and a bell-shaped velocity profile (McCrea et al., 2002; Chang et al., 2015). In individuals with stroke, the velocity profile is characterized by multiple velocity peaks and movement units (Cirsea & Levin, 2000; McCrea et al., 2002; Rohrer et al., 2002; Tomita et al., 2017; Wagner, et al., 2008). Thus, in a bimanual reaching task, the velocity profile of the non-paretic arm is smooth and bell-shaped, whereas the profile of the paretic arm is usually discontinuous, with more than one peak (McCrea et al., 2002; Trombly, 1992). In addition, the acceleration phase of the more affected arm is usually shorter than that of the less affected arm (Lin et al., 2010; McCrea et al., 2002; Wagner, et al., 2008). However, in the current review, none of the studies used any velocity profiles. Thus, future studies should implement both quantitative and qualitative measures in regards to the temporal control in end effector space.

In the joint space, temporal control can be measured by angular velocity and its derivatives such as acceleration. In the current review, the nature of temporal control of individual joints was not reported. However, the angular velocity of joints can be affected by stroke significantly. For example, the peak angular velocity of the elbow had significant differences between healthy individuals and stroke participants, as well as between those with moderate and mild arm impairments in unimanual reaching (Murphy et al., 2011). Also, in a reaching task, the peak angular velocity of the elbow was impaired during the first year after stroke, from the acute to chronic stage of recovery (Thrane et al., 2020). These findings indicate that the measure of angular velocity is sensitive to identify deficits of temporal control in joint space across different recovery stages and impairment levels (mild to moderate) (Murphy et al., 2011; Thrane et al., 2020).

Measuring Stability and Flexibility in Bimanual Actions

When examining the status of synergistic relations, emerging at any level of organization, the notion of stability and flexibility is essential. This is particularly true for bimanual, interlimb level of organization. In line with the premises of Haken-Kelso-Bunz model (Haken et al., 1985), which is one of the most prominent conceptual frameworks dealing with the issues of bimanual rhythmic actions, stability as well as flexibility can be examined by manipulation of so-called control parameter. When a variable, such as oscillation frequency or simply the speed of the movement is scaled up, the changes in coordination can be captured via the relative phase which allows researchers to make inferences about the temporal nature of synergistic relations between two effectors (Kelso et al., 1984). Thus, when the critical frequency is reached, the system self-organizes into a more stable coordination pattern. In this context, the patterns that are able to maintain its coordination across larger perturbations are considered as more stable and flexible. Often this point of transition is referred to as critical frequency and coincides with substantial increase in the variability of the relative phase, referred to as “hysteresis”.

In the past, HKB has been applied to tasks such as finger tapping (Haken et al., 1985; Kelso & Schöner, 1988), pronation-supination of the forearms (Temprado et al., 1999) and flexion-extension of the elbows (Lee et al., 2002). In the context of stroke, few studies have been carried out to address this issue, in the theoretical context of the dynamic system theory. The existing evidence revealed a decrease in the stability, accuracy, and synchrony of bimanual movements in individuals with stroke (Waller & Whitall, 2004; Rose & Winstein, 2005; Ustinova et al., 2006). In one study involving a bimanual finger-tapping task, less stability was found in individuals with stroke compared to healthy subjects (Waller & Whitall, 2004). Bilateral in-phase and anti-phase tapping was implemented, and the stability of bimanual coupling was calculated as the variability in the relative phase. In another bimanual arm-swinging task performed by stroke and healthy subjects, perturbations were applied when the arms were moving forward and backward (Ustinova et al., 2006). The perturbation was applied to both wrists in each trial. The relative phase was calculated as the displacements of endpoint markers attached to wrists. Both groups showed that the perturbations resulted in a transition from anti-phase to in-phase coordination, followed by regaining the anti-phase mode. However, stroke patients took a significantly longer time to recover from the perturbation compared to the control group which indicated less than optimal flexibility. Stable, pre-perturbed (anti-phase) coordination was regained within one cycle following perturbation for healthy subjects and within two cycles following perturbations for stroke participants (Ustinova et al., 2006). Thus, this finding suggested that stroke patients had impaired flexibility and adaptability in coordinating two end effectors facing unexpected constraints.

In terms of discrete actions, the stability of interlimb coupling was investigated in a bimanual reach-to-grasp task during the first six weeks after stroke (Metrot et al., 2013). The degree of stability in temporal coupling was measured via the synchronization of two hands. High variability was reported in the first three weeks after stroke, suggesting the temporal coupling is unstable (Metrot et al., 2013). The results also revealed that variability in interlimb synchrony was improved over time after stroke, which indicated that the nature of temporal coupling became more stable after the acute stage of recovery. Therefore, the degree of intra-individual variability in spatiotemporal relations between two arms is an important index of recovery in bimanual coordination.

Variability measures, such as standard deviation or coefficient of variation, should be calculated as a reflection of stability in coordinative structures. In bimanual continuous actions, more stable action could be inferred from either lower deviation in relative phase or higher critical frequency which is the point that the system shifts from anti-phase to the in-phase pattern. In bimanual discrete actions, the degree of stability in bimanual coupling can be evaluated by intra-individual variability in correlation coefficients or angle-angle plots. The flexibility, on the other hand, can be measured by introducing perturbations into the system with different dimensions of the task and analyzing how the order parameter (i.e., temporal and spatial coupling) is affected.

Conclusions

In the last few decades, many researchers examined the issues that individuals with stroke experience when performing both uni-manual and bimanual tasks. Some studies where descriptive in nature, while others focused on different rehabilitation approaches aimed at regaining the lost function. The methodologies implemented included a variety of different dependent variables ranging from clinical scales to more reliable and valid of measures of movement process and outcome derived from kinematics. The aim of the present study was to systematically review the implemented protocols in terms of how, if at all, they allowed making inferences about the nature of emerging movement coordination and control and provide suggestions in the context of the existing theories of motor control as related to bimanual actions.

In terms of the designs, the reviewed studies showed that although factors such as time after stroke, age, and gender, represent important factors which affect the nature of the emerging issues as well as the recovery, those have not been examined extensively. From the standpoint of measures, the majority of the research implemented a variety of clinical scales as the primary outcome measures, while kinematic analysis was only incorporated in less than half the studies. Although clinical scales have many advantages in regards to their efficiency, their reliability and validity they need to be further established in regards to specific training programs and samples. In regards to task constraints, both symmetrical and asymmetrical tasks were implemented, but the emerging inferences were limited due to the lack of well-established and frequently used measures of different aspects of coordination as well as control. Also, in the current review, only one study examined explicitly the issue of bimanual coordination by implementing correlation coefficients or angle-angle plots. As such, more qualitative and quantitative measures of bimanual coupling are warranted in future research, especially as applied to investigation of discrete tasks.

Lastly, an important issue that should be addressed in future research is the application of explicit theoretical frameworks and models. Surprisingly, none of the studies reviewed here were theory-driven. Thus, a significant shortcoming in the field of stroke rehabilitation is a general lack of theory-based research, as data-driven investigations contribute little to the understanding of the issue of bimanual coordination after stroke. It is critical that future research focuses on the examination of the nature of bimanual coordination in individuals with stroke in the context of well-known theories or models within cognitive or dynamical conceptual paradigms. More theories of motor control, especially those related to bimanual coordination, could explain and predict the emerging actions in the context of bimanual trainings, thus improve the quality of research in post-stroke arm rehabilitation.

Given the varied method and theories identified in stroke rehabilitation research, more reliable methodological approaches should be implemented in future research. In order to decrease the heterogeneity of samples, analysis of independent variables such as age and sex needs to be incorporated into the methodologies. In addition to pre-post study design, transfer tests and retention tests are necessary to examine the generalization as well as long-term effects of training protocols. In terms of the tasks measured in pre-post assessments, in addition to those in clinical scales, more bimanual discrete actions (e.g., symmetrical or asymmetrical) are warranted in the field of stroke rehabilitation. Most importantly, kinematic analysis of bimanual coordination and control should be the primary outcome measure when both arms are involved in the rehabilitation, in order to describe the coordinative structures in spatial and temporal domains in individuals with stroke.

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Appendix A

Table 1- ***Search terms in each database***

PubMed (1996 to week 1 May 2022)	(((Stroke OR "cerebrovascular accident*" OR "brain infarction*" OR "transient ischemic attack*" OR "brain hemorrhage*" OR "brain ischemia*") AND (bimanual OR "bi-manual" OR interlimb OR "inter-limb" OR bilateral)) AND (coordination OR "motor coordination" OR coupling OR coupled)) AND (intervention* OR rehabilitation* OR "stroke rehabilitation*" OR therap* OR "constraint induced therapy" OR "functional training*" OR neurorehabilitation* OR training* OR "intervention stud*") *Affiliation: All Field* *Apply filters: “English”, “humans”, “Adult: 19+years”*
CINAHL (1994 to week 1 May 2022)	(Stroke OR “cerebrovascular accident*” OR “brain infarction*” OR “transient ischemic attack*” OR “brain hemorrhage*” OR “brain ischemia*”) AND (bimanual OR “bi-manual” OR interlimb OR “inter-limb” OR bilateral) AND (coordination OR “motor coordination” OR coupling OR coupled) AND (intervention* OR rehabilitation* OR “stroke rehabilitation*” OR therap* OR “constraint induced therapy” OR “functional training*” OR neurorehabilitation* OR training* OR “intervention stud*”) *Search in “TX All Text”* *Apply related words; Apply equivalent subjects; Also search within the full text of the articles.* *Search modes - Boolean/Phrase* *Limiters: “peer-reviewed”, “English language”, “human”, “age groups: all adults (19 years and older)”.*
PsycINFO (1984 to week 1 May 2022)	Anywhere: (Stroke OR "cerebrovascular accident*" OR "brain infarction*" OR "transient ischemic attack*" OR "brain hemorrhage*" OR "brain ischemia*") AND Anywhere: (bimanual OR “bi-manual” OR interlimb OR “inter-limb” OR bilateral) AND Anywhere: (coordination OR “motor coordination” OR coupling OR coupled) AND Anywhere: (intervention* OR rehabilitation* OR “stroke rehabilitation*” OR therap* OR “constraint induced therapy” OR “functional training*” OR neurorehabilitation* OR training* OR “intervention stud*”) *Search in “Anywhere”* *Limited to peer-reviewed articles.* *Apply filters: “Humans”, “Adulthood (18 years and older)”*
Web of Science (1975 to week 1 May 2022)	ALL FIELDS: (Stroke OR "cerebrovascular accident*" OR "brain infarction*" OR "transient ischemic attack*" OR "brain hemorrhage*" OR "brain ischemia*") AND ALL FIELDS: (bimanual OR “bi-manual” OR interlimb OR “inter-limb” OR bilateral) AND ALL FIELDS: (coordination OR “motor coordination” OR coupling OR coupled) AND ALL FIELDS: (intervention* OR rehabilitation* OR “stroke rehabilitation*” OR therap* OR “constraint induced therapy” OR “functional training*” OR neurorehabilitation* OR training* OR “intervention stud*”) *Affiliation: All Fields* *Apply filter: “English”*

Appendix B

Table 2

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	P1
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.	P58
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	P59
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	P61-62
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.	P60
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Appendix A
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.	P63
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.	P63-64
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.	P64-66
	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
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.	P62-63
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.	N/A
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)).	P62-63
	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.	P65-66
	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.	P65-66
	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
Certainty assessment	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
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.	P68-69
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	P68
Study characteristics	17	Cite each included study and present its characteristics.	Appendix E
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	P70
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
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.	P70
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.	P109-110
	23b	Discuss any limitations of the evidence included in the review.	P94-95
	23c	Discuss any limitations of the review processes used.	P94-95
	23d	Discuss implications of the results for practice, policy, and future research.	P95-108
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

Appendix C

Table 3

Downs and Black Scale for quality assessment of selected studies

REPORTING	**Yes/No**	**Score**
1. Is the objective of the study clear?	Yes = 1, No = 0	
2. Are the main outcomes clearly described in the Introduction or Methods?	Yes = 1, No = 0	
3. Are the characteristics of the patients included in the study clearly described?	Yes = 1, No = 0	
4. Are the interventions clearly described?	Yes = 1, No = 0	
5. Are the distributions of principal confounders in each group of subjects clearly described?	Yes = 1, No = 0	
6. Are the main findings of the study clearly described?	Yes = 1, No = 0	
7. Does the study estimate random variability in data for main outcomes?	Yes = 1, No = 0	
8. Have all the important adverse events consequential to the intervention been reported?	Yes = 1, No = 0	
9. Have characteristics of patients lost to follow-up been described?	Yes = 1, No = 0	
10. Have actual probability values been reported for the main outcomes except probability < 0.001?	Yes = 1, No = 0	
EXTERNAL VALIDITY	**Yes/No/Unclear**	**Score**
11. Were subjects who were asked to participate in the study representative of the entire population recruited?	Yes = 1, No = 0, Unclear = 0	
12. Were those subjects who were prepared to participate representative of the recruited population?	Yes = 1, No = 0, Unclear = 0	
13. Were staff, places, and facilities where patients were treated representative of the treatment most received?	Yes = 1, No = 0, Unclear = 0	
INTERNAL VALIDITY	**Yes/No/Unclear**	**Score**
14. Was an attempt made to blind study subjects to the intervention?	Yes = 1, No = 0, Unclear = 0	
15. Was an attempt made to blind those measuring the main outcomes?	Yes = 1, No = 0, Unclear = 0	
16. If any of the results of the study were based on data dredging was this made clear?	Yes = 1, No = 0, Unclear = 0	
17. Was the time period between intervention and outcome the same for intervention and control groups or adjusted for?	Yes = 1, No = 0, Unclear = 0	
18. Were the statistical tests used to assess main outcomes appropriate?	Yes = 1, No = 0, Unclear = 0	
19. Was compliance with the interventions reliable?	Yes = 1, No = 0, Unclear = 0	

20. Were main outcome measures used accurate? (valid and reliable)	Yes = 1, No = 0, Unclear = 0	
INTERNAL VALIDITY-CONFOUNDING (SELECTION BIAS)	**Yes/No/Unclear**	**Score**
21. Were patients in different intervention groups recruited from the same population?	Yes = 1, No = 0, Unclear = 0	
22. Were study subjects in different intervention groups recruited over the same period of time?	Yes = 1, No = 0, Unclear = 0	
23. Were study subjects randomized to intervention groups?	Yes = 1, No = 0, Unclear = 0	
24. Was the randomized intervention assignment concealed from patients and staff until recruitment was complete?	Yes = 1, No = 0, Unclear = 0	
25. Was there adequate adjustment for confounding in the analyses from which main findings were drawn?	Yes = 1, No = 0, Unclear = 0	
26. Were losses of patients to follow-up taken into account?	Yes = 1, No = 0, Unclear = 0	
POWER	**Yes/No**	**Score**
27. Was the study sufficiently powered to detect clinically important effects where the probability value for a difference due to chance is < 5%?		

Appendix D

Table 4

AMSTAR 2

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 <u>and</u> 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 <u>and</u> 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

Shea, B. J., Reeves, B. C., Wells, G., Thuku, M., Hamel, C., Moran, J., ... & Henry, D. A. (2017). AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *bmj*, 358. https://doi.org/10.1136/bmj.j4008

Appendix E

Table 5

Demographic information and study characteristics

Authors, year	Study design	Participants	Main objectives	Types of intervention	Training protocols of interventions	Results	Outcome measures	D&B Score
#1[1] Ambreen et al., 2021	Pilot study	N=24 enrolled, 19 finished the study Age[2]: 53.6 9 F, 10 M >=3 months post stroke, 24 Ischemic stroke, Lesion side: 12 L, 12 R Purposive and convenience sampling	Evaluated and compared the effects of BAT between left (LHS) and right hemispheric (RHS) stroke patients	Bilateral arm training (BAT)	5 functional tasks: stacking cones; positioning the cup upright; throwing a tennis ball; carrying a block; button/unbutton a shirt. Follow-up assessment was NOT conducted.	FMA-UE: LHS: Distal arm function did not significantly improve. Overall score (p=.008), coordination (p=.02), and speed (p=.01) improved significantly. RHS: Coordination/speed of movement did not show significant improvement. Distal arm function (wrist p=.02; hand p=.007) and overall scores (p=.02) improved significantly. WMFT: No significant inter-group difference.	FMA-UE, WMFT	15
#2 Arya et al., 2019	Double-blinded pilot RCT	N=50 Experimental: n=26 Control: n=24 Age: 52.0 10 F, 40 M >6 months post stroke, 37 ischemic stroke,	Developed an interlimb coupling protocol and assessed its effect on motor recovery among post-stroke patients	BAT, Conventional treatment	BAT: a. Both symmetric and asymmetric tasks: marching on place; wall pegs; rocker board; sanding; lifting; pronation-supination; circle drawing. b. Symmetric tasks only: clapping; reaching,	FMA-UE: Experimental group showed significant improvement in overall scores (p<.001). mRS: No significant difference was found between groups. 15% experimental participants could reach to mRS-2 (slight	FMA-UE, mRS	21

		13 hemorrhagic stroke, Lesion side: 30 R, 20 L Purposive sampling			grasping, and throwing 2 balls. c. Asymmetric task only: pedocycle. Conventional treatment: Brunnstrom and Bobath approaches Follow-up assessment was NOT conducted.	disability) from moderate or severe disability. No control subjects could accomplish the level of mRS-2.		
#3 Burgar et al., 2011	Clinical single-blinded RCT	N=54, Low-dose experimental: n=19 High-dose experimental: n=17 Control: n=18 (63.1 yr. Gender not reported) 9-20 days post stroke, 54 Ischemic stroke Lesion side: 31 R, 23 L Purposive and convenience sampling	Assessed robot-assisted upper-limb therapy in acute stroke rehabilitation	Robot-assisted (RA) upper-limb therapy in low and high dose, Conventional therapy (not specified)	Functional and goal-directed set of tasks by reaching to physical targets. Bilateral mode: bilateral mirror-image movements. Unilateral mode: forward reaching to physical targets placed on the front, right or left side of the body. 6-month follow-up was conducted.	FMA-UE: Gains were not significantly different between groups at post-intervention and follow-up. Positive correlations were found between FMA-UE gains and the dose (r=.34, p=.04) and intensity (r=.45, p=.005) of RA at post-intervention; however, the correlation between dose and FMA gains were weakened at follow-up (r=.37, p=.04). Intensity still had strong correlation with FMA gains after 6 months (r=.66, p<.001). FIM: high-dose group had greater FIM gains than controls at discharge (p=.04), but no difference compared with low-dose group at follow-up. WMFT: No significant difference between groups. Motor power: No difference between groups. Ashworth score: high-dose group had significantly greater muscle tone at follow-up (p=.049).	FMA-UE, FIM, WMFT, Motor power, Ashworth score, Kinematic (not reported in the original paper)	20
#4 Caurau gh &	Clinical RCT	N=25 Bimanual with EMG: n=10	Evaluated the effectiveness of the coupled protocol of	Bilateral coordination training with EMG	Bilateral training group: bimanual wrist and finger extension with EMG-triggered stimulation and	Box and block test: Bimanual training group had significant improvement of the	Box and block test, force production of the wrist and	12

Kim, 2002		Unimanual with EMG: n=10 Control without EMG: n=5 Age: 63.7, 4 F, 21M, >1 year post stroke (mean= 39.1 months), Stroke type not reported, Lesion side: 12 R, 13 L Purposive sampling	bilateral coordination training and electromyogram (EMG)-triggered neuromuscular simulation on chronic stroke patients	triggered neuromuscular stimulation	assistance from unimpaired arm as wrist-finger extension was simultaneously executed. Unilateral training group: Wrist and finger extension of paretic arm with EMG-triggered stimulation. Control group only performed wrist-finger extension without EMG assistance. Follow-up analysis was NOT performed.	number of blocks moved than other two groups (p<.04). Unilateral training group had significant improvement of number of blocks moved than control group (p<.04). Force production test: Bimanual group had significant improvement in reaction time and stability control than other two groups (p<.001). Unimanual group had significant improvement in reaction time than control group (p<.001).	finger extensors: reaction time and stability control	
#5 Caurau gh et al., 2009	Single-blinded RCT	N=30 BAT with EMG and load: n=10 BAT with EMG and no load: n=10 BAT only: n=10. Age: 67.2, 10F, 19M >6 months post stroke, stroke type not reported, Lesion side: 17 R, 12 L purposive sampling	Determined the effect of coupled bilateral training: bilateral movement training (BAT) and ENG-triggered neuromuscular stimulation, on chronic stroke patients	Bilateral movement training and EMG triggered neuromuscular stimulation	Bilateral wrist and finger extension movements with or without a load on the unimpaired hand. The load was set as the doubled moment of inertia of the hand in stroke patients. Active neuromuscular stimulation was applied to the paretic hand in two experimental groups. Follow-up testing was NOT conducted	Box and block test: Two BAT groups with and without load both moved higher number of the blocks. BAT with load: p<.03; BAT without load (marginally better): p =.07 Force production: Two BAT groups had significantly more regularity in muscle contraction (p<.04). BAT load group had faster reaction time of muscle contraction than BAT no load group and control group (p<.004).	Box and block test, force production measure of the wrist and finger extensors: rapid muscle onset in a reaction time task, and deliberate muscle onset in a sustained contraction task	14
#6 Chang et al., 2007	Single-cohort study	N=20 Age= 57.1, 8F, 12F >6 months post stroke, stroke type not reported, Lesion side:9 R, 6 L	Analyzed the effect of conventional rehabilitation combined with bilateral force-induced isokinetic arm	Conventional training combined with robot-aided, bilateral force-induced isokinetic training	Bilateral symmetric push (shoulder flexion and elbow extension) and pull (shoulder extension and elbow flexion) movement at a pre-set constant velocity, with a robotic advice called bilateral force-induced	FMA-UE (p<.001), grip (p=.009), push (p=.001) and pull (p=.001) strength: significant improvement in post-intervention and retention test. FAT and MAS: no significant change. Kinematics:	FMA-UE, FAT, MAS, Isometric grip strength, pull and push strength,	15

		Purposive and convenience sampling	movement on stroke patients		isokinetic arm movement trainer. Retention test was conducted 8-week post intervention.	Movement time (p=.015), peak velocity (p=.035), percentage of time to peak velocity (p=.004), and normalized jerk score (p=.008) have significantly improved in post-intervention, but no difference in retention test.	Kinematic (paretic arm only)	
#7 Doost et al., 2021	Single-blinded RCT	N=49 Stroke: age = 63.9, n= 23, 11F, 12M, Control: age =27.4, n=26, >6 months post stroke, 20 Ischemic stroke, 3 hemorrhagic stroke, Lesion side: 12 R, 11 L Purposive and convenient sampling	Investigated and compared the effect of robotic active-assisted training mode versus robotic active mode on improving bimanual motor skill learning	Robot-assisted training (bilateral)	Bimanual cooperative task in which under active or active-assisted modes: participants needed to lift a tray on a screen by circular, in-phase mirror bimanual movements with or without robotic assistance. Overnight retention test was conducted as follow-up assessment.	SAT: both healthy and stroke subjects learned and retained bimanual cooperative tasks. Box and block test: The number of blocks transferred indicated no generalization to this task in both arms in stroke patients.	Speed-accuracy trade-off (SAT), Box and block test	14
#8 Gerardin et al., 2022	Clinical RCT	N=34 Stroke: age =61.0 n=24, Control: Age =64.0 n= 10, 17F, 17M >6 months post stroke, stroke type not reported, lesion side not reported, Purposive and convenient sampling	Determined whether chronic stroke patient could achieve bimanual motor skill learning from robotic training and compared bimanual motor skill learning between stroke patients and healthy individuals	Robotic-assisted training (bilateral)	Asymmetrical bimanual coordination task with robotic devices: a cursor on the screen was controlled by coordinated movements of the arms through robotic handles, in order to keep the cursor on track. (Each hand controlled the cursor along a single axis, either x-axis or y-axis). Overnight retention test was conducted as follow-up assessment.	BiSAT and BiCO: stroke patients showed improvements. BiSAT: healthy subjects had a larger motor skill learning than the patients with mild to moderate impairment (p<.001) but not significantly different from those with minimal motor impairment (p=.017). BiSAT revolution had a significant positive correlation with baseline FMA-UE and SIS. BiCO: the overall biCO progression was not significantly different among three groups and its generalization did not significantly differ.	FMA-UE; SIS, MoCA, ABILHAND Questionnaire, Box and block test, grip force, bimanual speed-accuracy trade-off (biSAT), bimanual coordination factor (biCO), bimanual forces against the virtual walls (biFOP). The clinical scales	18

						BiFOP: patients with mild to moderate impairment had significantly smaller progression than the healthy subjects (p<.001) and patients with minor motor impairment (p=.18). Generalization was larger in the healthy subjects than stroke patients.	were only implemented in baseline measures.	
#9 Jung et al., 2013	Pilot study	N=15 Mean age not reported, median=50-59 yr. 4F, 11M, >6 months post stroke, 6 ischemic stroke, 9 hemorrhagic stroke, Lesion side: 10 R, 5 L Purposive and convenience sampling	Examined effects of BAT on unilateral and bilateral reaching performance and performance of activities of daily living	BAT	Bimanual toweling, sanding, simulation of drinking, carrying blocks, stacking cones and pegboard. Follow-up assessment was NOT conducted.	COPM and MAL: showed significant improvement in amount and quality of the use of paretic arm. Average velocity and peak velocity of the paretic arm had significant improvement in bimanual and unimanual reaching. Trajectory ratio of the paretic arm had no significant changes in bilateral and unilateral reaching tasks.	COPM, MAL, kinematic (paretic arm only)	11
#10 Kale et al., 2019	Clinical RCT	N=30 CIMT: n=15 BAT: n=15 Age =50-65, 20F, 10M 3-9 months post stroke, stroke type not reported, lesion side not reported Purposive and convenient sampling	Compared the effect of constraint-induced movement therapy (CIMT) to bimanual task related training for stroke patients	CIMT, BAT	CIMT: performed daily activity tasks by the paretic hand and wore a mitten on the unimpaired hand. BAT: pouring water in a glass, fastening a button, putting on or removing a shirt, folding towels, and wiping windows. 6-month follow-up assessment was conducted.	ARAT BAT and CIMT groups both showed a significant difference before and after intervention (p<.01). NHPT: BAT and CIMT groups both showed a significant difference before and after intervention (P<.01).	ARAT, NHPT	20
#11	Single-blinded,	N=20 Experimental n=10 Control n=10	Investigated the effect of occupational-	Occupational-based BAT,	Occupational-based BAT: clothing arrangement, bath, make-	COPM: significant improvement was detected in both performance	COPM, SIS, ARAT,	18

Kim & Park, 2019	pilot RCT	Age= 59.5, 12F, 8M, >6 months post stroke, 10 ischemic stroke, 10 hemorrhagic stroke, Lesion side: 11 R, 9 L Purposive sampling	based bilateral arm training in the arm function recovery of stroke patients	Task-based BAT	up, ironing, hand wash, car wash, basketball play, wearing clothe, cooking, doing dishes, simple cleaning, cooking, cross-stitch, personal care, computer documents, woodcraft, sewing, knitting, manage scraping. Task-based BAT: cleaning desk with towels, pushing sanding, moving blocks, cup stacking, putting peg into and out of the board. Follow-up testing was NOT conducted.	(p=.01) and satisfaction (p<0.001). SIS: Strength (p=.018), ADL and IADL (p=.002), emotion (p=.001) and participant (p=.001) had significant progress; mobility, hand function, memory, and communication did not have significant improvement. ARAT: gross movement (p=.001) improved significantly; grasp, grip and pinch did not improve significantly. Y-BAT: satisfaction improved significantly (p=.002); quality of performance did not improve significantly. The use of affected side improved significantly (p=.02); the use of unaffected side did not improve significantly.	Y-BAT, The use of unaffected and affected hand which measured by accelerometer	
#12 Liao et al., 2011	RCT	N=20 Experimental n=10 Control n=10 Age =55, 7F, 13M >6 months post stroke, Stroke type not reported, lesion side: 13 R, 7 L Purposive and convenient sampling	Compared the effects on real-world arm activity and daily function in stroke patients receiving robot-assisted therapy with results in a dose-matched control treatment group	Robot-assisted therapy followed by functional activities, Control treatment	Robotic training: bilateral movement cycles consisting of forearm pronation-supination and wrist flexion-extension. Functional activities: twisting a towel, turning a key, opening a jar, carrying objects, using chopsticks, writing, folding clothes, picking up coins, turning a knob. Control treatment: gross and fine motor training, functional activities. Follow-up testing was NOT conducted.	FMA-UE (p=.002), Arm activity ratio (p=.026), MAL (p=.007), ABILHAND (p=.043): significantly improved compared to control group. FIM: no significant difference between experimental and control group (p=.88).	Arm activity ratio of the accelerometer data, FMA-UE, MAL, FIM, ABILHAND questionnaire	18
#13	RCT	N=33 Experimental n=16	Investigated the effects of	Bilateral isometric	Bimanual training: each subject was trained via	Experimental group demonstrated greater improvement on FMA-UE	FMA-UE, BI,	19

Lin et al., 2015		Control n=17 Age= 55.1, 5F, 28M >6 months post stroke, Mean= 23.6 months, 15 ischemic stroke, 18 hemorrhagic stroke, Lesion side:16 R, 17 L Purposive and convenient sampling	interlimb force coupling training on paretic arm in patients with chronic stroke	handgrip force training, Control treatment	the repetitive generation of bilateral hand grip forces to match the targeted forces and simultaneous relaxion. Control treatment: strengthening, stretch, practicing functional tasks, coordination and weight bearing of the paretic arm. Follow-up testing was NOT conducted.	(p<.001), WMFT (p<.001), MAS (p=.004), BI (p=.037) than control group. A moderate correlation was found between the improvement of scores for hand in FMA-UE and other portions of FMA-UE (r =.528, p=.018) or MAS (r =.596, p=.015) in the experimental group.	WMFT, MAS	
#14 Pandian et al., 2015	Double-blinded RCT	N=35 Experimental n=17 Control n=18 Age =43.1, 16F, 19M >4 months post stroke, Mean= 28.8 weeks, 16 ischemic stroke, 19 hemorrhagic stroke, Lesion side: 14 R, 21 L Purposive and convenient sampling	Evaluated the effects of the motor training involving the less-affected side (MTLA) in stroke subjects	MTLA and dose-matched conventional therapy based on neurophysiological approach	MTLA: bimanual-task training by utilizing progressive resistive exercises for the less affected side (various functional goal-oriented activities). Conventional therapy: reflective movement and synergistic muscle linkage to achieve voluntary control. Follow-up testing was NOT conducted.	Affected side showed significant improvement for BRS (p<.001) and FMA-UE (p<.001). Less affected side demonstrated significant improvement for MMDT (p=.003), PPBT (p=.01) and MMT (p<.001).	The affected side: BRS, FMA-UE. The less-affected side: MMDT, PPBT, MMT	19
#15 Van Delden et al., 2015	Single - blinded RCT	N=60 mCIMT n=22, mBATRAC n=19, control n=19, Age =59.8, 19F, 41M Mean = 9.4 weeks post stroke, stroke	Determined whether the degree of interlimb coupling was higher after bilateral than after unilateral	Unilateral training: modified CIMT (mCIMT), Bilateral training: modified	mCIMT: a unimanual motor task, involved cyclic passive movement of one hand and rhythmic movement in another hand by auditory pacing signal.	Correlation coefficient: No significant difference between group difference from baseline to post intervention and from post intervention to follow-up. Amplitude, harmonicity: mBATRAC group had greater movement harmonicity with the	Kinematic: mean amplitude (Paretic arm only), correlation coefficient, Movement harmonicity (the	20

		type not reported, Lesion side: 26 R, 34 L Purposive and convenient sampling	training and control treatment	MATRAC (mBATRAC) , dose-matched control treatment (DMCT).	mBARTAC: rhythmic wrist rotations in the horizontal plane paced by an auditory metronome. DMCT: therapy based on existing guidelines for upper-limb rehabilitation after stroke. Follow-up test was conducted 6-week after intervention.	paretic arm than control group and also had larger amplitudes with the paretic arm than mCIMT group (p=.004).	power of the peak movement frequency relative to the total power of frequency spectrum of the complete signal)	
#16 Waller et al., 2008	RCT	N=18 Experimental n=9 Control n=9 Age =56, 11F, 7M >6 months post stroke, 18 ischemic stroke, Lesion side: 8 R, 10 L Purposive sampling	Determined how the motor control and coordination of arm movements have changed in a bilateral and unilateral training protocol	Bilateral arm training with rhythmic auditory cueing (BATRAC) and dose matched therapeutic exercises (DMTE)	BATRAC: bilateral in-phase and anti-phase reach and return, which was cued with an external beat from a metronome. DMTE: unilateral arm training of the paretic side. Follow-up testing was NOT conducted.	Kinematic: In bimanual reaching, subjects after BATRAC were faster (paretic p<.01, nonparetic p<.02), with increased peak acceleration (paretic p<.04, non paretic p<.04), fewer movement units (paretic p<.04), smoother hand path (paretic p<.001, nonparetic p<.01). In unilateral reaching, subjects were faster after control treatment for paretic arm (p<.01). No significant within group changes were seen in control group for any kinematic measures. Peak velocity did not show any significant change for either group FMA-UE, WMFT: Within group functional gains were seen after BATRAC on FMA-UE (p<.05) and Wolf Motor Arm Test (time and weight, p<.05) and after control treatment on FMA-UE (p<.05) and Wolf weight (p<.05).	FMA-UE; WMFT; kinematic (unilateral and bilateral)	15
#17	Single group	N=14 (63.8 yr.	Investigated the hypothesis that	BATRAC	Patients pushed two handles away bimanually	FMA-UE (p<.0004), Wolf-time (p<.02), UMAQS (p<.002)	FMA-UE, WMFT,	12

Whitall et al., 2000	pilot study	8F, 8M) >1 year post stroke, Stroke type not reported, Lesion side: 7 R, 7 L Purposive and convenient sampling	bilateral arm training with rhythmic auditory cueing (BATRAC) would improve motor function in the hemiparetic arm of stroke patients		(shoulder flexion and elbow extension) and pulled them towards the body (shoulder extension and elbow flexion), which mimicked the behaviour of reaching and bringing the object to oneself. Retention test was conducted 8-week after training	showed difference over 3 testing period. Wolf-weight and quality of function did not show improvement. Strength of elbow flexion (p<.05 without post hoc difference) and wrist flexion (p<.02, pretest vs posttest) were significant for the paretic arm. Strength of elbow flexion (p<.02, pretest vs retention) and wrist extension (p<.02, pretest vs retention) were significant for the non paretic arm. Active ROM of shoulder extension (p<.004, pre vs post), and thumb opposition (p<.002, pre vs post, post vs retention), wrist flexion (p<.004, pre vs post, post vs retention) and passive ROM of wrist extension (p<.03, pre vs post) were significant for paretic arm.	UMAQS, Isometric strength of both arms, ROM of the joints of paretic arm	
#18 Whitall et al., 2011	Single-blinded RCT	N=111 enrolled, 92 completed the study. Experimental n=42 Control n=50 Age =58.7, 42F, 50M >6 months post stroke, stroke type not reported, Lesion side: 48 R, 43 L, 1 bilateral stroke. Purposive and convenient sampling	Tested the efficacy of bilateral arm training with rhythmic auditory cueing (BARTAC) versus dose-matched therapeutic exercises (DMTE) on upper-limb function in stroke patients	BATRAC, DMTE	BATRAC: continuous bilateral arm training, in which participants moved two handles away and towards the body simultaneously (in-phase) or alternatively (anti-phase), in time to a metronome. DMTE: customized exercises including thoracic spine mobilization, weight bearing with the paretic arm, opening the hand.	The improvements in UE function (BATRAC: FMA-UE p=.03, Wolf-time p<.00; Control: FMA-UE p<.00, Wolf-time p=.04) were comparable between groups and retained after 4 months. Satisfaction was higher after BATRAC than DMTE (p=.003). SIS: Hand and strength subsections improved after BATRAC, but no between group difference. Total score, hand and emotion improved after DMTE. Strength in elbow extension for both arms increased after BATRAC but not DMTE.	FMA-UE, WFMT, SIS, Isokinetic strength of elbow extension/ flexion, Isometric strength of both arms, ROM of joints of the paretic arm, Verbal assessments of	20

					Retention was conducted 4-month after intervention.	BATRAC significantly improved strength of shoulder extension, wrist extension, and wrist flexion in non-paretic arm and shoulder extension in paretic arm. DMTE improved strength of shoulder and wrist extension and elbow flexion in paretic arm. No mean changes were significant for ROM.	patients' perception	
#19 Wu et al., 2011	Double-blinded RCT	N=66 CIMT n=22 BAT n=22 Control n=22 Age = 53.1, 17F, 49M >6 months post stroke, Mean= 16.2 months, stroke type not reported, Lesion side 30 R, 36 L purposive sampling	Compared the efficacy of distributed CIMT, BAT and control treatment on motor control and functional performance of the upper limb in stroke patients	CIMT, BAT, Control treatment	CIMT: functional tasks of daily activities in the affected arm and restriction of the unaffected arm. BAT: simultaneous movements in symmetric or alternating patterns of both arms in functional tasks, involving lifting 2 cups, picking up 2 pegs, grabbing and releasing 2 towels, wiping the table using two hands. Control treatment: functional tasks for hand function, coordination, balance, stretching, and weight bearing of the affected arm. Follow-up test was NOT conducted.	CIMT and BAT groups had smoother reaching trajectories in unilateral (p=.037) and bilateral tasks (p=.03) than the control group. BAT group had a higher peak velocity than control group in both bilateral (p=.019) and unilateral reaching (p=.003). CIMT group had decreased WMFT time (p=.044) and higher functional ability scores (p=.020) than the control group. CIMT group had higher gains in MAL-AOU (p=.005) and MAL-QOM (p=.015) than BAT and control groups.	Kinematic (paretic arm only, only the reaching phase was measured), WMFT, MAL	17
#20 Wu et al., 2007	RCT	N=30 Experimental n=15 Control n=15 Age =54.0, 13F, 17M 1-3 years post stroke, Mean=	Evaluated motor control of the upper extremity during unilateral and bimanual functional tasks and functional changes during	mCIMT, Traditional therapy	mCIMT: training for the affected arm and restriction of the unaffected arm, including a procedure termed "shaping": selecting functional tasks tailored to the patient, increasing	Movement time (p=.013), total displacement (p=.011) and percentage of time to peak velocity (p=.009) were significantly improved in bimanual tasks in CIMT group. CIMT group also had greater gains in FIM (p=.004) and MAL-	Kinematic (paretic arm only, only the reaching phase was measured), MAL, FIM	17

	18.1 months, Stroke type not reported, Lesion side: 11 R, 19 L Purposive and convenient sampling	daily activities in stroke patients treated with modified CIMT		task difficulty when the performance consistently improved, providing feedback when the task was successfully completed. Traditional rehabilitation: neurodevelopmental treatment emphasizing balance, stretching, weight bearing of the affected arm and bimanual tasks of ADL. Follow-up test was NOT conducted.	AOU (p<.0001) and MAL-QOM (p=.012) in bimanual task. In unilateral task, CIMT had greater percentage of time to peak velocity (p=.023), but there was no group difference in temporal and spatial efficiency.	

Note: ARAT: Action Research Arm Test; BAT: bilateral arm training; BI: Barthel Index; biCO: bimanual coordination factor; biFOP: bimanual forces; BRS: Brunnstrom Recovery Stage; CG; control group; COPM: Canadian Occupational Performance Measure; D&B: Down & Black scale; EG: experimental group; FAT: Frenchay Arm Test; FIM: Functional Independence Measure; FMA-UE: Fugl-Meyer Assessment for Upper Extremity; MAL: Motor Activity Log; MAS: Motor Assessment Scale; MMDT: Minnesota Manual Dexterity Test; MMT: Manual Muscle Testing; MoCA: Montreal Cognitive Assessment; mRS: modified Rankin Scale; NHPT: Nine Hole Peg Test; PPBT: Purdue Peg Board Test; RCT: Randomized control trial; ROM: range of motion; SIS: Stroke Impact Scale; UMAQS: the University of Maryland Arm Questionnaire for Stroke; WMFT: Wolf Motor Function Test; Y-BAT: Yonsei-Bilateral Activity Test.

Additional Note 1: Each article was given a number to be referred to in the results. The numbers were sorted by the alphabetical order of the name of the first author.

Additional Note 2: “Age” represents the mean age of the participants in the original study.

Table 6

Details of methodological approaches and theoretical concepts

Authors, year	Bimanual discrete and continuous tasks in outcome measure	Kinematic variables	Symmetrical bimanual task in outcome measure	Asymmetrical bimanual task in outcome measure	Correlation/ angle-angle plot	Theoretical frameworks and concepts mentioned in the study
#1 Ambreen et al., 2021	N/A[1]	N/A	N/A	N/A	N/A	N/A
#2 Arya et al., 2019	N/A	N/A	N/A	N/A	N/A	Interlimb coupling (implicitly mentioned only)
#3 Burgar et al., 2011	Reaching (data not reported)	Not reported	N/A	N/A	N/A	N/A
#4 Cauraugh & Kim, 2002	N/A	N/A	N/A	N/A	N/A	*Dynamic system approach* appeared in both introduction and result: stable and coordinated movement patterns emerged spontaneously when two arms executed the same movement. The protocol of in-phase coordination and EMG-triggered stimulation was consistent with the concept of dynamic system which executed movements in through the interaction of sensory input and motor actions. Both arms were linked as a *coordinative structure* unit when the homologous coupling of muscle groups were performing a task. (implicitly)
#5 Cauraugh et al., 2009	N/A	N/A	N/A	N/A	N/A	Interlimb coupling (implicitly mentioned only)
#6 Chang et al., 2007	Unilateral reaching task: reaching and touching a cup with the paretic arm, without	Peak velocity, percentage of time to peak velocity, movement time,	N/A	N/A	N/A	N/A

	picking it up, as rapidly as possible	normalized jerk score				
#7 Doost et al., 2021	A coordinated bimanual task with robotic devices: controlling a virtual tray by circular mirror bilateral movements	SAT = speed/error = the speed of the tray/angle of the tray compared to horizontal axis	N/A	N/A	N/A	The application of *motor learning* principles might enhance motor recovery: repetition of a motor task leads to lasting improvements in motor accuracy; learning a motor skill shifts the speed-accuracy trade-off and decreases motor variability; motor skill learning can be featured by retention and generalization of the skill to untrained conditions.
#8 Gerardin et al., 2022	A coordinated bimanual task with robotic devices (reaching to a target by controlling the handle along a single axis for each hand)	BiSAT= speed/error BiCO = the minimum value between hand velocities/ the velocity of both hands.	N/A	N/A	N/A	*Motor learning principles* were consistent with the aim of the stroke rehabilitation. A learned motor skill can be retained for long periods of time, thus leading to lasting performance improvements.
#9 Jung et al., 2013	Bimanual reaching and unilateral reaching	Mean velocity, peak velocity, trajectory ratio (movement straightness)	Bimanual symmetric reaching	N/A	N/A	N/A
#10 Kale et al., 2019	N/A	N/A	N/A	N/A	N/A	N/A
#11 Kim & Park, 2019	N/A	N/A	N/A	N/A	N/A	N/A
#12 Liao et al., 2011	N/A	N/A	N/A	N/A	N/A	*Motor learning* facts: stroke patients usually had difficulties in transferring motor skills learned in therapy to daily living environment.
#13 Lin et al., 2015	N/A	N/A	N/A	N/A	N/A	Interlimb coupling (implicitly mentioned only)
#14 Pandian et al., 2015	N/A	N/A	N/A	N/A	N/A	Interlimb coupling, coordinative structures (implicitly mentioned only)

#15 Van Delden et al., 2015	N/A	Mean amplitude (the distance between peak extension and peak flexion divided by 2), cross-correlation coefficient	N/A	N/A	Cross-correlation was calculated for coupling strength in bimanual rhythmic wrist movement, in which a positive coefficient indicated in-phase pattern.	The authors hypothesized that bimanual training would induce stronger *interlimb coupling effect* between the hands compared to unimanual training. The degree of *interlimb coupling* was assessed using rhythmic bimanual tasks in which patients needed to simultaneously flex and extend the wrists in specific coordination patterns.
#16 Waller et al., 2008	Unilateral reaching with the paretic or non-paretic arm; bilateral reaching as rapid as possible	Movement onset and offset; movement time; peak velocity; peak acceleration; number of movement units; hand path ratio	Bilateral symmetric reaching	N/A	N/A	Fitts' law: the fundamental basis of using a bilateral arm training was to take advantage of the neuromotor functional coupling noted when both arms move together. (Implicitly mentioned only) Task specificity: different types of training would incur different motor control gains. (Implicitly mentioned only)
#17 Whitall et al., 2000	N/A	Active/passive ROM of the joints of paretic arm	N/A	N/A	N/A	Repetition (forced use), goal setting (real object) and receiving feedback (auditory cues and visual information) were fundamental to *motor learning*. Coordinative structures (implicitly mentioned only)
#18 Whitall et al., 2011	N/A	ROM of joints of the paretic arm	N/A	N/A	N/A	BARTAC was based on *motor learning principles* including repetition, feedback, and goal setting. Interlimb coupling Coordinative structures (implicitly mentioned only)
#19 Wu et al., 2011	Bimanual discrete cooperative task at a comfortable speed, Unimanual reach-to-press task as fast as possible	Movement time, movement unit, peak velocity, percentage of movement time where peak velocity occurred.	N/A	Pulling a drawer with the affected hand and retrieving an eyeglass case inside the drawer with the unaffected hand at a comfortable speed.	N/A	BAT and CIMT both based on principles of *motor learning*, including repetitive practice, task orientation, and goal directedness. Interlimb coupling (implicitly mentioned only)

#20 Wu et al., 2007	Bimanual discrete cooperative task at a comfortable speed, Unimanual reach-to-press task at a comfortable speed	Movement time, total displacement, The percentage of movement time when peak velocity occurs	N/A	Opening a drawer with the affected hand and using the unaffected hand to retrieve an eyeglass case inside at a comfortable speed	N/A	N/A

Note 1: N/A represents “not applicable”, which indicates that the study did not provide the information of interest