ABSTRACT

STUDY OF TRAJECTORIES OF VISUALLY GUIDED MOVEMENT OF UNIMANUAL AND BIMANUAL TASKS

by
Deepthi Anand

Restitution of upper limb mobility following stroke is one of the major challenges facing clinicians in the country today. The complexity of performing skilled tasks with fine movements makes restitution of mobility all the more complex for rehabilitation specialists. Although several techniques have been evolved for, limited success with transfer of training from the clinical environment to functional performance clearly indicates a need for research and development in the area of upper extremity rehabilitation.

Bimanual coordination has recently surfaced as a novel and effective way to fast and lasting recovery. The success of bimanually coordinated training encourages a better understanding of the underlying neural, physiological and engineering principles involved which in turn would result in improved treatments for people with hemiparesis. An apparatus developed in this project enables such an understanding, by successfully being able to collect, record and analyze the movement trajectories of both the hands simultaneously with a high degree of accuracy.

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By

Deepthi Anand

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STUDY OF TRAJECTORIES OF VISUALLY GUIDED MOVEMENT OF UNIMANUAL AND BIMANUAL TASKS

Deepthi Anand

12/19/01

Dr. Richard Foulds, Dissertation Advisor — Date
Associate Professor and Associate Chair for Research,
Biomedical Engineering, NJIT

12/19/01

Dr. David Kristol, Committee Member — Date
Professor and Acting Chair, Biomedical Engineering, NJIT

12/19/01

Dr. Stanley Reisman, Committee Member — Date
Professor, Biomedical Engineering, NJIT

BIOGRAPHICAL SKETCH

Author:	Deepthi Anand
Degree:	Master of Science in Biomedical Engineering
Date:	January 2002

Undergraduate and Graduate Education:

- Master of Science on Biomedical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 2002

- Bachelor of Science in Biomedical Engineering,
  Manipal Institute of Technology, Manipal, India, 1998

Major: Biomedical Engineering

Presentations and Publications:

Anand D., Niranjan U.C,

> "Watermarking Medical Images with Patient Information." IEEE-EMBS International Conference on Biomedical Engineering. Hong Kong, December, 1998.

You see things, and you say “Why?” but I dream of things that never were,

and I say "Why not?" -**George Bernard Shaw**

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CHAPTER 1

INTRODUCTION

1.1 Bimanual Reaching

In a landmark study conducted by Kelso (1979), it was found that irrespective of the differences in difficulty of the task, when two hands performed simultaneously, they reached the target at almost the same time. This data was interpreted as indicative of an underlying coordinative structure where "the two limbs were constrained to perform as a single synergistic unit within which component elements vary in a related manner". (Kelso et. al. 1983).

Studies conducted by Steenbergen et al. (1996) demonstrated a similar tight temporal coupling in people with hemiparesis. Large asymmetries that were present in unimanual reaching were appreciably reduced when the same task was performed bimanually, when the subjects moved the impaired and non-impaired limb to separate targets. A reduction in the reaction time of the affected limbs was reported in this study, in contrast to the slower reaction times when performing the same task unimanually. Sugden and Utley (1995) observed two different ways in which the patients actually achieved the coupling. In some instances, the execution time of the impaired hand was reduced, while at other times, the execution time of the non-impaired hand was increased.

Swinnen et al. (1997) have found that movements in-phase (where both the hands move toward or away from the midline) to be more stable than anti-phase movements (one hand moves toward the body, the other moves away). Mudie

(1996, 2000) reports improvement in the performance of the affected limb with bilateral isometric training over a period of time.

Such normalization of upper limb movement encourages a deeper understanding of the underlying principles behind bimanual coordination. So far, it has been observed that during visually guided reaching movements, temporal coupling is achieved and reaction and execution times are shortened in the affected limb in people with hemiparesis (Steenbergen, Mudie, Swinnen). However, few empirical studies have observed the movement strategies adopted during bimanual movement. It is the purpose of this research to develop tools to critically and scientifically observe the kinematics of reaching tasks associated with bimanual reaching of those with hemiparesis due to stroke.

1.2 Motivation

Each year, about 400,000 people in the United States survive strokes, such that the number of stroke survivors now approaches three million. The estimated cost exceeds $7 billion per year for rehabilitation and lost revenue. Persons with hemiparesis following stroke constitute the largest group of patients receiving rehabilitation services in this country.

Attempts to facilitate recovery of motor function are a major part of traditional rehabilitation programs for stroke. Approximately 70-80% of persons with ischemic stroke have some degree of motor impairment, and this is often the most obvious deficit to the patient and the family. Surveys of persons with stroke suggest that recovery of motor function is one of the most desired outcomes of rehabilitation.

Restitution of upper extremity movement poses a particular challenge to clinicians specializing in movement rehabilitation. The hand needs to be able to grasp, manipulate, and stabilize objects to the required location. Sophisticated motor control mechanisms have evolved to ensure the coordination of reaching and grasping to effectively manipulate objects with variable properties in a range of contexts. Given this complexity, it is not surprising that the upper extremity is challenging to rehabilitation. Limited success with transfer of training from the clinical environment to functional performance (Kelso, 1983) clearly indicates a need for research and development in the area of upper extremity rehabilitation.

CHAPTER 2

BACKGROUND

2.1 The Development Of Bimanual Coordination

Much of the repertoire of human skills is performed conjointly with both hands and with high spatial and temporal precision for proper bimanual coordination and its neural control is central to skillful human behavior as well as to the neurology of movement disorders.

When attempting to perform various combinations of tasks with upper limbs, it becomes apparent that some skills are easier to perform, whereas others are extremely difficult. Patterns of interference arise from a natural tendency to synchronize the upper limbs, resulting in preferred patterns of interlimb coordination. The synchronization tendency is often so powerful that considerable practice is required to overcome this effect in order to produce differentiated patterns of activity in the limbs.

In recent years, systematic attempts have been undertaken to describe and characterize preferred patterns of intralimb and interlimb coordination. With respect to interlimb coordination, a distinction is frequently made between two kinds of coordinative patterns.

Some coordinated patterns require the active participation of both hands with relatively similar output, examples are separating the yolk from the white of the egg and piano playing. Other complimentary bimanual movements require asymmetrical roles from the two hands, one hand assuming a more passive role in holding and stabilizing an object while the other hand manipulates it. Examples are threading a needle, opening a drawer to pick something up, cutting with a pair of scissors; these actions do not necessarily have to imply symmetry of movement in reference to body space. In addition, in some bimanual activities requiring complementary movements, the hand that becomes passive is more active in the initial stages of learning, as will be discussed later in this chapter. Nevertheless, it is obvious that symmetry, related to either role or movement, is particularly relevant when studying bimanual coordination, in terms of child development as well as in terms of learning.

Development of bimanual coordination must be approached from this point of view. Children acquire complex bimanual skills, involving similar as well as complimentary coordinated movement patterns, such as tying shoelaces, buttoning shirts and lifting objects. The aim of this chapter is to describe how the early, more symmetrical bimanual patterns of movement give way to more complex forms of coordination.

2.2 Bilaterality in Early Motor Patterns

Symmetrical bilateral patterns of arm movements have been a clear part of an infant's motor response repertoire. These movements can be observed at birth in primitive reflexes, such as Moro's reflex, that involve symmetrical arm abduction and extension with the hands open and fingers generally flexed (Andre-Thomas, 1952; Illingworth, 1978; Mitchell, 1960). Symmetrical arm extension has also been observed in conjunction with the first respiratory movements of the newborn (Bergeron, 1947) and in an infant's spontaneous motor activity during the first month. These movements consist of poorly coordinated bilateral extensions of all segments of the arms (Launay, 1962). Whether or not these neuromotor patterns are involved in some way in later, more complex coordinative patterns is an unresolved issue. In any case, the term bimanual coordination is inappropriate before voluntary control of action is possible in normal conditions. Moreover, most of the spontaneous hand movements of the newborn are unilateral or asymmetrical (Cobb, Goodwin and Saelens, 1966).

2.3 Hand Interplay and Bilateral Reaching: Role of Postural Development

"Mature" object prehension in 5 to 6 month olds is mostly unimanual, when the size of the object permits it. Between the unilateral response to an object of the 2-month-old and the unilateral object prehension in older infants, there are stages of bilateral arm activity with or without the presence of an external object. These bilateral arm movements form early parts of bimanual coordination. As the tonic neck reflex fades, the arms are released from their asymmetric posture. They are less limited in the variety of positions that they can take, and they can move in similar patterns. This allows mutual discovery of the hands at some point near the middle of the infant's chest.

The infant's earliest patterns of bilateral arm activity consist of playing with parts of his/her own body, such as hand interplay or clasping hands at the midline. These patterns are initially nonvisual and usually occur several weeks before the child begins to look at this tactual interplay of his/her hands (White, Castle & Held, 1964). This behavior is not seen before 3 months of age. Shortly thereafter, the infant's response to object representation changes.

Unilateral responses that are commonly reported in 2 -3 month olds are replaced by responses that are in most cases bilateral. However, bilateral responses such as hand clasping over the midline are first restricted to midline representations of objects. At 3 1/2 months bilateral responses begin to predominate even to a side presentation (White et al., 1964). It is about this same age that Provine and Westerman (1979) observed that infants could cross the midline to reach for an object presented in a side position when the other hand is restricted. These authors see this behavior as an important step in the emergence of bilateral coordination. At 4 to 4 1/2 months bimanual reaches are the most common responses to all presentations.

In the first responses to object presentation, grasping is not yet directed toward the external object, but rather remains centered on the tactual interaction of the infant's own hands. Between 2 and 4 months changes occur in the extension synergy during response to object presentation. After 2 months of age, hand opening, which is part of the extension energy of the newborn, becomes restricted to condition in which the infant fixates the object and can therefore be considered as a meaningful adaptive behavior (von Hofsten, 1984). A few weeks later, at about 4 to 41/2 months, crude attempts at grasping the object appear. At the same age, although arm transport toward the object is still bilateral and rather symmetrical, one hand reaches the object first. After visually guided reaching and smooth grasping are well established, at 5 to 6 months of age (von Hofsten & Fazel-Zandy, 1984), there is a linear decrease in the number of bimanual reaches with age (Bresson, Maury, Pieraut-Le Bonnied & de Schonen, 1977). From this age, bimanual reaches depend on the characteristics of the object.

2.4 Bilateral Reaching and Object Perception: The role of Object Presentation and Object Size

After 5 months of age, bilaterality versus unilaterality of reaching is a function of factors such as object presentation and object size. Bresson et al. (1977) have shown that the age up to which bilateral reaching for an object remains predominant is dependent on the way the object is presented. This period is relatively short when the object is placed on the fingertips, longer when on the palm or on a cube, and still longer when presented on a board. This is interpreted as resulting from a perceptual effect of a dual system of borders (object and support), in line with the Piagetian interpretation of the difficulty encountered by 8-month-old infants in grasping an object when it is placed on certain kinds of supports (Piaget, 1937).

It has been shown that object size influences the pattern of response to object presentation even before the infant is capable of reaching for and grasping the object (Bruner & Koslowski, 1972). After 7 months of age, the modality of approach (bilateral or unilateral) toward the object to be grasped varies with the size of the object: bilateral for large objects, more unilateral for small objects (Flament, 1975).

These findings suggest that the kind of movement pattern used by the infant for reaching is a function of both postural development and perception of the object properties. It is through the acquisition of the midline position of the head and postural development that infants achieve greater symmetrical positions of the limbs. This may help them become aware of their two upper limbs, first tactually, then visually, and they experience their first voluntary grasping on parts of their own bodies. This midline coordination is an important first step towards bimanual coordination.

Bilateral arm extensions in response to object presentation in 3-4 month olds and bilateral reaching in 4 and 5 month olds may be seen as initial evidence of bilateral coordination and also as precursors to bimanual coordination seen a few weeks later in object manipulation. These early patterns of bilateral coordination mainly (but not entirely) involve symmetrical movements of the two limbs. But bilateral reaching movements of the two limbs are not exactly symmetrical; one hand reaches for the object first.

2.5 Bimanual Coordination in Early Object Manipulation: Similarity of Output from the Two Hands

At an age when grasping of an object becomes mostly unimanual, its manipulation becomes bimanual. Postural acquisitions, such as the sitting posture, allow for considerable transformation in object manipulation during the second half of the first year of life. In turn, these manipulations increase the infant's knowledge of object properties (Piaget, 1937), which is reflected in later stages of object manipulation. After about 7 months of age, infants begin playing with two toys at a time. Behavioral patters involving association between objects increase after this age (Flament, 1975).

In a study of bimanual coordination of 7 - 24 months old children, Jacqueline Fagard (1990) found that all 10-month-old infants in the study could separate a tube from the cylindrical wooden container in which it was inserted and so very easily by pulling the parts with mirror movements. This suggests that the capacity to coordinate symmetrical movements of the two hands is present in infants before they are capable of complementary asymmetric activities.

A change in spatiotemporal relations of bimanual movements for reaching has been observed between 7 and 11 months of age. Goldfield & Michel (1986) observed a "loosening" of the temporal linkage between movements of the two hands. Changes in the nature of interlimb coordination also concern spatial relations between both hand movements. In their study, the 7 month olds moved both hands in the same direction. Such "loosening" of the spatiotemporal linkage may represent a step toward bimanual coordination of asymmetrical movements, a prerequisite for most bimanual complementary movements.

2.6 Onset of Complimentary Bimanual Movements

Ramsey & Weber (1986) reported developmental changes in bimanual coordination between 12 and 18 months of age. Here the two hands take on coordinated asymmetrical roles, one hand being active (generally the preferred right hand) in contrast to the more passive (supporting, stabilizing) role of the other (most often the left hand). Some authors (Bresson et al., 1977; de Schonen, 1977) have observed the earliest stage of role differentiation in the slight asymmetry of bilateral reaching at 4 to 5 months of age when one hand reaches the support earlier and the other hand follows on the object.

Studies on the development of complementary bimanual movements have at times been complicated by the fact that the activities chosen for the testing involve not only complimentary movements from the two hands, but also sequential, ordered components of action. Complementary two-handed strategies become increasingly frequent at the start of the second year. Eventually, by approximately the middle of the second year of life, bimanual attempts involving complete differentiation of roles for the two hands predominate: infants open the door with one hand and remove the object with the other hand. Bruner concluded that there is a progressive differentiation and integration of the component acts.

2.7 Laterization in Bimanual Coordination

The symmetrical bilateral approach to the object presented at the midline is associated with a unimanual first contact with the object. From 22 weeks onward, it is mostly the right hand that contacts the object first (Flament, 1975; Bresson et al., 1977). Ramsay & Willis (1984) found no evidence for a preference in this collaborative reaching. Goldfield & Michel found that unimanual hand-use preference contributes significantly to the selection of a leading hand in nonsimultaneous bimanual reaching for a large object.

A hand preference in tasks requiring bimanual coordination of complementary movements in which one hand holds the object for the other hand to explore has been found to emerge at the end of the first year (Mitchell et al., 1985; Ramsay, 1980). For most children, the left hand holds the object to allow the right hand to perform active manipulation. In one study (Ramsay, 1980), the onset of bimanual handedness in infants was observed to be related to a specific milestone in their speech development: the appearance of expressions with a different consonant and vowel sounds across syllables. In the Michel et al. study (1985) measures of hand-use preference of 6 through 13-month-old infants were compared in reaching for objects, manipulating objects, and for coordinating complementary bimanual actions. Handedness characteristics for bimanual action were found to be similar but not identical to those for manipulating and reaching. Discordance of hand-use preference for coordinating bimanual action and reaching mainly concerned the 13-month age group, the only age group for which a right hand use preference did not predominate over a left preference.

In the Ramsay & Weber (1986) box-task study, the 13 year olds used the right hand more often to open the door, whereas 17-19 month olds used the left. The authors argue that this might reflect the progressive ability of the dominant hemisphere to control the non preferred as well as the preferred hand and to sequence their separate movements. Whatever the underlying neural control, it is worth noting that the younger children change their hands to formerly non preferred hands, apparently to facilitate using the preferred one for the more active role in manipulation, a change no longer needed later on when retrieving the toy becomes as easy as opening the door. The pattern of bimanual handedness is thus closely related to the level of sensorimotor skill involved in the bimanual activity, as well as its anticipation by the infant.

2.8 Development of Bimanual Coordination During Childhood

After the second year, the variety and complexity of tasks that can be performed using both the hands increases drastically. There is an overall improvement in the acquisition of motor skills during childhood. Aside from cognitive factors involved in motor learning related to information processing, learning strategies and the like, motor constraints make the organization or reorganization of subroutines of motor learning become more or less difficult. These constraints concern the temporal and spatial relationships between parameters involved in the different effectors of the synergy, the problems are somewhat different when the skill to be learned involves bilateral segments, as for bimanual coordination. The symmetrical organization of the body- the fact that each hemisphere mainly controls the opposite limb and that interhemispheric fibers mostly connect homotopic sensorimotor areas of the cortex- induces supplementary motor constraints on bimanual coordination. It has already been observed that symmetrical coordinated patterns appear earlier in development rather than asymmetric coordinated patterns. This is an important constraint.

2.9 Age Changes in Patterns of Complementary Bimanual Movements in Familiar Activities

Two different studies have focused on the modification of strategies in complementary movements involving both hands. Both show that role differentiation between the two hands increases with age. Bruml (1972) studied the change in bimanual preference in 5, 8 and 10-year-old children in three different situations. Children were asked to thread beads, with a thread around a spool, and applaud. All three tasks were scored for the presence of a pattern of use reflecting coordinated roles for the two hands, in which one hand remained in a stable position while the other hand moved. In all three tasks the moving hand tended to be the right for right-writing children.

With age, the child's repertoires of bimanual skills grow. Moreover, activities tend to be more asymmetrical. Whenever a new bimanual task is being learned, facilitation for symmetrical patterns of movements, as opposed to other patterns, crops up (Fagard, 1990).

2.10 Age Changes in Bimanual Coordination in Different Conditions of Task Constraints

Several studies on bimanual learning have compared children's performance as a function of the required relationship between movements of two hands. They tend to show that the easiest patterns of movements are the mirror movements, that is, movements symmetrical with reference to the body axis. Drawing circles and horizontal lines with both hands simultaneoulsy was achieved without much difficulty by 4 - 13 year olds. Drawing squares, however, depended on the muscle groups employed together. In order of increasing difficulty, the tasks are unimanual, bimanual with total muscular homology (mirror drawing), bimanual with partial muscular homology (parallel drawing) and bimanual without muscular homology (parallel drawing without starting at different points for the two hands).

In a study by Fagard & Barbin (1987), a series of experiments were conducted to compare performances between mirror and parallel movements in children. It was observed that when tasks required the subject to move both hands at the same velocity, moving the hands in a mirror image resulted in better performance than moving it in the same direction. This difference in ability decreased with age. All movement conditions and all ages performed much better when the task required both hands to rotate at the same velocity than when different. Practice improved the performance of only 7-9 year olds significantly. In the same velocity conditions, the deviations toward the right hand controlled axis were more than the left.

This series of exercises reflect upon the fact that different constraints affect the early stages of acquisition of a bimanual skill of this type and affect the younger more than the older children. This is the case of the temporal coupling of simultaneous similar movements. The limbs are apparently constrained to act as a single unit. This facilitates interlimb coordination when the task requires identical motor output from both limbs but interferes with interlimb coordination when the task requires asynchronous output. Another example is found in the symmetry constraint with respect to the body axis. When the required movements are at the same velocity, mirror movements are easier than parallel movements for younger children. Manual lateral symmetry reveals a third constraint on this kind of task. A slight lead of the preferred hand hampers perfect synchronization and symmetry. Manual symmetry in a bimanual task with similar roles for both hands has also been found in rhythmic tapping (Wolff & Hurwitz, 1976). When subjects are required to alternate hands in tapping at a steady beat in time with a metronome and to maintain the same rhythm after the metronome is turned off, younger right-handers are more precise with their right than left hands.

2.11 Bimanual Coordination in Adults

Adult human skills typically require the cooperation of both hands. Motor control learning studies reveal that the preference for bilateral performance of the upper extremities continues into adulthood (Kelso, 1983; Schmidt, 1988). When the two upper extremities perform bilaterally, the spatial and temporal relationships within the muscle groups in the extremities appear to be constrained to behave as coordinated units (Tuller et al., 1982). This phenomenon is referred to as entrainment (Tuller et al., 1982). Additionally, when the two upper extremities perform an action simultaneously with the same temporal and spatial constraints, entrainment is so pronounced that interference with the actions of one extremity by imposing a perturbation is "mirrored" in the action of the other extremity (Kelso, 1983).

There is no simple answer as to how the two brain hemispheres cope with the problem of bimanual coordination - each task demands something different- and the coordination seems to be primarily constrained by the environment itself. For example, swimming requires a strong coupling of both arms, whereas peeling an orange with one hand while holding it in another is an entirely different bimanual act. A bimanual skill like typewriting requires to a large extent, independent manipulations. Playing a musical instrument like the piano is a particularly skillful bimanual motor performance. It is most likely that the individuated finger movements of each hand are controlled by the respective contralateral hemisphere via the cortico-motoneuronal component of the pyramidal tract. Yet the individuated finger movements are also subject to controls of an entire phrase of music; to the phrase the artist will consciously attend and put into it all his or her interpretation of the music.

Kelso, Southard, and Goodman (1979) had subjects make two-handed aiming movements to separate targets. In one condition, the right hand had to move as quickly as possible a short distance to a large target on the right, while the left hand had to move a large distance to a small target on the left. Strong determiners of the time required to make these moves are the movement distance and the size of the target to which the limb is aimed, according to Fitts' (1954) law. Fitts' law predicts that because the right hand has a shorter distance and a larger target, the time for the right hand should be far shorter than the time for the left. (When the moves are done in isolation, one at a time, this result occurred.) Which hand arrives first to its respective target when the subject is instructed to move both hands at the same time? Kelso et al. found that, rather than arriving at markedly different times as Fitts' law would predict, the two hands arrived at their respective targets almost simultaneously. Moreover, the two hands appeared to be "locked" or entrained, in that the time of maximum height of the hand, the time for peak acceleration, the shapes of the trajectories, and so forth, were remarkably similar for the two hands.

In another experiment, when the two hands moved the same distance to the same sized target, Kelso et al. placed a cardboard barrier between the starting location and the left-hand target only, so that the left hand had to move with a trajectory of approximately twice the height to clear the barrier. Even though the right hand did not have this barrier, when the two hands were moved to their respective targets at the same time, the right had moved over its "barrier" just as the left hand did. Again, the two hands appeared to be strongly "locked" together, and this effect persisted for 10 to 20 trials, although a symmetrically lower trajectory in the right hand occurred over trials.

2.12 Between Limb Asynchronies During Bimanual Coordination

Kelso et al. (1979, 1983) and Schmidt et al. (1979) interpreted these findings to mean that a single structure was controlling both hands. Certain features of the movements- predominantly the phasing characteristics of the two limbs- appeared to be invariant across the two hands. Other features, however, such as the distance the limbs traveled, appeared to be easily changed between the two hands, and this might mean that distance was determined by parameters to the two limbs (an overall force parameter) that were selected differently for the right and left hands (Schmidt et al. 1979). Marteniuk, MacKenzie, and Baba (1984) and Corcos (1984) however, found this coupling between hands was as tight as Kelso et al. (1979) had suggested, with the hands having slightly different movement times (as much as 16% in Corcos' study) when the movements were increasingly different in extent.

A study conducted by Swinnen (1996) under different vision conditions showed that the interlimb asynchronies become evident at the micro scale analysis. Further more, they showed that this asynchrony is a function of manual dominance and attentional bias. This finding was supported by previous research by Stucchi and Viviani (1993), who identified a similar phenomenon during bimanual ellipse drawing in the frontoparallel plane. They found that the dominant hand led the non-dominant hand by about 15-30msec, depending on the coordination mode.

That this asynchrony was found to be less apparent in left-handers than right-handers is interesting because they invite some speculations about the cerebral control of bimanual cyclical coordination. Liepmann (1908) found that left-hemisphere of right-handers plays a primary role in motor control functions in general and interlimb coordination in particular (cited in Swinnen, 1995). This is inferred from the fact that the dominant limb led the non-dominant limb and also from the formers overall superior circle drawing capabilities in Swinnen's (1995) experiment. These findings are consistent with the hypothesis that the left hemisphere in right- handers is superior in movement execution (Carson, 1992; Fisk, 1985). In addition, the left hemisphere may also be endowed with superior bilateral control functions that are possibly recruited during the production of bimanual coordination patterns. The underlying neural mechanisms involved in bimanual coordination are explained in more detail in the next chapter.

CHAPTER 3

THE UNDERLYING MECHANISMS OF BIMANUAL COORDINATION AND THEIR DEVELOPMENT

3.1 Coordination synergetics

Interlimb coordination has been the subject of much experimental investigation in the field of neuromuscular research and psychology alike, particularly from a dynamical system perspective (Kelso, 1995). This perspective is based on three tenets, mainly inspired by synergetics, a theory on self-organization in complex systems (Haken, 1983):

a) Coordination patterns emerge from the mutual influences between interacting systems (e.g. neural, muscular, mechanical etc.);

b) These patterns can be characterized by an order parameter, that is a variable which capture the reduction of the degrees of freedom of the interlimb action system (Kelso, 1995); and

c) Pattern stability, loss of stability and the transition between existing patterns reflect underlying coordination dynamics than can be captured formally by an equation of motion of the order parameter (Haken et. al, 1985).

Some of the most promising support for this approach has been shown in bimanual coordination tasks. Bimanual coordination is characterized by two preferred patterns:

- In phase
- Anti phase

The in-phase pattern involves symmetrical motion of the hands in opposite directions due to the simultaneous activation of homologous muscles. Anti-phase patterns involve motion in the same direction with simultaneous activation of homologous muscles. As mentioned earlier, the in-phase pattern proves to be more stable than the anti-phase pattern, and an unavoidable switch from the latter to the former occurs when the oscillation frequency of the two limbs increases beyond a critical threshold.

The behavioral picture of this spontaneous dynamics of bimanual coordination was formalized through the dynamics of the relative phase between the components, using non-linear oscillators that are coordinated by a low energy (non-linear) coupling function (Kelso, Haken et. al, 1995). At a conceptual level, relative phase may be considered an abstract coordination variable rather than an expression of the inherent properties of the neuromuscular-skeletal system (Kelso, 1994).

3.2 Coalition of Constraints

3.2.1 Temporal constraints and coordinative structures

The fact that different effectors of a synergy are constrained in their temporal and spatial relationships between the effectors by dislocating "pre-existing arrangements of inherited or habitual repertoire of action" (Paillard, 1986) and reorganizing new temporal and spatial relationships between the effectors involved. Temporal constraints have received much attention in the context of bilateral activities through the notion of coordinative structures.

The symmetrical pattern appears prior to asymmetrical ones and that the difference between mirror and parallel movements decreases with age suggests that some maturation is taking place, which helps the child progressively, depart from his basic synergies while building new ones. Mirror coactivation may need to be inhibited and interactions between hemispheres developed for asymmetrical movements to be coordinated more easily. The role of interhemispheric interactions in bimanual coordination has been assessed by studies on bimanual coordination of patients having partial or complete section of the corpus callusum lost. There is some anatomical evidence that mylenation of the corpus callosum is not completed until the end of the first decade of life (Yakolev & Lecours, 1967). Electrophysiological evidence also suggests maturational changes in commissural transmission time that are consistent with the sequence of myelination of the corpus callosum.

Few behavioral studies provide direct support for a developmental increase in functional communication between the two hemispheres. The decrease in contralateral coactivation during unilateral motor activity and the increase of interhemispheric motor and tactile transfer between the two hands may be considered arguments in favor of this argument.

Mirror coactivation during unilateral movements is normal in children. These so-called synkineses decrease during childhood (Abercombie, 1964). The progressive inhibition of mirror movements may be involved in progress in bimanual coordination, in particular for the symmetrical to asymmetrical pattern of development.

The many degrees of freedom of the human motor system are thought to be controllable through coordinative structures that limit considerably the number of effectors to be controlled simultaneously and individually by the executing system (Bernstein, 1967; Kelso, Putnam & Goodman, 1983). In adults performing bilateral pointing tasks, for instance, the two limbs are apparently constrained to act as a single unit. As was observed previously, Fitts' Law does not hold well in the case of bimanual coordination. The same bilateral pointing task was studied in children within the ages of 5 and 14 (Southard, 1985). The results concerning movements of equal difficulty are interpreted as indicating the existence of coordinative structures as early as 5 years of age.

When the difficulty differs between the two hands however, a synchronous reach is often not found. Bimanual movements on different temporal parameters studied in adults in rhythmical finger tapping tasks reflected this difficulty in most cases (Klapp, Hill et. al., 1985; Peters, 1977). Such constraints may be overcome with practice, and learning consists of the reorganization of units for the solution of the new motor problem.

The levels of organization on which temporal coupling is applied may be built-in structures such as reflexes or inherent patterns such as mirror movements, or they may be gradually built into the system in functional sets specific to repeated movements (Clark, 1982). The ease of applying temporal coupling to mirror movements, as shown in the experiments previously presented, may be due not only to the fact that mirror movements are more "natural". When synchronous bimanual movements are executed simultaneously by homologous muscles, processing of movement-derived feedback may create less of a load, because it is redundant for both limbs, than when the same movements are executed by non-homologues muscles (Cohen, 1971).

Maturation of interhemispheric communication may or may not be responsible for the developmental decrease in mirror movements. The corpus callosum is one of the possible ways through which contralateral inhibition, whatever its pathways, and the development of interhemispheric transfer of information play a role in the increase of the capacity to learn asymmetrical patterns of bimanual coordination (Fagard, 1990).

Do changes in task-constraints, likely to affect movements of one limb (load changes or cutaneous anesthesia of the pulling hand) or of both limbs (removal of vision), also affect bimanual coordination? Perrig et al. (1999), found that changing constraints on one hand indeed resulted in significant delays in the execution of the non-disturbed contralateral hand. Since the adjustment is immediate, it is suggested that a single command to both arms was responsible for bimanual coordination. It seems like proper coordination is achieved by multiple sources of sensory signals, including visual, somatosensory and perhaps also spurious acoustic cues (Perrig et. al., 1999). Loss of one source could thus be effectively compensated for by other modalities. The important source of proprioceptors, which was not removed in their digital nerve-block experiments, may have been essential in preserving the goal invariance.

3.2.2. Movement Direction Constraints

Swinnen (2001) studied the effect of movement direction constraints (Figure 3.1). Abrupt directional shifts were made in one limb while preserving a particular direction in the other limb. Interference was evident and was maximal when orthogonal orientations were to be produced simultaneously with both limbs.

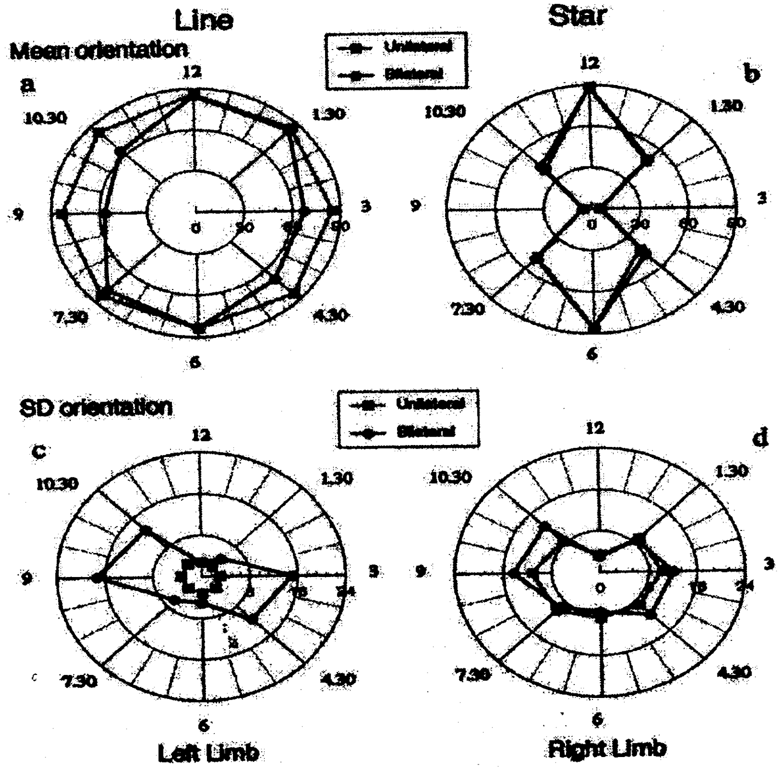


Figure 3.1: Polar plots from Swinnen's studies representing mean orientation (upper) and SD of orientation (lower) of left line drawing and right star drawing across the three mass-loaded conditions during unimanual and bimanual performance.

This may be because of the consequence of the neural architecture of the central nervous system, generating structural interference (Swinnen, 1997). There is strong evidence that the direction parameter is encoded in the CNS and interhemispheric pathways exchange information about spatiomotor information between the control centers of both upper limbs. Swinnen (2001) suggests that it is reasonable to assume that the production of bimanual movements involves the generation of two population vectors, one in each hemisphere. If the actual movements point in the same direction, then the neural population vectors are hypothesized to be compatible with each other and will not generate interference. Instead, they might even facilitate each other. If, however, different movement directions have to be performed simultaneously, interference between both population vectors is likely to emerge, giving rise to behavioral expressions of this interference at the level of movement kinematics.

Another interesting hypothesis made by Swinnen (2001) is that direction is to be understood within an egocentric rather than allocentric reference frame. This implies that the left and right limb movement directions are considered compatible when their orientation relative to the longitudinal axis of the body is the same even though this implies different directions in extrinsic space. The predominant tendency to move hands in a symmetrical fashion has been documented by Miege (1901) and Westphal (1873). Symmetrical limb movements constitute one of the most primitive modes of interlimb coordination that is largely unaffected by brain pathology (Wiesendanger, 1994). Symmetrical bilateral limb movements can be performed easily in intact subjects and even in patients who suffer from various CNS disorders (Wiesendanger, 1994).

3.2.3 Amplitude Constraints

When amplitudes differed in Swinnen's (2001) amplitude constraint experiments, it was predictably noted that the hand performing the larger amplitude tended to slow down. Also, some interaction between variables (direction and amplitude) was also observed. This indicates that higher-level processing in the nervous system pertains to the specification of both movement direction and movement amplitude that are associated with distinct neural resources. Also, it has been noted that several movement parameters co vary with movement amplitude such as velocity, acceleration, force/torque and muscle activity. Cross-talk is a frequently invoked concept to account for the observed interference in bimanual coordination (Marteniuk and MacKenzie, 1980; Marteniuk et. al., 1984; Preilowski, 1975; Swinnen, 1992). Generally spoken, cross talk refers to the phenomenon that two or more concurrent activities mutually influence each other. Bimanual movements with different amplitudes can be performed concurrently with the amplitudes becoming somewhat similar (Marteniuk and MacKenzie, 1980; Marteniuk et. al., 1984; Sherwood, 1990). Further, Spijkers (1997) demonstrated that pre cueing of the hands decreases reaction times considerably.

3.2.4 Force Constraint

Biased force, both spring loaded and mass loaded, did not reflect in any unusual interference (Swinnen, 2001). This might mean that if the motor cortical areas were strongly involved in the specification of muscle activation patterns to produce the different orientations, then changes in these patterns would modulate the degree of interhemispheric interference and give rise to an alteration of directional and amplitudenal specifications in the limb without the force constraint.

3.2.5 Biomechanical and Neuromuscular Constraints

Recent debate has focused upon the issue of whether general principles and laws of movement coordination may be derived without reference to anatomical, mechanical and physiological mechanisms (Carsin, 1996, 1998). It has been proposed that self-generated movements are governed by a coalition of constraints (Beek, 1998). Biomechanical constraints are seen as arising from the pendular dimensions of the limb or limb segments, whereas nuero muscular constraints are commonly associated with nervous and metabolic processes. The relative contribution of these constraints is thought to depend on the size of the effective pendulum constituted by the limb (Temprado et al., 2001).

Recent studies suggest that coordination dynamics are strongly influenced by the means through which they are implemented physiologically. In a study using a classical dual-task methodology, it has been shown that alterations of coordination patterns stability determine the attentional demands incurred by the central nervous system (CNS) to perform these patterns (Monno et. al., 2000; Temprado, 1999; Zanone, 1999). In these experiments, a dual task methodology was used to assess the attentional demands incurred by the CNS to maintain and stabilize voluntarily in-phase and anti-phase coordination patterns at different levels of oscillation frequency. The results of these experiments showed that pattern stability (i.e. relative phase variability) and attentional demands (i.e. reaction time (RT)) strongly co-varied. Specifically: (a) the most stable pattern (in-phase) was the less costly to maintain (Temprado, 1999). And (b) a loss of pattern stability, observed as oscillation frequency was manipulated around the preferred frequency, was paralleled by an increase in central cost. In an experiment by Temprado et al. (2001), it was seen that the effect of load on one hand was resulted in the loss of relative phase stability from intermediate levels of frequency. This suggested that the impact of inertial loading on coordinated two-hand movement is a function of oscillation frequency. Such a destabilization leads to an increase in the number of phase transition and a decrease in the time before transition.

To determine whether behavioral modifications of pattern stability involve a central cost for the CNS, Temprado (1999) compared the Reaction Times (RT) of the coordination patterns of anti-phase and in-phase bimanual movements. The results showed that pattern stability and the central cost expanded by the CNS to sustain preferred bimanual patterns co varied when oscillation frequency increased, suggesting that a modification of neuromuscular constraints manifested itself both in behavior and in central cost. Such a result could be expected on the basis of dynamical models of bimanual coordination and given the energetic interpretation of pattern stability and change. Neuromuscular constraints and a change in musculo-skeletal geometry affect the central cost incurred by the nervous system to maintain preferred coordination patterns.

3.3 Learning a New Bimanual Task: the Role of Feedback

Research on motor learning has predominantly been concerned with the acquisition of movement parameters, such as overall timing or force (Swinnen, 1997). This implies that pre existing movement patterns have to be scaled in accordance with externally imposed requirements. Studies of interlimb coordination are increasingly being examined relative to advances made in the area of interlimb *control* since the early eighties (Swinnen et al., 1994).

As discussed earlier, subjects find it relatively easy to produce bimanual oscillations with a 1:1 frequency ratio and the same amplitudes, with no phase offset. But it is much harder to produce the same oscillations with a higher phase offset. Swinnen designed a series of tests to examine the role of augmented feedback on the acquisition and retention of producing these oscillations with a 90° offset. Three groups of people were tested with reduced, normal and enhanced feedback. Their experiments demonstrated that concurrent relative motion information was beneficial to acquiring the coordination pattern in comparison to normal vision conditions and practice conditions with reduced feedback, as shown by the overall superiority of the enhanced feedback group. More importantly, the acquired skill transferred successfully to other transfer test conditions, relative to the other groups. This was rather striking because of recent reports that an excess of information feedback may be detrimental to retention and transfer as subjects might become too dependent on the feedback. This could be a significant tool in the rehabilitation of patients with CNS damage.

CHAPTER 4

STROKE AND REHABILITATION

Stroke is the third leading cause of death in developed countries, and the major cause of disability in adults. It is defined as the abrupt onset of new neurological abnormalities due to lack of blood flow to (ischemia) or bleeding (hemorrhage) in the brain. Approximately 85% of all strokes are ischemic, with hemorrhages accounting for about 15%. Often caused by disease of the cerebral blood vessels, strokes also can result from primary diseases of the heart or other parts of the body.

4.1 About Stroke

Roughly half a million Americans suffer strokes each year. More than 3 million people in the United States have survived strokes, of which more than 2 million suffer crippling paralysis, speech loss and lapses of memory. The total cost of stroke in this country is roughly $43 billion a year. The average patient incurs more than $15,000 in medical care costs during the first three months following the attack, although some severely stricken patients incur costs up to three times higher.

4.2 Anatomy of the Brain

The blood that is destined to supply different parts of the brain comes from the heart, and travels through a series of blood vessels known as arteries. These are tube like structures that carry the blood from the heart to various parts of the body. The largest vessel, the aorta, starts where blood passes from the left ventricle of the heart. A set of important arteries that supplies the anterior (front) part of the brain is known as the carotid arteries. The left carotid artery arises directly from the aorta, and the right comes from another blood vessel that arises from the aorta. They pass through the neck, and enter the skull. They then branch into a complex series of arteries which each have a responsibility to bring blood to specific areas of the brain. Important arteries include the middle cerebral and anterior cerebral arteries. The arteries that supply the posterior (back) part of the brain are known as the vertebral arteries. They arise from a vessel that comes form the aorta. They too, divide into smaller blood vessels that supply vital structures with blood. The major vessels in this distribution include the basilar artery, and posterior cerebral arteries.

All of these major, fairly large caliber arteries subdivide to form many small blood vessels that send blood to the deeper parts of the brain. The system has some built in protection against the acute interruption of blood flow, but this certainly does not protect against stroke in all cases. The presence of more than one blood vessel necessary to supply a particular area of brain is known as collateralization. If blood flow is interrupted, in some cases it can be delivered to brain structures by other existing pathways.

Arteriosclerosis (deposition of cholesterol and blood clot) often forms where arteries divide, as there is often more turbulence in blood flow at these sites. Common vessels involve the carotid and the vertebral arteries before they enter the brain, and the branches of these blood vessels once they enter the skull and supply the brain tissue.

4.3 Ischemic Stroke Types and Causes

The major subtypes of ischemic stroke include "large artery infarcts", lacunar infarcts (smaller penetrating arteries), and cardiac cerebral embolism.

Large Vessel Infarctions occur in one of the major blood vessels that supply blood to the brain. These include the middle, anterior and posterior cerebral arteries, and the basilar artery and its major branches. They result primarily from arteriosclerosis, in which a thrombus or accumulation of plaque, cholesterol and blood clots, begins to form in the blood vessel wall, eventually increasing to the point where blood flow is impeded. When these plaque deposits reach a critical size, they may develop cracks. Blood platelets may build up around these cracks, forming a bigger clot, which further diminishes blood flow. Stroke symptoms may emerge slowly as the blood flow is diminished, or they may come on suddenly if flow is completely interrupted. Bits and pieces of the plaque may also break off and travel downstream in the arterial network, impeding or stopping blood flow in other vessels. This process is called thromboembolism.

Lacunar Infarctions involve the many small arteries that supply the deeper parts of the brain. The process involved in these strokes is different from that of large vessel infarctions. In lacunar infarctions, disorders such as long-term high blood pressure cause parts of the walls of these tiny arteries to deteriorate. This thickens the blood vessel wall, which then causes platelets to build up into small blood clots in the area, gradually interrupting blood flow. These smaller strokes occur in areas known as sub cortical brain structures, so named because they are deep and "under" the cortex or surface of the brain. The specific anatomic points affected by these strokes can produce different symptoms and necessitate different forms of treatment.

About 20% of ischemic stroke are related to an abnormality in the heart. In these *cardio embolic strokes*, an embolus - a piece of thrombus that is formed in one part of the heart or arterial tree - is ejected with blood from the ventricles and travels down the circulatory system, passing from one large artery to another until it lodges and impedes blood flow. Emboli leaving the heart can interfere with blood flow in other organs. When they obstruct blood flow in a cerebral vessel, the result is a stroke.

Various cardiac problems can cause a decrease in or stagnation of blood flow, which in turn promotes thrombus formation. These problems include: atrial fibrillation, the irregular pumping of one or more of the heart's chambers; coronary artery disease that results in a heart attack; valvular heart disease, including valve damage resulting from rheumatic fever, and clots that form on artificial or replacement heart valves, cardiac tumors or aneurysms, cardiomyopathy, disorders associated with the heart muscle (myocardium) itself, and intracardiac defects, such as holes or defects in the walls of the heart.

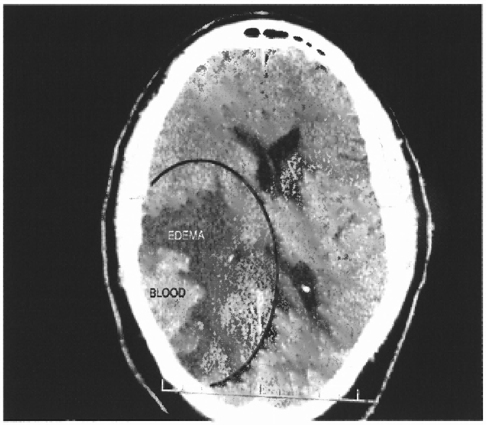


Figure 4.1: Hemorrhagic CVA (Cerebrovascular Accident)

4.4 Stroke Rehabilitation

There are approximately 4 million Americans living with the effects of stroke. In addition, there are millions of husbands, wives, children and friends who care for stroke survivors and whose own lives are personally affected.

According to the National Stroke Association:

- 10% of stroke survivors recover almost completely
- 25% recover with minor impairments
- 40% experience moderate to severe impairments that require special care
- 10% require care in a nursing home or other long-term facility
- 15% die shortly after the stroke
- Approximately 14% of stroke survivors experience a second stroke in the first year following a stroke.

Successful rehabilitation depends on:

- Amount of damage to the brain
- Skill on the part of the rehabilitation team
- Cooperation of family and friends. Caring family/friends can be one of the most important factors in rehabilitation
- Timing of rehabilitation – the earlier it begins the more likely survivors are to regain lost abilities and skills

The goal of rehabilitation is to enable an individual who has experienced a stroke to reach the highest possible level of independence and be as productive as possible. Because stroke survivors often have complex rehabilitation needs, progress and recovery are unique for each person. Although a majority of functional abilities may be restored soon after a stroke, recovery is an ongoing process.

4.5 Effects of Stroke

Effects include:

1. Weakness (hemiparesis) or paralysis (hemiplegia) on one side of the body that may affect the whole side or just the arm or leg. The weakness or paralysis is on the side of the body opposite the side of the brain affected by the stroke.
2. Spasticity, stiffness in muscles, painful muscle spasms
3. Problems with balance and/or coordination

4. Problems using language, including having difficulty understanding speech or writing (aphasia); and knowing the right words but having trouble saying them clearly (dysarthria)
5. Being unaware of or ignoring sensations on one side of the body (bodily neglect or inattention)
6. Pain, numbness or odd sensations
7. Problems with memory, thinking, attention or learning
8. Trouble swallowing (dysphagia)
9. Problems with bowel or bladder control
10. Fatigue
11. Difficulty controlling emotions
12. Depression
13. Difficulties with daily tasks

4.6 Time Course and Patterns of Motor Recovery

Approximately 70-88% of persons with ischemic stroke have some degree of motor impairment and this is often the most obvious deficit to the patient and family. Surveys of persons with stroke suggest that recovery of motor function, especially ambulation, is one of the most desired outcomes of rehabilitation (Boannon, 1991). Ischemic stroke usually affects the lower face, arms and legs. However, the severity of weakness and rate of recovery show considerable individual variation. In one recent study, a score of motor function soon after stroke onset accounted for only half of the variance in the six-month motor function, but the motor score at thirty days explained 86% of the six-month score (Duncan, 1992).

Arm weakness is more common than leg weakness and less likely to recover. Overall, long term stroke survivors have a good prognosis for motor recovery. There is a general agreement that most recovery occurs in the first three months following stroke and is complete by six months (Smith, 1985; Kotila, 1984; Langton Hewer, 1990; Duncan, 1992). Nonetheless, there are some notable exceptions to this, and some studies have shown improvement between six and twelve months after stroke (Kotila, 1984; Wade, 1983; Newman., 1972) although only in a very small percentage of patients. Selected motivated patients have even demonstrated improvement in motor function many years after stroke (Tangeman, 1990; Wade, 1992; Taub 1993).

Twitchel noted over forty years ago that motor recovery after stroke usually followed a typical pattern. The initial is flaccidity, followed by return of reflexes and the development of spasticity. Return of voluntary movement follows, usually in a proximal to distal pattern. Initial movement occurs in a synergy pattern, with flexor synergies generally appearing first, followed by extensor synergies.

When it comes to measuring the outcome of motor recovery, simple measures of motor function such as torque and velocity are inadequate to describe the progress of the patient in terms of gaining motor activity necessary to function in daily life. Consequently, measures that emphasize motor skills during functional tasks have found more favor in studies of motor recovery following stroke (David C. Good, 1994).

4.6.1 The Physiologic Mechanisms Underlying Recovery

Neurophysiologic mechanisms of recovery after stroke are not fully understood, but greater insight into these processes is emerging. One approach to improving motor performance is the use of amphetamines and haloperidol, both pharmaceutical drugs. Many theories of motor recovery are related to concepts of brain "plasticity"(Good, 1994). There is a clear evidence of both adaptive and maladaptive reorganization of neural networks following injury. If this reorganization could be favorably manipulated, improvement in motor function might result.

The emergence of neuroimaging techniques like Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) scanning has made it increasingly possible to understand the exact changes the "plastic" brain undergoes during recovery. One possible mechanism underlying recovery of function following stroke is the resolution of *diaschisis*. Recently, there has been a renewed interest in the concept of functional depression in intact neurons in regions remote from damaged neurons (although anatomically connected), which was first proposed by Von Monakow in 1905. There is increasing evidence that diaschisis may be amenable to treatment, including pharmacological intervention.

Another possible mechanism for reorganization is "unmasking", which suggests that alternate areas of the brain can substitute for damaged areas through altered activity in preexisting synapses (Wall, 1980). Implicit to this concept is the assumption that there is a certain degree of redundancy in functional neuronal networks. In some patients, activation of motor cortex ipsilateral to the side of the affected limbs was observed. Other potential models of plasticity are neuronal sprouting, neuronal regeneration and synaptogenesis. Axonal sprouting is defined as an outgrowth of processes from axons or terminals derived from undamaged neurons. Synaptogenesis refers to the loss and replacement of synapses that occurs in response to the stimulus. There is evidence that axonal sprouting and regeneration are greatly influenced by tropic and growth factors (Cotman, 1989).

The relevance of neuronal sprouting, regeneration, and synaptogenesis to rehabilitation following stroke are unclear, but it seems logical to presume that any or all of these mechanisms may accompany the slow recovery of motor function following stroke (Good., 1994). Additionally, physiologic processes important in other forms of memory and learning, including long-term potentiation (LTP), might be applicable to motor learning (Goldstein, 1991). LTP is an activity-dependant change in synaptic efficacy that may provide the physiologic basis for information storage in the brain. Whatever the physiologic or neurochemical mechanisms, it is clear that specific motor training results in modulation of cortical motor output in normal persons. In vivo physiologic markers of this "learning process" are now available in humans.

Theories of physical therapy often rely heavily on the assumption that motor activity can be "relearned". However, even those who accept this underlying assumption differ on whether any specific technique is superior to another.

4.6.2 Specific Strategies For Enhancing Motor Recovery

The most widely practiced attempts at improving motor function are programs of physical therapy. There are many theories of physical therapy, which have been reviewed recently, including:

- Proprioceptive Neuromuscular Facilitation of Knott and Voss
- Neurodevelopmental Treatment Approach of Bobath
- Brunnstrom Approach.

These are techniques developed by experienced clinicians, but approaches of one might clash with the others.

All of the early methods have been classified as "neurophysiologic", in the sense that they claim to facilitate motor control, as opposed to merely teaching compensatory techniques (Price, 1994). A more recent motor relearning approach was devised by Carr and Shepherd (1987). This philosophy emphasizes the learning and practice of functional motor skills, which should be "task specific". In reality, modern physical therapists often integrate components of two or more philosophies into their treatment regimens.

Unfortunately, the underlying principles of most schools of physical therapy lack sound scientific proof. There is no compelling approach that any one method is better than the others (Good, 1994). Similarly, the timing and intensity of motor training programs has also been under serious scrutiny.

Other strategies employed besides physical therapy include Functional Electric Stimulation (FES), biofeedback, and vibration. Several studies using FES, sometimes combined with biofeedback or conventional physical therapy, have shown increased muscle torque and improvement in functional motor activities (Wagenaar., 1991). Complex multiple FES for hemiparetic patients have not yet found wide scale acceptance.

EMG biofeedback to facilitate movement of paretic muscles, sometimes performed in conjunction with a conventional therapy program, has been shown in some studies to be superior to therapy alone (Inglis, 1984; Basmajian, 1982). However, other studies have shown no improvement over standard therapy (Wagenaar., 1991). Whether any of these treatment strategies produce long-lasting improvement in motor function remains unclear.

4.7 Treatment of Upper Limb Disability

Although spasticity is a frequent feature of hemiparesis, it is seldom the limiting factor in motor recovery. Muscle weakness and other features of the "upper motor neuron syndrome", including abnormal patterns of motor movement (i.e. synergy, co-contraction of agonists and antagonists) and impaired velocity and control of movement, are much more likely to result in functional disability. In one recent study, early pharmacological treatment to prevent the development of spasticity soon after stroke failed to produce any relevant effect (Katrak, 1992).

Treatment of stroke patients with upper limb disability is complicated, and involves a wide variety of factors, including activity, fatigue, anxiety, and concurrent medical illness. Reports of the percentage of patients who regain functional use of the hemiplegic upper extremity with rehabilitation varies from 5% reported by Gowland (1982) to 52% reported by Dean and MacKay (1992). The inability to regain a functional upper extremity not only affects performance of daily activities, but also has a significant impact on a person's lifestyle. Restitution of upper extremity movement poses a particular challenge to clinicians specializing in movement rehabilitation. The hands need to be able to grasp, manipulate and stabilize objects while the arm accurately transports objects to the required location. Also, questions of available time for treatment, and cost of rehabilitation, pose further problems to the treatment strategies. Given this complexity, it is not surprising that the upper extremity is challenging to rehabilitation. Empirical data of current treatment approached have reported limited success with transfer of training from the clinical environment to functional performance (Kraft, 1992; Gordon, 1987).

4.8 Bimanual Practice in People with Stroke

To establish the validity of testing bimanual practice, some of the ongoing research is studied. With this information, it can be shown that bimanual practice can effectively improve the performance of people with hemiplegia. As mentioned in the previous chapters, bimanual coordination has been shown as something that is inherent in all subjects. Despite its promise however, current research in adopting bilateral practice has remained experimentally neglected. Nevertheless, small but certain steps are being taken toward it.

4.8.1 Bimanual Coordination and Fitts' Law

A Fitts' task was used to see if large movement asymmetry in subjects with spastic hemiparesis could be reduced or eliminated with bilateral practice by Steenbergen et al. (1995). Fitts' Law has been established as a premiere way of testing bimanual movements. The work done by this particular group is being reported in more detail here in order to establish the fact that bimanual coordination is very much evident in both normal and disabled people and that both groups basically do not subscribe to Fitts' Law.

Subjects: The experiment was performed on two groups of subjects, first, a control group of normal healthy individuals. Secondly, a hemiparetic group was used consisting of fourteen children of mean age about eighteen years of which six were hemiparetic on the left side and eight were hemiparetic on the right side.

Apparatus and design: The experimental setup is displayed schematically in Figure 4.2. Each subject performed a block of trials in each of the eight experimental conditions. In four unimanual conditions, the dominant or non-dominant hand moved in isolation to either smaller (13 mm) or bigger (44 mm) hole. In four bimanual conditions, the hole sizes were either equal (13mm or 44 mm) or unequal.

The subjects were required to pick the balls and place them in the holes as quickly as possible both in the unimanual and bimanual trials with no explicit instruction given to synchronize both hands in the case of bimanual tasks.

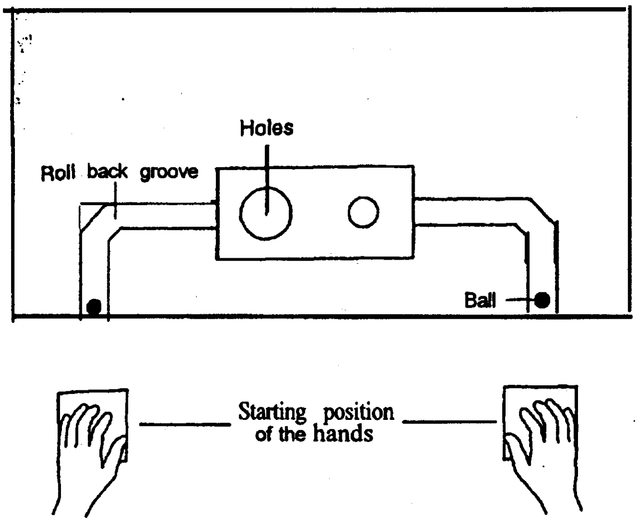


Figure 4.2: The set-up of Steenbergen's experiment (top view)

Results:

- **Reaction time:** Mean reaction times and the corresponding standard deviations for the student group are shown in Table 4.1.

Table 4.1: Mean reaction times (and standard deviations), in milliseconds, for the student group in the unimanual and bimanual conditions

Condition	**Students (n=10)**	
	Dominant Hand	**Non-Dominant Hand**
Unimanual	255(22)	257(34)
Bimanual	281(32)	275(36)

There were no effects attributable to hand. These data indicate that in the bimanual conditions, movements of the dominant and non-dominant hand were initiated simultaneously. These results concurred with those obtained by Kelso et al. (1979, 1983). Also, moving with two hands prolonged reaction time compared with the unimanual conditions [278ms vs. 256 ms; F(1,9)= 8.05, $P<0.05$]. The mean reaction time for the hemiparetic group is shown in Table 4.2. Movements of the impaired hand took longer to initiate than those of the non-impaired hand [F (1,12)=8.92, P<0.05] in the case of unimanual conditions. In the case of bimanual conditions, however, the difference in reaction time between the hands was 11ms, which was not significant.

Table 4.2: Mean reaction times (and standard deviations), in milliseconds, for the spastic hemiparesis group in the unimanual and bimanual conditions. A distinction is made between subjects suffering from spastic hemiparesis on the left side and on the right side

Condition	**Hemiparesis left side (n=6)**		**Hemiparesis right side (n=8)**	
	Non-impaired hand	Impaired hand	Non-impaired hand	Impaired hand
Unimanual	291 (60)	312 (30)	341 (60)	433 (14.5)
Bimanual	335 (54)	349 (65)	407 (44)	416 (57)

- **Total response time:** *a) Bimanual facilitation:* Movements performed in the bimanual conditions were slower than those performed in unimanual conditions [F (1,9)=23.05, P<0.01] in case of the control group (Figure 4.3). In the bimanual conditions both hands reached the target holes at essentially the same time, whereas in the unimanual conditions, the advantage in favor of the dominant hand was on average 90ms. Consistent with the prediction of Fitts' Law, movements to the small hole were, on average of greater duration (by 139 ms) than to the larger hole in both

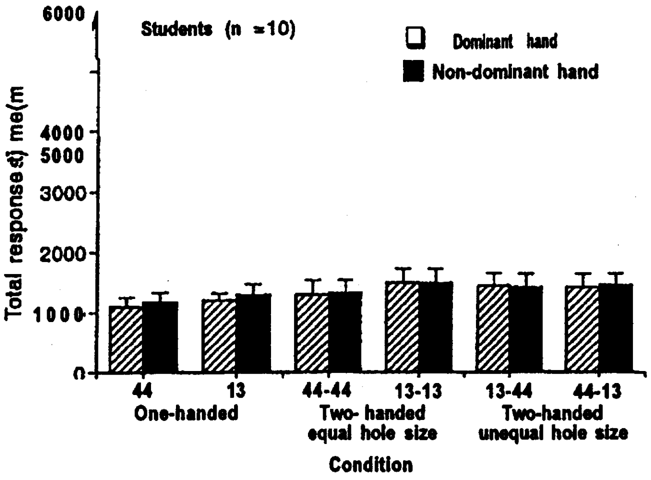


Figure 4.3: Total response times (ms) and standard deviations for the student group (n=10) in all movement conditions

unimanual and bimanual conditions. Again, in the case of the hemi paretic group, analysis showed that the differences in response time between the hands were confined to unimanual conditions (Figure 4.4). When moving both the hands however, the difference in response time between the impaired and non-impaired hands was approximately 8% of that present when the hands were moved independently (unimanual and bimanual differences amounting to 1755ms and 133ms, respectively [F (1,12)=17.94, P<0,05]). In the case of the bimanual movements, the correlation within subjects between the impaired and non-impaired hand ranged from 0.42 to 0.99. This provided further indication of a tight coupling between the hands in the bimanual conditions in which the hands moved toward equal sized targets. Response time was greater for small sized targets when compared to larger ones. *b) Bimanual coupling:* It was evident that both hands reached the holes at similar times in all four bimanual

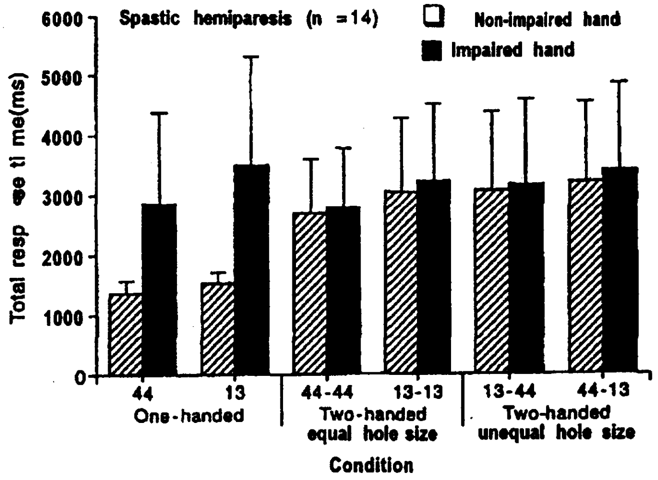


Figure 4.4: Total response times (ms) and standard deviations for the spastic hemiparesis group (n=14) in all movement conditions

conditions. This indicated that there was a tight coupling between the hands. In case of the hemiparetic group, moving hands to targets of unequal size had a response time difference of approximately 152 ms between the impaired and non impaired hands. Unimanually, it was about 175.5ms. When bimanual movements were directed to targets of unequal size, there was a tendency for the non-impaired hand to reach the target somewhat in advance of the impaired hand.

4.8.2 Bimanual Coordination and Rhythmic Attentional Cueing

Upon training of people with stroke with simultaneous auditory cueing, significant and potentially durable increases in the following: Fugl-Meyer-Upper Extremity Motor Performance Test of impairment ($P<0.0004$) , Wolf Motor Function Test (performance time measure, $P<0.02$), and University if Maryland Arm Questionnaire for Stroke measuring daily use of the hemi paretic arm ($P<0.02$) were observed. Active range of motion improved for paretic-side shoulder extension ($P<0.01$), wrist flexion ($P<0.004$) and thumb opposition ($P<0.002$), and passive range of motion for paretic wrist flexion ($P<0.03$). Six weeks of BATRAC improved functional motor performance of the paretic upper extremity as well as a few changes in isometric strength and range of motion. These benefits are largely sustained at 8 weeks after training cessation.

4.8.3 Bimanual Coordination and Neural Reconstruction

Clinical observations prompted Heather Mudie (2000) to investigate if bilateral movement would promote interhemispheric disinhibition and allow reorganization by sharing of normal movement commands from the undamaged hemisphere.

Methods: Twelve subjects who had suffered from cerebrovascular accident (CVA) were asked to perform standard reach to target tasks.

Results: At least one significant movement pattern of task performance was seen. Even in subjects with higher impairments showed better performance patterns with bimanual reaching.

Conclusions: By virtue of the similarity in the command patterns of bilateral isokinematic movement, bilateral training could provide access to an undamaged representation of action commands, thereby supplying a potential informational 'template' for reorganized networks. Second, it may facilitate recruitment of new pathways to supplement the depleted neural network.

4.8.4. Bimanual Coordination to Improve Unilateral Performance

Mudie and Matyas (1996) compared unilateral practice with bilateral simultaneous practice in a series of single case, multiple baseline experiments.

Method: Eight patients with CVA were chosen to perform a series of activities including unimanually and bimanually placing blocks, simulating drinking, and targeting pegs. The effect was studied over a course of eight weeks.

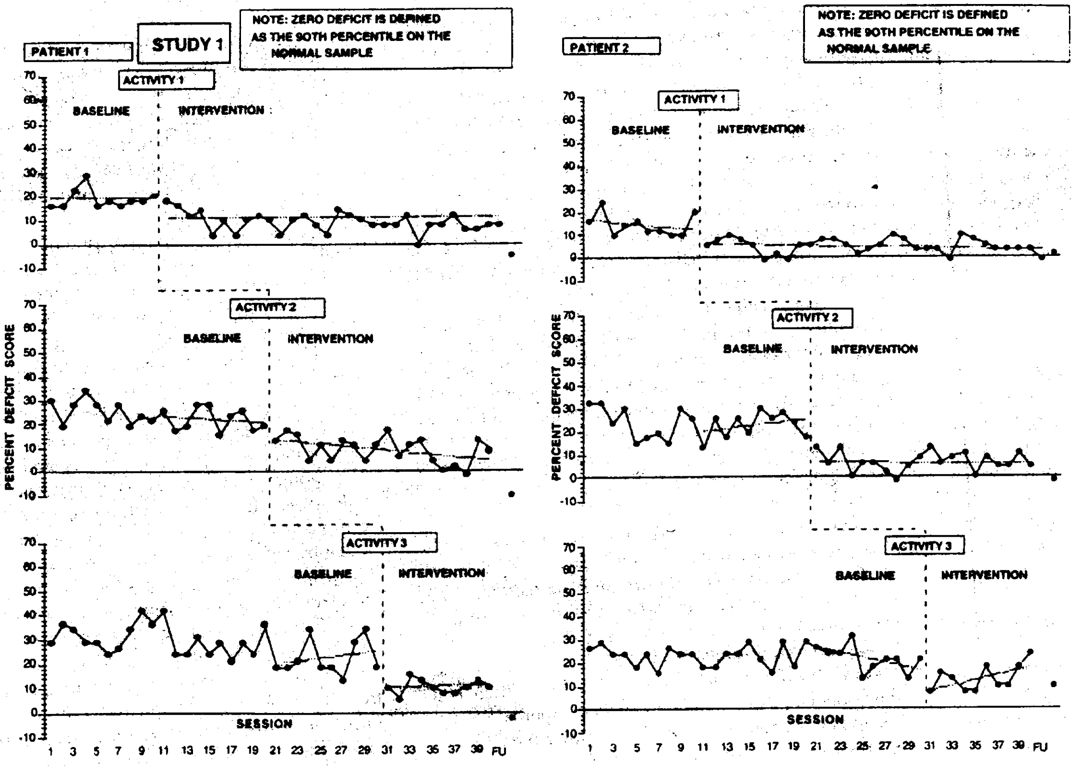


Figure 4.5: Mudie's study: results for two stroke patients

Results: The time series graphs of two patients are shown here (Figure 4.5). Relative quick changes emerged to show the two patients benefited in all three activities. The majority of time series displayed deficits in the order of 10% or less by the end of intervention. In other words, the abnormality scores fell close to or below the 90th percentile of normal controls.

Conclusion: A significant aspect of the results is that improvements achieved in hemiplegic extremity movement during BIT were recorded during unimanual performances. This observation suggests that some permanent reorganization of the normal process of unimanual movement activation resulted from BIT. BIT appears to be a promising method of upper extremity movement restoration following stroke.

CHAPTER 5

OBJECTIVE AND METHODOLOGY

To test the effectiveness of the software in terms of it's utilization to study reaching movements, especially in people with hemiparesis, the objective of this thesis was to study reaction times, movement times and velocity profiles of both unimanual and bimanual reaching.

5.1 The Data Collection System

5.1.1 Hardware

The Flock of Birds (FOB) is a six degree of freedom measuring device that can be configured to simultaneously track the position and orientation of up to thirty receivers by a transmitter. Each receiver is capable of making from 10 to 144 measurements per second of its position and orientation when the receiver is located within ± 4 feet of its transmitter. An optional extended range transmitter increases this operating range to ± 8 feet. The FOB determines position and orientation by transmitting a pulsed DC magnetic field that is simultaneously measured by all receivers in the flock. From the measured magnetic field characteristics, each receiver independently computes its position and orientation and makes this information available to the host computer.

An FOB consists of one or more Ascension Bird electronic units or extended range transmitter controllers interconnected via a Fast Bird Buss (FBB). Because each bird attached to the bus has its own independent computer, the FOB can simultaneously track each receiver, providing up to 144 measurements per second from each. Three birds were used for the purpose of this thesis, each collecting data simultaneously at a rate of 91Hz. This frequency was chosen because the FOB's can sample data at a maximum frequency of 100Hz (although a baud rate of 115K is possible, the Birds only read redundant data). A frequency less than slightly less than a 100Hz accommodated for possible errors in reading data from the Birds.

5.1.2 The Host Computer

An Intel Pentium III processor based processor in a Windows environment provided the necessary operating system.

5.2 Software

The software developed for this thesis uses LabVIEW (version 6) and MATLAB. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a development environment based on graphical programming. The GUI based interface allows programmers to quickly design and implement complex test and measurement and automation applications. With LabVIEW, the software defines the system - saving both development time and resources. The data files were saved in Microsoft Excel and analyzed using MATLAB. A more detailed description of the LabVIEW software is documented in Chapter 7.

5.3 Experimental Setup

The experimental setup involved testing movement capabilities in touching three targets of varying difficulty (Trombly, 1992). Target 1 was located contralaterally, approximately 45° from midline, to require reaching into extensor synergy; Target 2 was located directly in front of the tested shoulder to require partial movement out of synergy; Target 3 was located ipsilaterally, approximately 45° from midline to require movement out of synergy. Each target was a 3-in circle. Targets were arranged horizontally so that each one was 50 cm from the start pad that was located at the edge of the table directly in front of the body of the subject (Figure 5.1). Two birds, one on either hand was used to record the X, Y, Z positions. The LabVIEW software enabled the user to control the experiment externally. Since the software was built to work with people with stroke, this was thought to provide better control over the experiments.

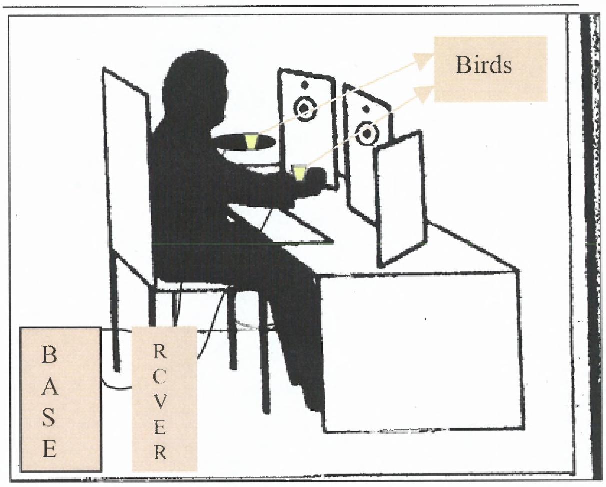


Figure 5.1: Experimental set up

5.4 Procedure

For the experiment, the subject sat on a straight-backed chair with the shoulder of the arm to be tested directly in line with Target 2 and the hand resting on the start pad. The subject was told which target to aim for before the start of the trial. A trigger sound indicated to the subject that the experimental trial had begun. Data was collected for

1000 samples. Two scorable trials were completed for each experiment. The tasks involved a normal and weighted arm:

- Reaching with the right hand to the middle, ipsilateral and contralateral target, each of which began with the hand on the start pad.
- Reaching with the left hand to the middle, ipsilateral and contralateral target, each of which began with the hand on the start pad.
- **In phase:** Reaching with both hands to middle, ipsilateral and contralateral targets, each of which began with both the hands on the start pad.
- **Out of phase:** Reaching with both hands to middle, ipsilateral and contralateral targets, but while starting in opposite places, i.e., one hand at rest on the start pad, and the other on the target, and then trading places.

5.5 Data Analysis

Data from the Birds was stored in Excel spreadsheets. The average of the two trials was calculated and stored as text files. Using Matlab (version 6), the position data of each of the Birds were plotted against the total samples to read the reaction times and total movement times. The mean of two separate sets of trials for each experiment was used for analysis. The reaction and total movement times of each of the trials were compared across handedness and between unimanual and bimanual reaching. The velocity profiles for each of the trials were calculated from the Bird data. The profiles were checked for smoothness or ballistic movement and discontinuous movement.

CHAPTER 6

RESULTS, CONCLUSION AND FUTURE SCOPE

6.1 Results

The reaction and movement times for the left and right hand unimanual reaching is shown in Table 6.1. A difference in times between the left and the right hands is evident; the reaction time of the left hand was slightly higher than the right hand but the movement time of the left hand was slower than the right hand. However, no conclusions can be attributed to handedness, as the data collected is not statistically significant.

Table 6.1: Mean reaction times (RT) and movement times(MT) (in milliseconds) for the test subject in unimanual and bimanual conditions

Condition	**Left Hand (ms)**			**Right Hand (ms)**		
	RT	MT	(RT+MT)	RT	MT	(RT+MT)
Unimanual	680	940	1620	810	710	1520
Bimanual *In phase*	430	890	1320	460	890	1350
Bimanual *Out of Phase*						
Center	380	810	1190	460	810	1270
Left	500	810	1310	460	810	1270
Right	560	910	1470	430	910	1340

These data indicate that in bimanual reaching, both the right and the left hands reached simultaneously. The movement times of both the hands during bimanual reaching movements, in both in-phase and out of phase trials, were almost equal to each other. Both hands took 890 milliseconds to reach the task in the in-phase trial, 810 milliseconds for the left and center target during the anti phase trials, and 910 milliseconds to reach the right most target. Also, entraining was observed during the in-phase trial, i.e. both the hands took almost the same time to complete the task.

It was observed in the case of out of phase bimanual reaching studies that the reaction times of the left hand was slightly higher than the right.

Post-hoc comparisons revealed that the subject took longer to reach the target unimanually than bimanually by an average of 100ms. Movements directed to the right most target took the most amount of time to complete in case of the out of phase experiment.

Weighted experiments

The reaction time of the weighted left hand was slightly lower than the right hand during unimanual conditions. No difference was observed in terms of reaction times of the weighted and unweighted left hands during the unimanual task. However, a delay of 710ms was observed to complete the movement in case of the weighted left hand when compared to the normal hand (Table 6.2).

The movement times for the weighted arm were slower than normal unimanual reaching. The weighted hand took 1700ms to complete the task whereas in the normal unimanual task, the left hand took 940 ms.

In case of bimanual reaching studies, the movement times for the right hand were the same as the weighted left hand during the in-phase trial. The total time taken was almost the same for both the left hand and the right hand. Hence a strong bimanual coordination was observed.

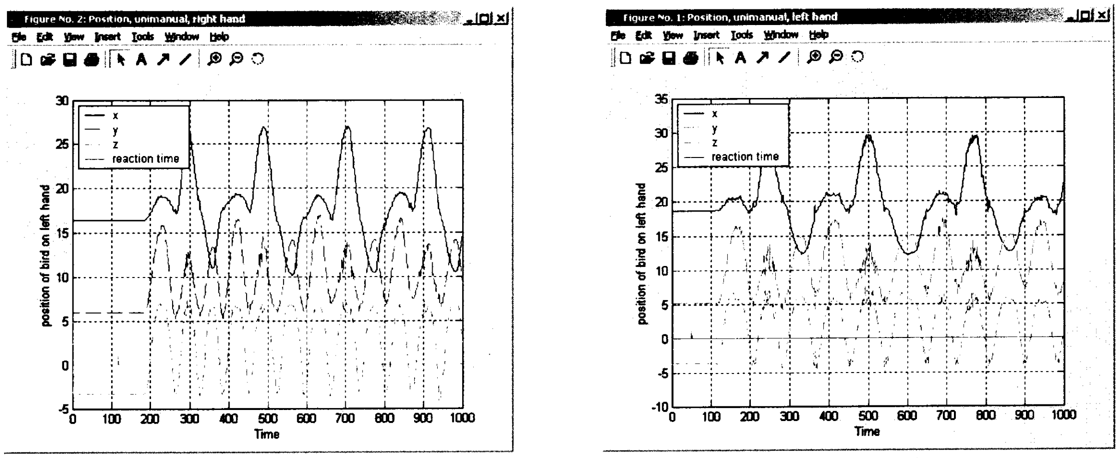
Table 6.2: Mean reaction times and movement times (in milliseconds) for the test subject in weighted unimanual and bimanual conditions

Condition	**Left Hand (weighted) (ms)**			**Right Hand (ms)**		
	RT	MT	(RT+MT)	RT	MT	(RT+MT)
Unimanual	630	1700	2330	810	710	1520
Bimanual *In phase*	580	2300	2880	600	2300	2900
Bimanual *Out of Phase*						
Center	560	1500	2060	530	1600	2130
Left	460	1370	1830	840	840	1620
Right	660	1270	1930	910	1100	2010

In case of out of phase trials, the reaction time for the right hand was higher when moving to the central target as compared to the weighted left hand, but was lower for the left and right targets. The movement times were higher for the left hand as was expected. The weighted hand reached the target slightly faster than the right hand.

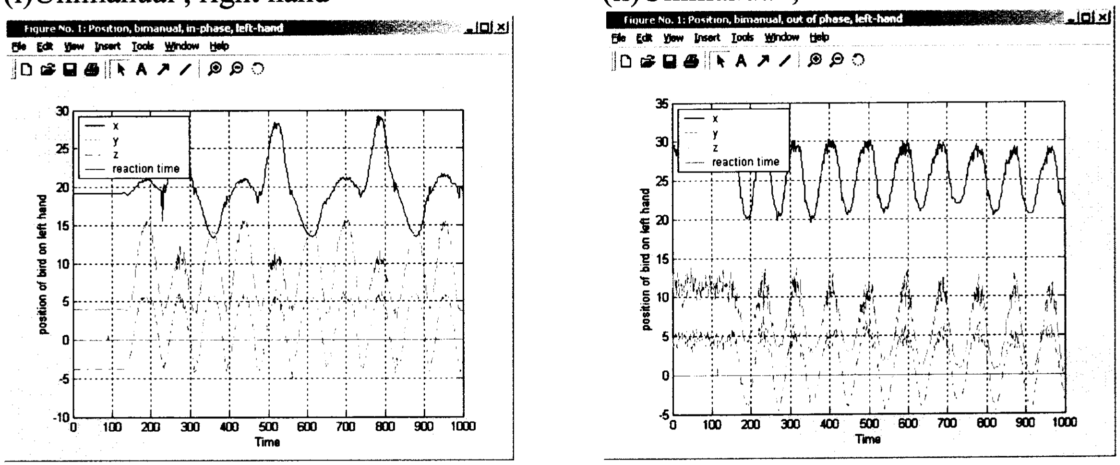
Velocity profiles

The velocity profiles of the left and right arm look alike when not weighted. In the weighted left arm, a more discontinuous pattern is observed. Further algorithms need to be developed to fully understand the velocity trajectories.



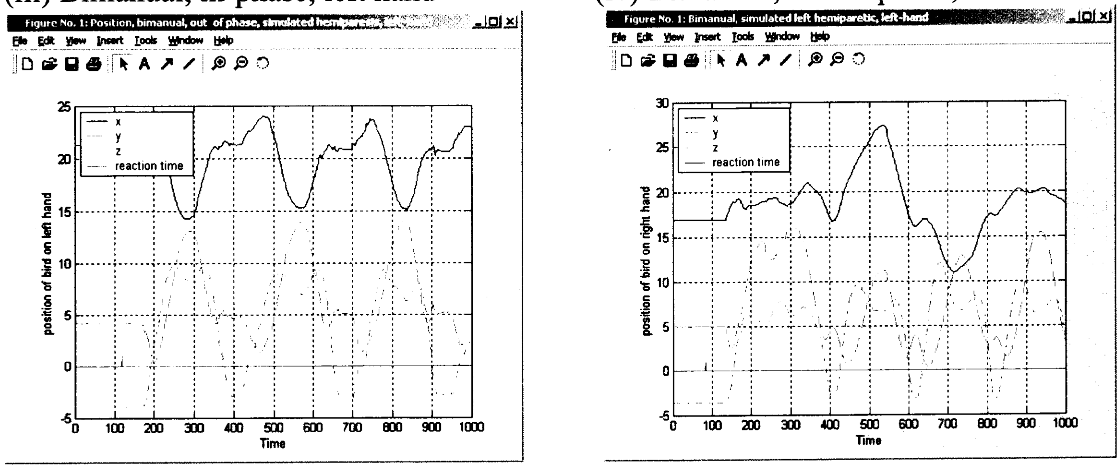
(i)Unimanual , right hand

(ii)Unimanual , left hand



(iii) Bimanual, in-phase, left hand

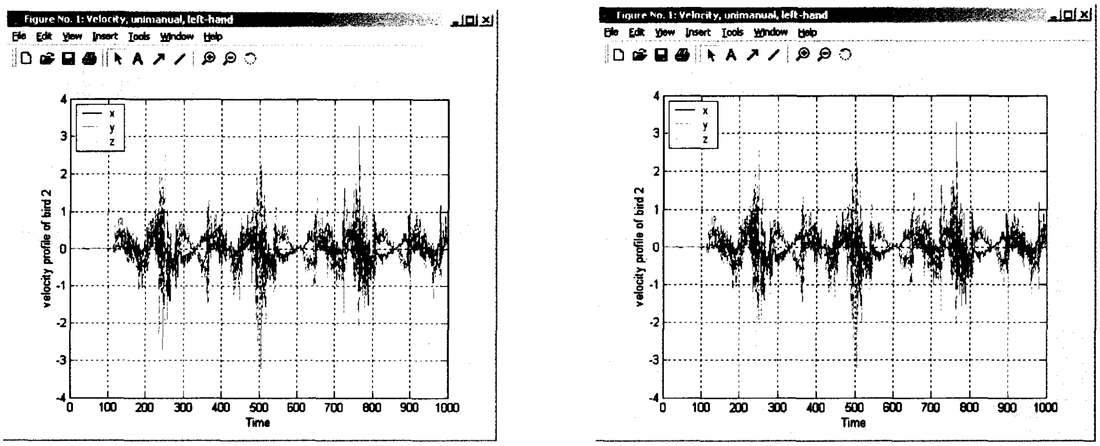
(iv) Bimanual, out-of-phase, left hand



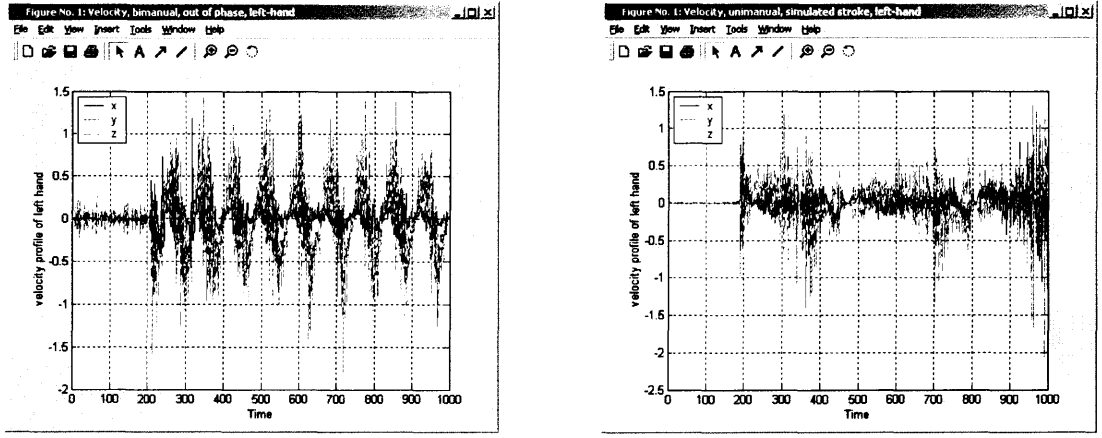
(v) Bimanual, out of phase, weighted left

(vi) Bimanual, in-phase, weighted left

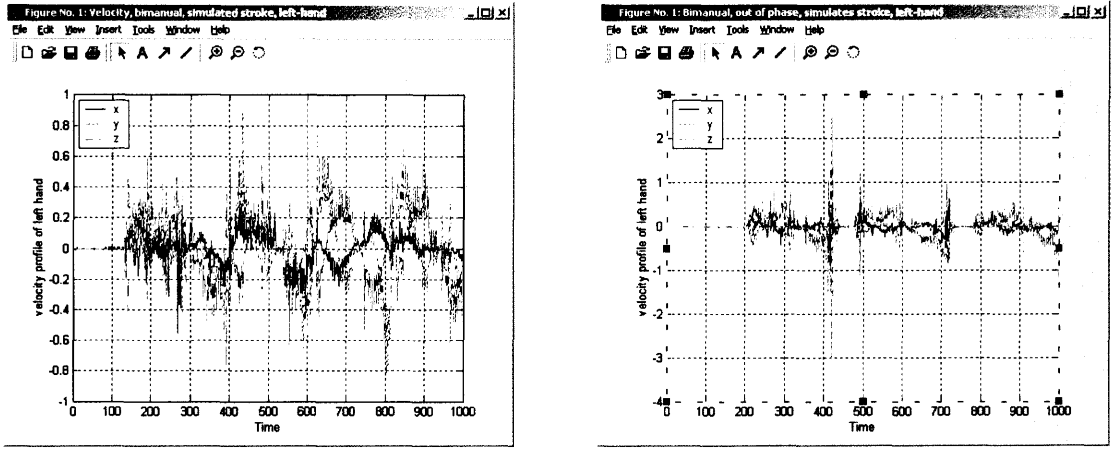
Figure 6.1: Position profiles of the bird on the left hand in various test conditions



(i)Unimanual , right hand (ii)Unimanual , left hand



(iii) Bimanual, out-of-phase, left (iv) Bimanual, out-of-phase, weighted left



(v) Bimanual, in-phase, weighted left (vi) Bimanual, in-phase, left

Figure 6.2: Velocity profiles of the bird on the hand in various test conditions

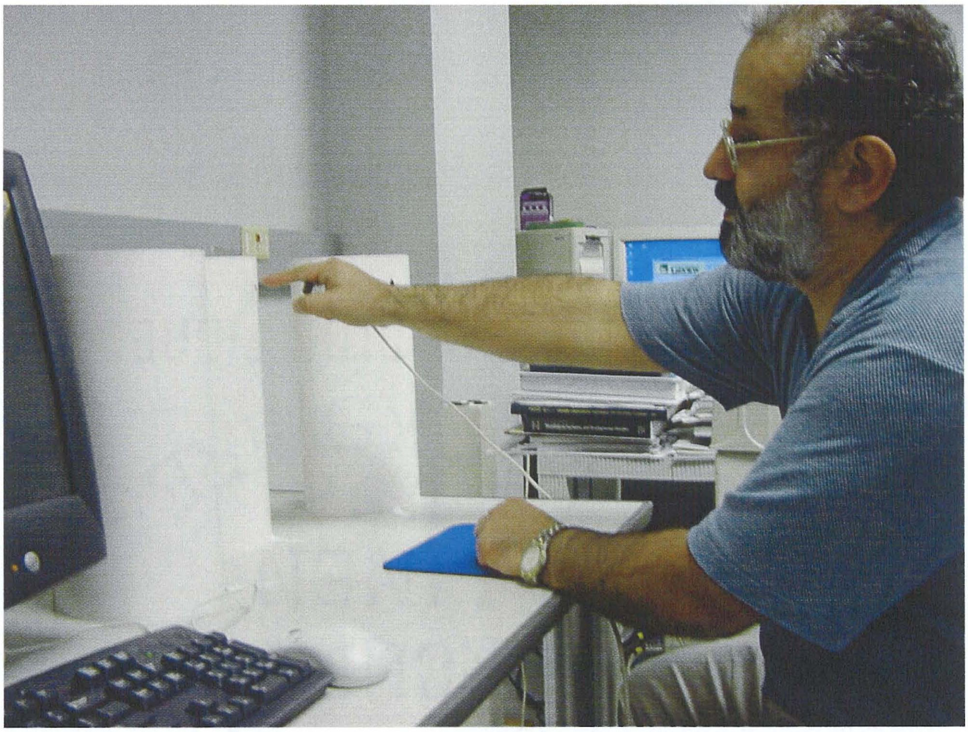


Figure 6.3: Subject reaching for the target for a unimanual right hand task

Figure 6.4: Experimental set up with the Flock of Birds

6.2 Conclusions and Future Scope

The results obtained, although very preliminary, demonstrated the ability of the software to successfully collect and record reaction and movement times to an accuracy of 2 decimal places. The delayed movement times in the weighted left hand and the successive speeding up of the same during bimanual conditions validate the research reported in Chapter 2, 3 and 4. The smooth velocity profiles with the normal hand and the multi-peaked, non-ballistic movement of the weighted hand confirms the findings of Trombly(1992). The software can collect data at a speed of about 91Hz, which is almost equal to the optimum speed the Birds can send data over the serial port. The future task will be to optimize the speeds even further, with probable simultaneous use of accelerometers and A/D cards to ensure more accurate measurement times. Also, possible future studies should involve a statistically significant group of controls and people with hemiparesis to validate the findings of this pilot study. The pilot study does indicate strong temporal coupling, which can prove extremely beneficial to training people with hemiparesis.

CHAPTER 7

SOFTWARE DEVELOPED FOR THE FLOCK OF BIRDS

This chapter describes some of the principal features of the software developed by Desktop Laboratories and the lab at NJIT in LabVIEW (version 6) to read, collect and save data from the Flock of Birds.

7.1 The System

As mentioned in Chapter 5, the Flock of Birds is a six degree-of-freedom measuring device that configured to simultaneously track the position and orientation of up to thirty receivers by a transmitter. The FOB determines the position and orientation by transmitting a pulsed DC magnetic field that is simultaneously measured by all

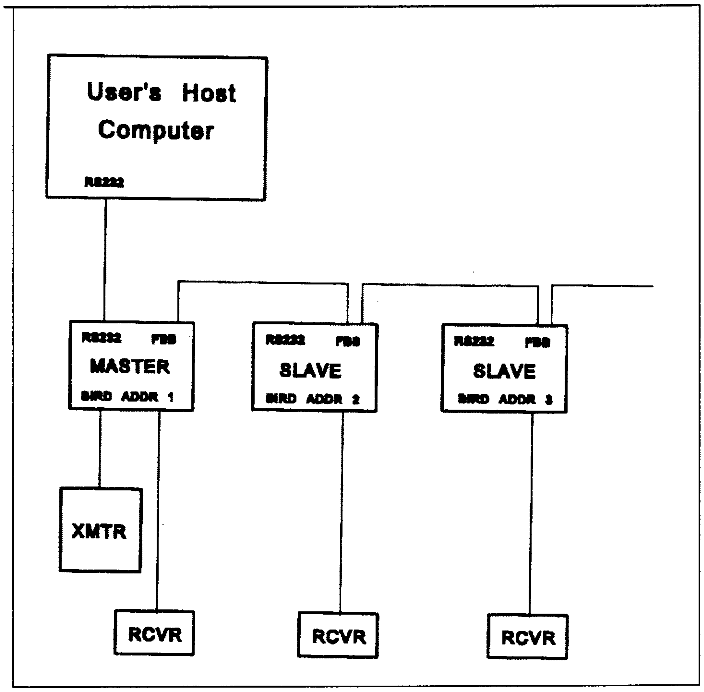


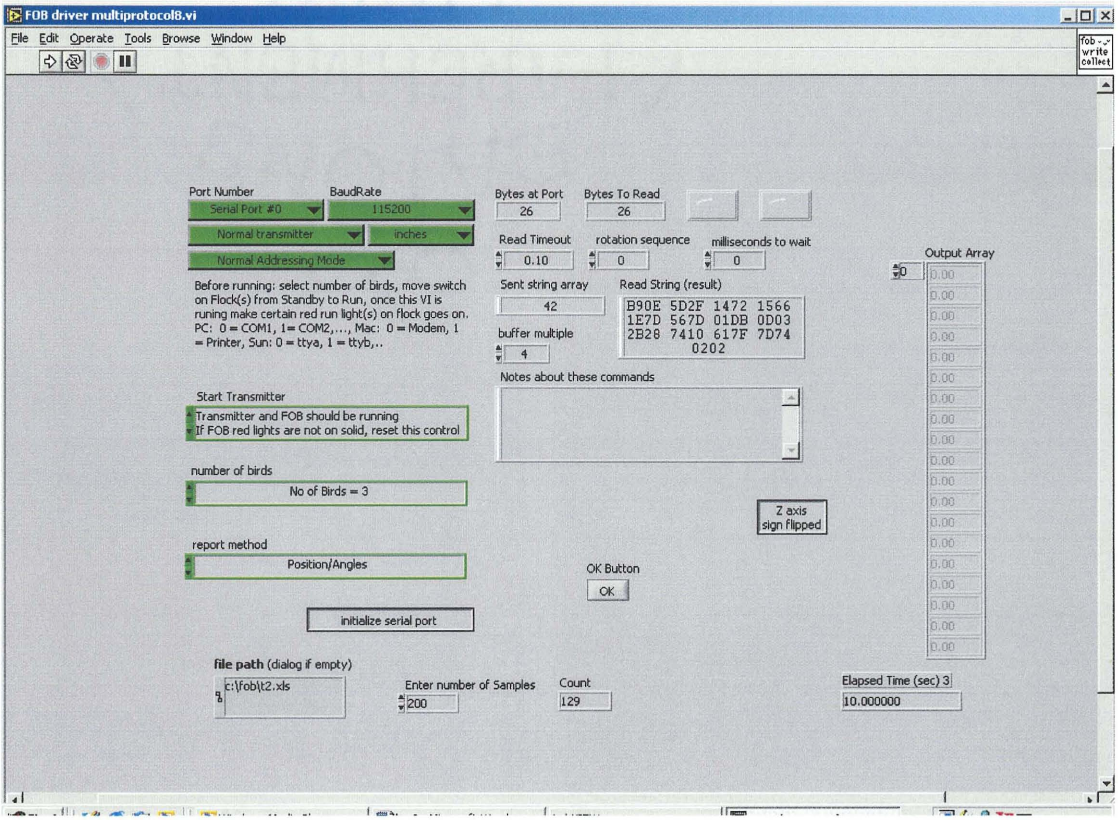
Figure 7.1: The Flock of Birds interfaced to the host computer with a RS 232 interface

receivers in the flock. From the measured magnetic field characteristics, each receiver independently computes its position and orientation and makes this information available to the host computer.

The Flock of Birds (FOB) can be configured so that a single RS 232 interface commands and receives data from all Bird units (Figure 7.1). In this case there is a master Bird that is the flock Bird that controls and coordinates the operation of all slave Birds- slaves because they can only speak when spoken to by the master or host. The User's host computer communicates with the master to start and stop the flock and perform other major flock control functions.

7.2 The Software

The role of the LabVIEW software is to request and collect the data from the FOB using the RS 232 interface, present it in a form the user can understand, and save the data for analysis. The basic files you create with LabVIEW are called Virtual Instruments, or VIs. Each VI consists of two main parts - the front panel and the block diagram. The front panel contains the user interface of the underlying VI(s). An image of the front panel window is presented in Figure 7.2.



Port Number: Serial Port #0

BaudRate: 115200

Normal transmitter

inches

Normal Addressing Mode

Before running: select number of birds, move switch on Flock(s) from Standby to Run, once this VI is runing make certain red run light(s) on flock goes on. PC: 0 = COM1, 1= COM2,..., Mac: 0 = Modem, 1 = Printer, Sun: 0 = ttya, 1 = ttyb,..

Start Transmitter: Transmitter and FOB should be running
If FOB red lights are not on solid, reset this control

number of birds: No of Birds = 3

report method: Position/Angles

file path (dialog if empty): c:\fob\t2.xls

Enter number of Samples: 200

Count: 129

Bytes at Port: 26

Bytes To Read: 26

Read Timeout: 0.10

rotation sequence: 0

milliseconds to wait: 0

Sent string array: 42

buffer multiple: 4

Read String (result):

```
B90E 5D2F 1472 1566
1E7D 567D 01DB 0D03
2B28 7410 617F 7D74
        0202
```

Notes about these commands

Output Array: 0

```
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
```

Elapsed Time (sec) 3: 10.000000

Figure 7.2: Front panel

For the LabVIEW software to communicate with the FOB through the RS 232 interface, four parameters have to be specified: the *baud rate* of the transmission, the number of *data bits* encoding a character, the sense of the optional *parity* bit, and the number of *stop bits*. The user can set the Baud Rate on the front channel for optimum data collection, a rate of 115,200 baud was used for the current experiment. Eight data bits, one stop bit and zero parity were used.

The *report* button in the front panel allows the user to collect data in various forms, position, orientation, quaternion, etc. Reinitializing the serial port manually clears the port and the problems associated with a full buffer. The user can also specify the number of samples required interactively.

Steps involved in starting to collect data:

1. Open the driver multiprotocol.vi program.
2. Specify the baud rate. The rate displayed on the front panel has to match the baud rate set on the FOB.
3. Manually reinitialize the serial port.
4. Turn the FOB from standby to run mode.
5. Hit the start button and run this program for some time.
6. Open the driver multiprotocol8.vi program.
7. Repeat steps 2 through 4.
8. Determine the number of samples.
9. Specify the file path for saving the data.
10. Hit the star button to start collecting and saving data.
11. Hit the OK button to trigger the experiment.

Note: In case of problems, turn the FOB off and turn it on again. Also, manually reinitializing the serial port helps clear the buffer.

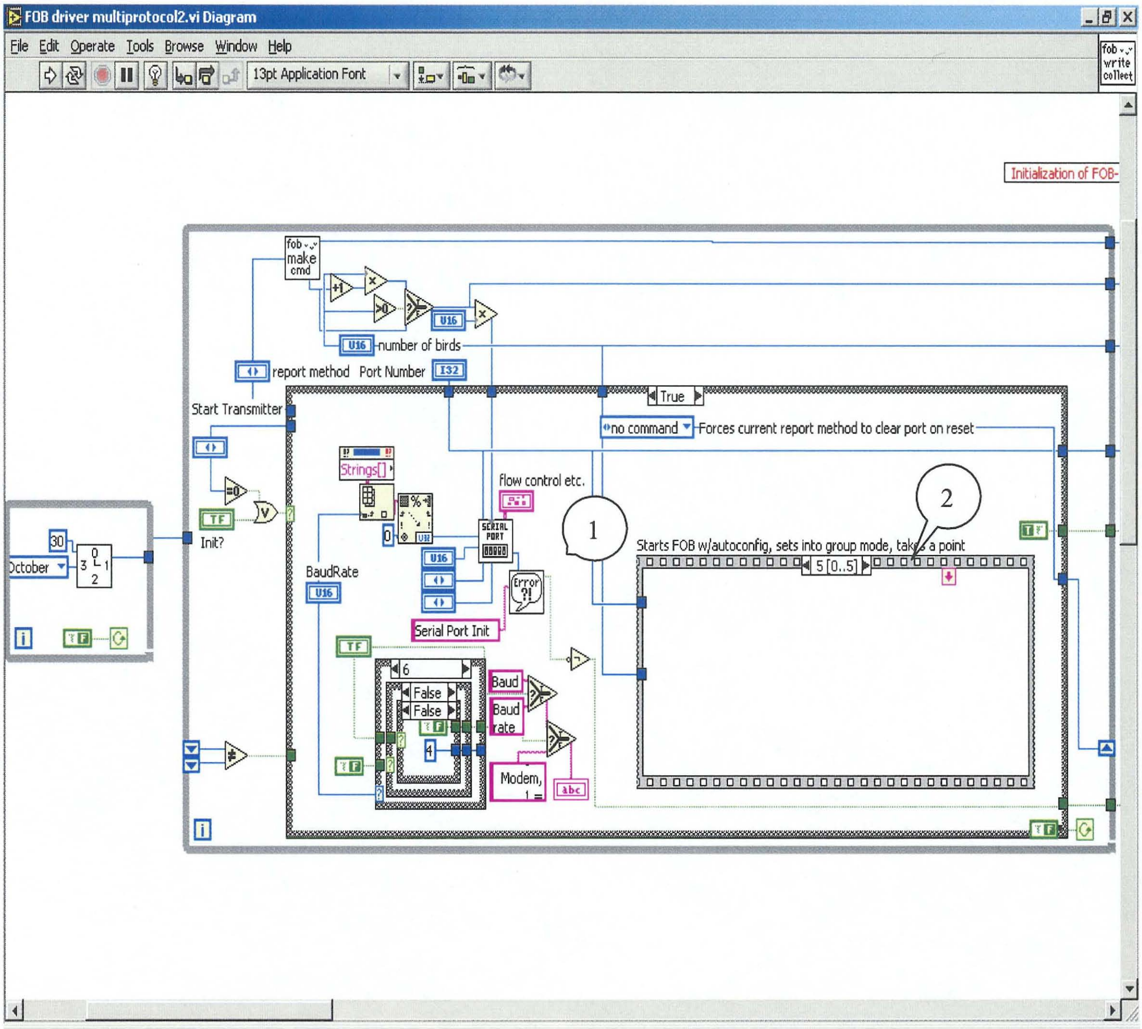


Figure 7.3: Block diagram of the VI-initialization of FOB

The block diagram contains the graphical code for the VI. Figure 7.3 shows the first part of the VI, wherein the FOB is initialized. 1 sets the date of expiry for the program. 2 specifies the baud rate, start, stop and parity bits for the serial port. 3 sends information to the subVIs about the number of birds, the number of transmitters and receivers, etc. to configure and prepare the rest of the VI and starts the transmitter to collect data. It also enables to VI to collect a single data to check if the FOB's and the VI are running smoothly.

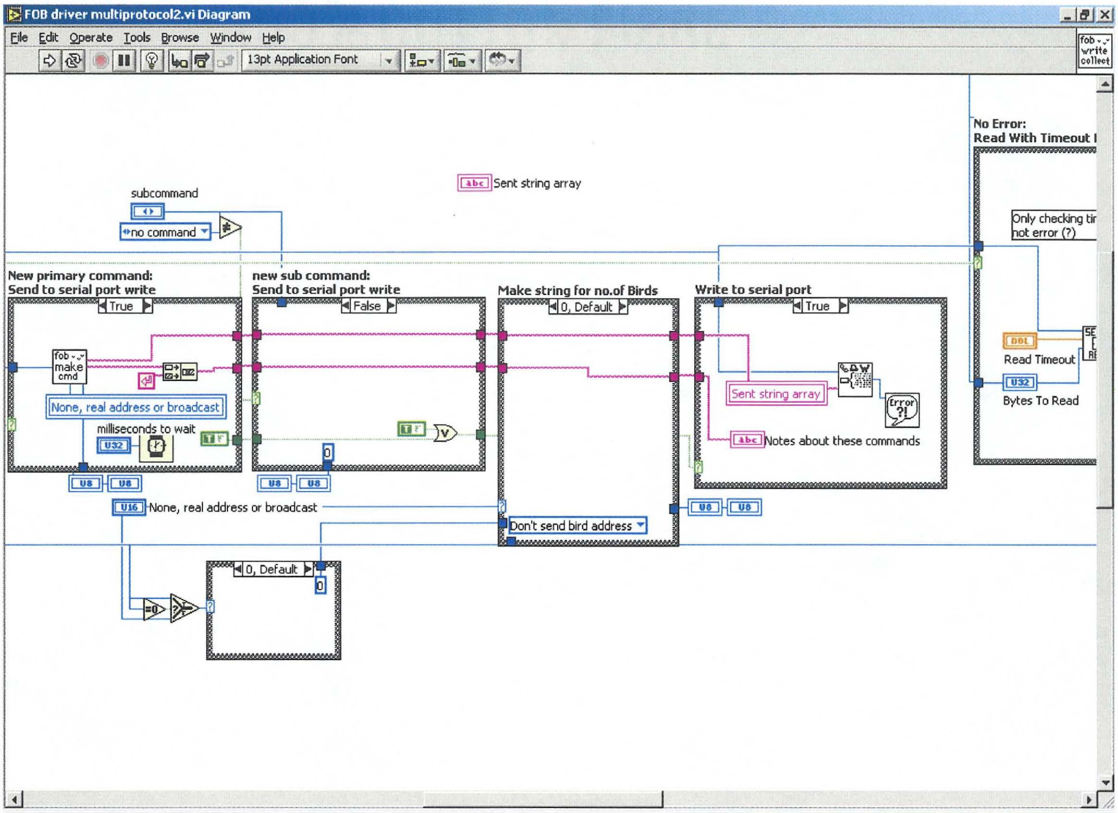


Figure 7.4: Running the Flock

This part of the VI sends commands to the Flock using the RS232 interface (Figure 7.4). Each RS232 command consists of a single command byte followed by N command data bytes, where N depends upon the command. A command is an 8-bit value that the host transmits to the Bird using the format shown below.

Table 7.1: RS232 command format

RS232 COMMAND	MS BIT STOP	7	6	5	4	3	2	1	LS BIT START
	1	BC7	BC6	BC5	BC4	BC3	BC2	BC1	0

BC7- BC0 is the 8 bit command value and the MS BIT (Stop=1) and LS BIT (Start=0) refers to the bit values that the UART in the host computer's RS232 port automatically inserts into the serial data stream as it leaves the computer.

The RS232 command data format is as follows:

Table 7.2: RS232 data format

RS232 DATA	MS BIT STOP	7	6	5	4	3	2	1	LS BIT START
	1	BD7	BD6	BD5	BD4	BD3	BD2	BD1	0

where BD7-BD0 is the 8 bit data value associated with a given command.

Since a single RS232 port was used to talk to all the Birds in a flock, each RS232 command is prefaced with a RS232 to FBB command.

If there is an error reading from the Bird, the software times out after 0.10 seconds. Else, two types of binary data are read from the Bird:

1. Position/orientation data and,
2. Change/examine value data.

Position/orientation data are the data returned from the Bird in the angles, position, matrix, position/angles, position/matrix, position/quaternion and quaternion formats. All other types of data that the Bird sends are in the change/examine value format.

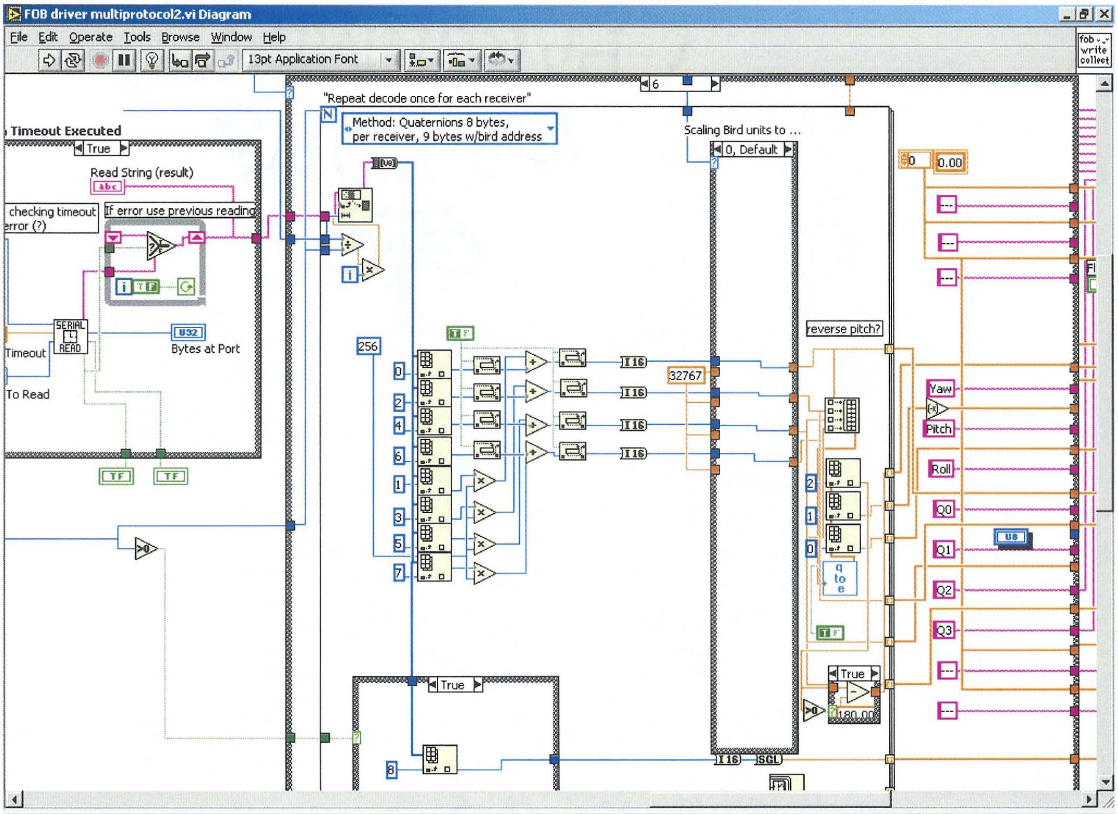


Figure 7.5: Decoding received data from the birds

This part of the vi converts the hexadecimal data received from the birds into integer data, scales it, segregates the various position, angle, quaternion, etc. data and stores the numbers in an array.

The last part of the vi (Figure 7.6) stores the bird data in an excel file whose path can be specified interactively on the front panel. The data is stored in 3 columns, each column containing the data of one bird's set of data i.e. the number of the bird, time the data was logged, X,Y,Z, yaw, pitch, roll, Q0, Q1, Q2, Q3, etc. repeatedly till the end of trial.

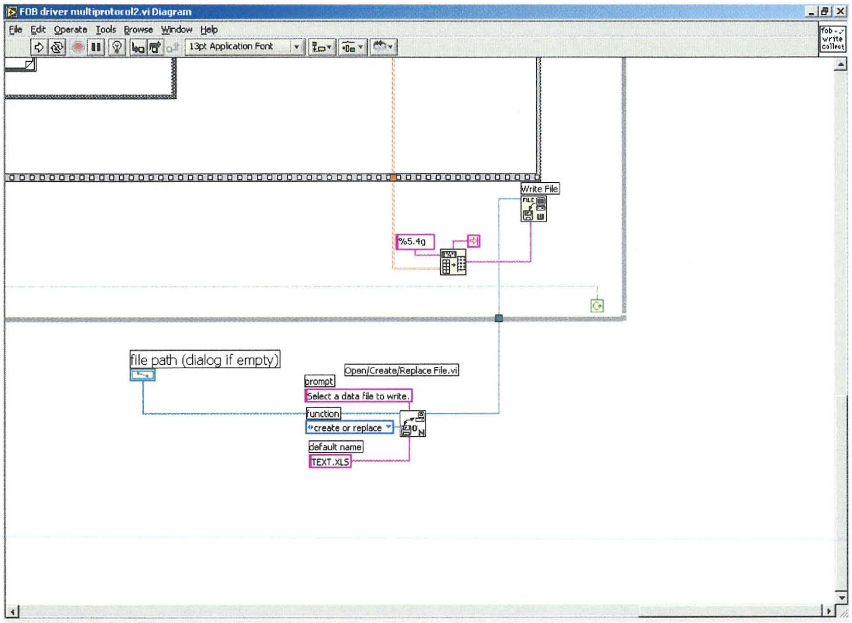


Figure 7.6: Storing the Bird data

The trial is repeated as many times as specified on the front panel, depending on the number of samples required. As was mentioned before, the vi is set to sample at 91Hz and a Baud rate of 115,200. It is capable of collecting data from upto 5 Birds at the same time at a sampling rate of 91Hz. The software is capable of running at much higher speeds, however the Bird can only collect data at 100Hz, hence any speed above that would only result in redundant data. The current software is accurate to 2 decimal places. Simultaneous use of accelerometers and A/D cards would ensure more accurate measurement times.

BIBLIOGRAPHY

Andre, T. (1952). Evolution de la motilite des members superieurs. Etudes Neurologiques sur le Nouveau-ne et le Jeune Nourisson. Paris, Masson.

Basmajian, J. V. (1982). EMB feedback treatment of upper limb in hemiplegic stroke patients: A pilot study. Archives of Physical Medicine and Rehabilitation, 65, 755-59.

Bergeron, M. (1947). Les manifestations motrices spontanees chez l'enfant. In Wallon (Ed.), Actualites Scientifiques et industrielles. Paris: Hermann.

Berstein, N. A. (1967). The Coordination and Regulation of Movement. New York: Pergamon.

Bohannon, R.W., Horton, M. G., Wikholm, J. B. (1991). Importance of four variables of walking to patients with stroke. International Journal of Rehabilitation Research, 14, 246-250.

Bresson et. al. (1977). Organization and laterilazation of reaching in infants: An instance of asymmetric functions in hands collaboration. Neuropyschologia, 15, 311-320.

Bresson et. al. (1976). A propos de la construction de l'espace at de l'object: La prise d'un objet sur un support. Bulletin de Pyschologie, 327, 150-158.

Bruml, H. (1972). Age changes in preference and skill measures of handedness. Perceptual and Motor Skills, 34, 3-14.

Bruner, J. S. (1972). Visually preadapted constituents of manipulatory action. Perception, 1, 3-14.

Carr, J. H., Sherpherd, R. B. (1987). A motor relearning programme for stroke. London: William Heinemann Medical Books.

Carson, R. G. (1995). The dynamics of isometric bimanual coordination. Experimental Brain Research, 105, 465-547.

Carson, R. G. (1992). Asymmetries in the discrete and pseudo-continuous regulation of visually guided reaching. Brain and Cognition, 18, 169-191.

Carson, R. G. (1996). Neuromuscular skeletal constraints upon the dynamics of perception action coupling. Experimental Brain Research, 99-110.

Carson, R. G. (1998). Moving beyond phenomenology: neuromuscular-skeletal constraints in movement dynamics. In Piek, J. P. (ed.), Motor Behavior and Human Skill: A Multidisciplinary Perspective (209-230), Champaign, Illinois.

Cobb, K., Goodwin, R. (1996). Spontaneous hand positions of newborn infants. Journal of Genetic Psychology, 108, 225-237.

Dean, C., Mackay, F. (1992). Motor assessment scale scores as a measure of rehabilitation outcome following stroke. Australian Journal of Physiology, 38-81.

Duncan, P. W., Goldstein, L. B., Matchar, D., Divine, G. W., Feussner, J. (1992). Measurement of motor recovery after stroke, Stroke, 1084-1089.

Eggers, O. (1998). Occupational Therapy in the Treatment of Adult Hemiplegia. London: W. Heinemann Medical Books Ltd.

Fagard, J. (1990). The development of bimanual coordination. In Bard, C., Fluery, M., & Hay, L. (ed.), Development of Eye –Hand Coordination Across the Life Span. Columbia: SC, University of SC Press.

Fagard, J., Barbin, Y. (1987). Apprentissage moteur bimanual: Couplage et decouplag dans e'elaboration de nouvelles synergies. Cahiers de Pyschologie Cognitive, 7(6), 561-572.

Flament, F. (1975). Coordination et Prevalence Manuelle Chez le Nourisson(2nd Ed.). Paris: C.N.R.S.

Fisk, J. D., Goodale, M. A. (1988). The effects of unilateral brain damage on visually guided reaching: hemispheric differences in the nature of the deficit. Experimental Brain Research, 72, 425-435.

Fisk, J. D., Goodale, M. A. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Experimental Brain Research, 60, 159-178.

Fowler, B., Duck, T., Mosher, M., Mathieson, B. (1991). The coordination of bimanual aiming movements: evidence for progressive desynchronization. Quarterly Journal of Experimental Psychology [A], 43, 205-221.

Goldfield, E. C. (1986). Spatiotemporal linkage in infant interlimb coordination. Development Psychobiology, 19(3), 259-64.

Good, D. C. (1994). Treatment strategies for enhancing motor recovery in stroke rehabilitation. Journal of Neuro Rehabilitation, 177-186.

Goodman, D., Kobayashi, R. B., Kelso, J. A. S. (1983). Maintenance of symmetry as a constraint in motor control. Canadian Journal of Applied Sport Science, 8, 238.

Gordon, J. (1987). Assumptions underlying physical therapy intervention: theoretical and historical perspective. In Carr, J. H., Shepherd, R. B., Gordon, J., Gentile, A. M., Held, J. M. (ed.). Movement Science: Foundations for Physical Therapy in Rehabilitation. London: Heinemann Physiotherapy.

Gowland, C. (1982). Recovery of motor function following stroke: profile and predictors. Physiotherapy Can, 34, 77-84.

Haken, H. (1983). Advanced Synergetics, Springer, Berlin.

Hofsten, C. (1984). Development of visually guided hand orientation in reaching. Journal of Experimental Pyschology, 38, 208-219.

Inglis, S. (1984). Electromyographic biofeedback treatment of upper limb in hemiplegic stroke patients: a pilot study. Archives of Physical Medicine and Rehabilitation, 63, 613-616.

Karniel, A., Inbar, G. F. (1997). A model for learning human reaching movements. Biology Cybernetics, 77, 173-183.

Katrak, P. H., Cole, A. M. D. (1992). Objective assessment of spasticity, strength and function with early rehabilitation of dantrolene sodium after cerebrovascular accident: a randomized double-blind study. Archives of Physical Medicine and Rehabilitation, 73, 4-9.

Kelso, J. A. S., Southard, D. L., Goodman, D. (1979a). On the coordination of bimanual movements. Journal of Experimental Psychology, 5, 229-238.

Kelso, J. A. S., Southard, D. L., Goodman, D. (1983). On the space-time structure of human interlimb coordination. Quarterly Journal of Experimental Psychology,[A], 35, 347-375.

Kelso, J. A. S. (1995). Dynamic Patterns: The Self-organization of Brain and Behavior. Cambridge, Massachusetts: M. I. T. Press.

Kotila, M., Waltimo, O., Niemi, M., Laaksonen, R., Lempinen, M. (1984). The profile of recovery from stroke and factors influencing outcome. Stroke,15, 1039-1044.

Kraft G.H, Fitts SS, Hammond M.C(1992). Techniques to improve function of the arm and hand in chronic hemiplegia. Archives of Physical Medicine and Rehabilitation, 220-227.

Langton, H. R. (1990). Rehabilitation after stroke. Quarterly Journal of Medicine, 76, 659-674.

Meige, H. (1901). Les mouvements en miroir: leurs applications pratiques et therapeutiques. Rev. Neurol,19,780-782.

Launay, J. (1962). Le developpement de l'activite volontaire chez des enfants de 5 a` 9 mois. Archives of Physiology, 46, 33-57.

Liepmann, H. (1908). Drei Aufsatze aus den Apraxiegebiet. Karger, Berlin.

Mudie, H. M., Matyas, T. A. (1996). Upper extremity retraining following stroke: effects of bilateral practice. Journal of Neuro Rehabilitation, 10(3).

Piaget, J. (1937). Law Construction du Reel. Paris: Neuchatel, Delachaux and Niestle.

Parker, V. M., Wade, D. T. (1986). Loss of arm function after stroke: measurement, frequency and recovery. Institute of Rehabilitation Medicine, 8-69.

Perrig, S., Kazennikov, O., Wiesendanger, M. (1999). Time structure if a goal-directed bimanual skill and its dependence on task constraints. Behavioral Brain Research, 95-104.

Price, S. J., Reding, M. J. (1994). Physical therapy philosophies and strategies. In: Good, D. C., Couch, J. R. (ed.). Handbook of Neuro Rehabilitation. New York: Harper and Row (1970).

Provine, R. R., Westerman, J. A. (1979). Crossing the midline: limits of early eye-hand behavior. Neuropsychologia , 24(6), 793-804.

Schmidt, R. A. (1988). Motor Control and Learning: A Behavioral Emphasis, (2nd Ed).

Smith, D. L., Akhtar, A. J., Garraway, W. M. (1985). Motor function after stroke. Age and Aging,14,46-48.

Sugden, D., Utley, A. (1995). Interlimb coupling in children with hemiplegic cerebral palsy. Developmental Medicine and Child Neurology, 37, 293-309.

Steenbergen, B., Hulstijn, W., de Vries, A., Berger, M. (1996). Bimanual coordination in spastic hemiparesis. Experimental Brain Research, 110, 91-98.

Stuchu, N., Viviani, P. (1993). Cerebral dominance and asynchrony between bimanual two-dimensional movements. Journal of Experimental Pyschology: Human Perception and Performance, 19, 1200-1220.

Swinnen, S. P., Timothy, D. L. (1997). Interlimb coordination: learning and transfer under different feedback conditions. Human Movement Science,16, 749-785.

Swinnen, S. P., Jardin, K., Meulenbroek, R. (1997a). Egocentric and allocentric constraints in the expression of patterns of interlimb coordination. Journal of Cognitive Neuroscience, 348-377.

Swinnen, S. P., Dounskia, N., Levin, O., Duysems, J. (2001). Constraints during bimanual coordination: the role of direction in relation to amplitude and force requirements. Behavioral Brain Research, 201-218.

Swinnen, S. P., Jardin, K., Meulenbroek, R. (1996). Between limb asynchronies during bimanual coordination: Effects of manual dominance and attentional cueing. Neuropsychologia, 34(12), 1203-1213.

Swinnen, S. P. (1995). The organization of patterns of multilimb coordination as revealed through reaction time measures. Experimental Brain Research, 104, 153-162.

Tangeman, P. T., Banaitas, D. A., Williams, A. K. (1990). Rehabilitation of chronic stroke patients: changes in functional performance. Archives of Physical Medicine and Rehabilitation, 71, 876-880.

Taub, E., Miller, N. E., Novack, T. A., Cook, E. W., Fleming, W. C. (1990). Technique to improve chronic motor deficit after stroke. Archives of Physical Medicine and Rehabilitation, 74, 347-354.

Temprado, J. J, Chardenon, A., Laurent, M. (2001). Interplay of biomechanical and neuromuscular constraints on pattern stability and attentional demands in a bimanual coordination task in human subjects. Neuroscience Letters, 303, 127-131.

Trombly, C. A. (1992). Deficits of reaching in subjects with left hemiparesis: A pilot study. American Journal for Occupational Therapy, 887-897.

Tuller, B., Turvey, M. T., Fitch, H. L. (1982). The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. In: Kelso, J. A. S. (ed.), Human Motor Behavior (255-257). Hillsdale, NJ: Lawrence Erlbaum Publishers.

Wade, D. T., Langton, H. R., Wood, V. A., Skilbeck, C. E., Ismail, H. M. (1983). The hemiplegic arm after stroke: measurement and recovery. Journal of Neurology, Neurosurgery and Psychiatry, 46, 521-524.

Wade, D. T., Collen, F. M., Robb, G. F., Warlow, C. P. (1992). Physiotherapy intervention late after stroke and mobility. Biomedical Journal, 304, 609-613.

Wade, D. T., Wood, V. A., Heller, A., Maggs, J., Langton, H. R. (1987). Walking after stroke. Second Journal of Rehabilitation Medicine, 19, 25-30.

Wagenaar, R. C., Meijer, O. G. (1991). Effects of stroke rehabilitation (1), a critical review of the literature. Journal of Rehabilitation Science, 4, 61-73.

Wall, P. D. (1990). Mechanics of plasticity of connection following damage in adult mammalian nervous system. In: Bach, R. P. (ed.). Recovery of Function: Theoretical Consideration for Brain Injury Rehabilitation (91-105). Baltimore: Univeristy Press.

Westphal, C. (1873). Ber einige Bewegungsercheinungen an gelahmten Gliedern. Archives fur Psychiatry Nervenkrankhteiten, 4, 747-759.

White, B. L., Castle, P. (1964). Observations on the development of visually directed reaching. Child Development, 35, 349.

Wiesendanger, M., Wicki, U., Rouiller, E. (1994). Are there unifying structures in the brain responsible for interlimb coordination? In: Swinnen, S. P., Heuer, H., Massion, J. (ed.). Interlimb Coordination: Neural, Dynamical and Cognitive Constraints (179-207). San Deigo: Academic Press.

Winters, J. M., Crago, P. E. (2000). Biomechanics and Neural Control of Posture and Hand Movement (Rev. ed.). NY: Springer-Verlag Inc.

Wolff, H. I. (1967). Sex differences in finger tapping: A developmental study. Neuropsychologia, 14, 35-41.