School of Physiotherapy

An Examination of Selected Upper Extremity Functional Activity from the Perspective of the Dynamic Pattern Theory of Motor Control

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This thesis is presented as part of the
requirements for the award of the
Degree of Doctor of Philosophy
of
Curtin University of Technology

January 1996

Abstract

An examination of throwing was performed in a controlled environment with the aim of identifying the control and order parameters of throwing as proposed by dynamic pattern theory. A pilot study was conducted to test the possibility that the mass of a ball, the distance thrown and the size of targets were the control parameters. Based upon the results of the pilot study, only the distance was manipulated as an independent variable in the principal study.

Three-dimensional motion was recorded using three video cameras in the motion analysis laboratory and later analysed using the Peak motion analysis system (software version 5.0, 1992). Sixteen right handed adult females, aged 18 - 35 years, volunteered to participate in the principal study. Subjects were seated with their trunks secured to the back support of an adjustable chair. Ten different targets (0.6 to 6.91 m) were labelled on the floor in front of the subjects. A large area for each target was defined so that the throwing skill of subjects could be ignored as a factor in the research design. Subjects were asked to throw a 0.5 kg ball to ten different distances using their own styles which allowed them to change the pattern of throwing as the distance thrown increased.

All 16 subjects selected either an overarm or an underarm throw or employed both patterns. No subject used other patterns of throwing. At the shortest distance, a greater number of subjects selected an underarm throw. As the distance thrown increased, some subjects switched to the overarm throw. At the distance of 3.36 m, there were eight subjects (50%) using each style of throwing. Alteration of the throwing pattern mainly occurred from the underarm to the overarm throw. The results suggest that the distance thrown may be one of the control parameters in the throwing movement.

Furthermore, the presence of both throwing patterns for all distances thrown suggests the presence of a multiple stable state in throwing motions. Trajectories of movement become more uniform as the distance thrown increased. Variability was greatest when subjects threw to the shortest distance for both patterns. These results imply that as the distance thrown increased the stability of both throwing patterns increased.

Moreover, these results also imply a phase transition within each throwing pattern, in addition to the phase shift between the pattern of throwing.

No result could directly illustrate the period of the transition. This may be due to the fact that phase transition in a multistable system is the result of an external force which drives the system from one state to another. Alteration of the pattern does not occur as a result of loss of the stability of the previous state. However, some of the results such as the hysteresis graph presented indirect evidence, which could imply a phase shift between throwing patterns. In addition the higher degrees of joint angle recruitment in the overarm throw suggest that the stability of the system may be better maintained in the overarm throw than in the underarm throw.

Alteration of the sub-styles of throwing within the same throwing pattern seemed to occur in between the shortest and the longest distances thrown. Many of the results supported this concept, for example, data related to the relative timing, the total ROM, the releasing joint angles, the trajectories of the movement, the phase plane plots, the angle-angle plots, and relative phase. However, the presence of sub-styles in the underarm throw was not as obvious as was the case for the overarm throw.

In conclusion, the changes in motor behaviour during throwing as the distance thrown increased as examined in the present study can be explained by dynamic pattern theory in some aspects. However, further investigation of the stability of the patterns and energy utilisation necessary for the execution of the underarm and overarm throw are essential to determine the most suitable order parameter and to confirm the proposed control parameter (distance thrown) identified.

ACKNOWLEDGEMENTS

> *What we are today comes from our thoughts of yesterday, and our present thoughts build our life of tomorrow*
>
> *-The Buddha*

The following people have contributed significant time and effort to assist me during the completion of this thesis, I would like to express my sincere gratitude to you all.

To:

Professor J. Cole for the opportunity, encouragement and support given to me while conducting the research. Her valuable time spent correcting draft version of this thesis are much appreciated.

Anne Furness for her constructive criticism during the preparation of the research proposal.

Dr. J. Sommer for his guidance, statistical support, and for his explanation of non-equilibrium dynamic theory. In addition, his comments on the methodology and results chapters of this thesis have been invaluable.

Don Cooper for his technical support, time and patience in teaching me polar coordination and joint angle calculation, and for the time spent correcting the first draft.

Dr. Michael R. Zomlefer for his guidance during Stage One data analysis.

Dr Brian von Konsky for his comment on the methods of joint angle calculation.

Dr Timothy M. Barker from Queensland University of Technology for the time he spent writing a program for computing the joint moment data.

Dr Chris Kirtley for contacting Dr Barker, making the elbow orthosis, and for his support.

Klaus Sussenbach for his talent and technical expertise in solving projectiles and markers problems.

Ray Smith for his technical help and assistance during Stage Three data collection.

Tanya Keen Lyttle for her occupational therapy knowledge in solving the flying rod marker at the elbow joint, her friendship and for participating as a subject in this study.

Tamis Pin for volunteering as a subject and acting as a model for the photographs. The photographs have been used many times.

M.C. (Molly) Verrier from University of Toronto for her comments and suggestions during her academic visit to Curtin University of Technology.

Dr Connie Price, Dr Garry Allison, Gillian Marks, and Dr Sally Raine for their suggestions, comments and friendships while we shared the office as postgraduate students.

John Owen for his skill in making spectacular posters for my presentation.

Craig Cobb for his help in preparing the equipment and laboratory room.

Paul Parin for his photographic skill.

Ross Kemp for the time spent in solving my computer problems especially those occurring with the optical drive and optical discs.

To all of those who participated as subjects, without them this research would not have been completed.

To all of my friends (Ajarn Suparb, George, Jenny Cook, Marilla Hogan, Chamlong, Chenisa, Joy, Dr Nawarat, and Dr Vachirapong) for their moral support, encouragement, and especially their friendship.

To the Buddhist and Thai community with whom I have spent many weekends restoring my energy and motivation to come back to School on Monday.

This research would not have been possible without the financial support of the Australian Government. Special thanks to Katarina Tap at AUSAID.

To all of those not appearing on this acknowledgement list, but whom assisted me in some way during my stay in Perth. Your assistance during the preparation of this thesis is gratefully appreciated.

Poster Presentation

Part of this thesis has been presented as poster at:

Multisegmental Motor Control: Interfaces of Biomechanical, Neural and Behavioural Approaches, August 13-18, 1995, New Hampton School, New Hampshire, United State.

The Third Biennial Motor Control and Human Skill Research Workshop, December 2-3, 1995, Perth, Western Australia.

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Abbreviations

3-D	Three dimension
abd	Abduction
AD	Angular displacement
add	Adduction
AV	Angular velocity
CNS	Central nervous system
CPG	Central pattern generator
DLT	Direct linear transformation
Elb	Elbow flexion and extension
ext	Extension
flex	Flexion
Forrot	Forearm rotation
HVB	Horizontal velocity of ball
JCS	Joint coordinate system
Lt	Left
Max	Maximum
Min	Minimum
Pm	Muscle power
Prep	Preparation time
pron	Pronation
rad	Radial deviation
Rel	Releasing time
RMS	Root mean square
ROM	Range of motion
rot	Rotation
Rt	Right
Sh ad/ab	Shoulder adduction and abduction
Sh ext.rot	Shoulder external rotation
Sh fl/ex	Shoulder flexion and extension
Sh int.rot	Shoulder internal rotation
Sh rot	Shoulder rotation
sup	Supination
TMT	Total movement time
uln	Ulnar deviation
Wr fl/ex	Wrist flexion and extension
Wr ul/ra	Wrist ulnar and radial deviation

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Chapter 1

Introduction

You cannot discover new oceans
unless you have the courage to
lose sight of the shore.

- Unknown author

Control of movement is one of the most difficult issues in the area of human function. A range of different research approaches have been employed in an effort to understand human motor control, however knowledge of the mechanisms associated with limb movement are still limited. This is partially because in the research situation it is necessary to choose a movement to study and the output of the experiment becomes specified by the testing task. Also in order to identify the influence of one factor on the motion, it is necessary to control other factors within the study. This controlled environment is not consistent with what normally happens during natural motion and may lead to outcomes which may change the mechanism controlling the movement. Understanding of movement control, therefore, has been limited by task constraints (Newell, 1989).

To produce a functional movement or synergy, the movement components have to be sequentially processed and temporally organised and their relative magnitudes need to be determined (Scholz, 1990), The complexity of coordinative motions causes difficulty in designing experiment at situations which can explore the mechanisms of control. Newell (1989) has pointed out that the study of coordination has been confined by many of the task protocols used in the last 100 years.

In addition, Kelso, Putman and Goodman (1983) have commented that little attention has been devoted to determining principles that might underlie human upper limb coordination. Most of the existing research has involved only single limb or one degree of freedom movements (Kelso, et al., 1983; Newell, 1989) such as finger rhythmic movement (Kelso, Scholz, & Schöner, 1988).

Dynamic pattern theory is a motor control model which employs a different perspective in looking at movements (Scholz, 1990). The model proposes that behavioural movement arises from the self-organisation of sub-systems involved in the movement (Kelso, 1995). This nonlinear dynamic theory considers the role of constraints upon the task as integral to the study of the underlying movement control (Newell, 1989). Dynamic pattern theory proposes that small quantitative changes in task constraints can lead to qualitative changes and significant alteration in motor behaviour. However, examples of task goals that require manipulation of environmental conditions to induce transition between different phases of coordinated pattern are very limited in experiments related to motor control (Newell, 1989).

Dynamic theory provides a contrast to many other motor control theories which have failed to explain the effect of small changes in task constraints (Newell, 1989). The applications of dynamic pattern theory and its concepts have been developed through the investigation of rhythmic motion patterns. Limited experimental attention has been given to discrete movements (Schöner, 1990). Schöner (1990) has described the difficulties in applying dynamic pattern theory to discrete movements and Scholz (1990) has pointed out that characterising functional multijoint movements requires attention to more than one movement parameter.

Although a number of studies have applied dynamic pattern theory to locomotion (which is a functional movement), it is important to verify the application of this theory to functional upper extremity motions. The functions of the upper limb are different from those of the lower limb (Hogan & Winters, 1990). To maintain appropriate function of the upper extremity requires stability and flexibility as well as precision. The actions of muscles of the upper limb are not designed to support the body weight and have no stereotyped rhythmic motion pattern comparable to locomotion.

Several significant terms are used in explaining movement characteristics within the dynamic pattern theory. For example, movement is said to be stable under fixed environmental conditions until it reaches a point where the controlling characteristics are no longer functional. The pattern becomes unstable and enters a stage of phase transition as the pattern is altered and a new version, more suited to the emerging environmental conditions is reached (Scholz, 1990). The variability and instability of movements are considered to be critical conditions by which many characteristics of movements can be identified. For example, a parameter that changes the stability of the system may act as a control parameter (Scholz, 1990). Control parameter is the term used to identify the particular factor which causes the instability and leads to the phase transition resulting in the new pattern of movement (Scholz, 1990).

A preferred coordinated movement pattern which occurs under particular environmental conditions is called an attractor (Kay, Saltzman, & Kelso, 1991). When the system is perturbed it tends to return to its attractor, unless the perturbation causes a condition of instability in which case, the system may shift to another state of attractor (Kay et al., 1991).

An order parameter is one which characterises a particular stable pattern of motion (Scholz, 1990). It may be the relative phase of movement as occurs in rhythmical movements or it may be any one of a variety of kinematic variables which capture the relative motion or action of the component, or their coordination and prove to be constant for a given movement under specific environmental conditions (Scholz, 1990). Obviously as the movement enters a phase transition then it is likely that the order parameters become less stable and may change completely as the effect of the control parameter causes a new movement to emerge (Scholz, 1990).

In dynamic pattern theory, systematic variability indicated that upcoming instability and should not be confused with the concept of error as generally dominated in field such as learning (Kelso & Ding, 1993). Dynamic pattern theory considers all the systemic components as well as the environmental conditions, whereas, other approaches concentrate on a particular body segment. Thus different ways of approaching the description of movement may provide a new insight into motor control.

The present study has been designed to explore some of the limitations in motor control studies using dynamic pattern theory as the basic model to examine functional coordinated movements of the upper extremity. The concepts of dynamic pattern theory (Kelso, 1995) including self-organisation, attractor, stability and phase transition as well as proposed parameters which, from the perspective of dynamic pattern theory, are identified as order and control parameters, will be examined for a selected motion, a throwing task.

Throwing is a non-repetitive discrete motion which provides a useful model for study. Alteration in throwing styles as the parameters involved in the movement are changed, such as the length of the throw, the weight, size, and shape of projectile and the accuracy required in the throw are readily observed. The variety of throwing patterns is dependent on the specific range of these throwing parameters. For example, a number of alternate movement patterns are more apparent when the target distance is about the length of the subject's arm compared with that for a very long distance throw. That is one can drop, place or using different styles of throwing to bring an object to a short target distance, whereas, one can only use throwing action to fulfil the same task when target is at a long distance. However, no studies have examined the change in throwing pattern under these different circumstances. Rather most studies of throwing movements reported are concerned with kinematic or kinetic measurements related to performance in sport.

1.1 Aims and Objectives

The aim of the present study is to examine the application of dynamic pattern theory to a functionally discrete motion of the upper extremity. To identify and solve problems related to the shifting of throwing patterns under different conditions, a detailed analysis of kinematic variables of throwing motion was designed using three-dimensional motion analysis. Examination of throwing motion will be performed in a set environment. Three throwing variables, the distance thrown, the weight of the object and the accuracy of the throw were selected for manipulation.

The specific objectives of this study are:

a) to identify a control parameter likely to be responsible for changes in a throwing movement.

b) to identify the order parameters which appear to be essential to characterise a throwing movement; and

c) to examine the changes in throwing behaviour which can be explained by dynamic pattern theory.

Examination of movement pattern requires a measurement which can quantify the topological forms of movements (Winstein & Garfinkel, 1989). That is the shapes of the movement parameter profiles are important variables. A number of qualitative measurements of movement coordination are employed in the present study, for example, a phase plane plot which demonstrates the relationship of angular displacement and angular velocity of a joint of interest, an angle-angle plot which shows the intersegmental coordination, and a relative phase plot which informs the differences of the phase between two joints. In addition, time series curves of kinematic data are also illustrated. The sign of joint actions has been defined as follows: flexion, adduction, internal rotation, pronation, and ulnar deviation have a positive sign; whereas extension, abduction, external rotation, supination, and radial deviation have a negative sign.

1.2 Significance of the study

The application of dynamic pattern theory to clinical practice has been described by a number of authors (Giuliani, 1991; Scholz, 1990; Smith & Thelen, 1993). Identification of a control parameter in the movement is an important step which must be undertaken before determining suitable order parameters and attractors of the movement of interest. Determination of order parameters is also an essential factor for assessment of the motor behaviour. Accurate measurement of motor systems will lead to the better intervention and understanding of movement control.

Although the present study will examine the selected task in normal subjects, the expansion in knowledge resulting from this study may contribute to the understanding of pathological movements. Moreover, this proposed study is the first which attempts to examine a functional non-repetitive motion using dynamic pattern theory. The results of the present study may provide some insight into motions in daily life which do not occur in repetitive modes and to sporting activities involving throwing skills. The study may also identify limitations or problems which could effect the application of dynamic pattern theory in the analysis of discrete motions.

The proposed study was carried out within The School of Physiotherapy at Curtin University of Technology in Perth, Western Australia. Approval of the University's Human Research Ethics Committee was sought and granted prior to carrying out the study protocol.

Chapter 2

Literature Review

A full understanding of human movement can only come about if we integrate behavioural work (which tends to focus on the outcome of performance) with kinesiology (which provides us with information about the kinematics of human movement) and neurophysiology (which tells us the nature of underlying neural mechanisms involved in controlling movement).

-J. A. Scott Kelso (1982, p. 4)

2.1 Introduction

The present review aims to describe the theories and research related to motor control theories. The specific foci of the review are the dynamic pattern theory, throwing movements and measurement of coordination. However, other motor control theories which provide information related to movement control of the upper limb are also presented.

Kelso (1982) has commented on issues which are necessary for a full understanding of human movement, and the quotation appears at the beginning of this chapter. That is, integration of the outcome performance, the kinematics of human movement and neurophysiology are required to fully understand human movement. Based on this comment, the exposition of motor control theories will be introduced using the defined diagram of factors related to movement developed for this study (Figure 2.1).

Many systems of the body are involved in movement, the musculoskeletal and nervous systems are the most important components in human motion. Item 1, 2, & 3 indicated in Figure 2.1 are part of the controllers of movement in which structures and functions

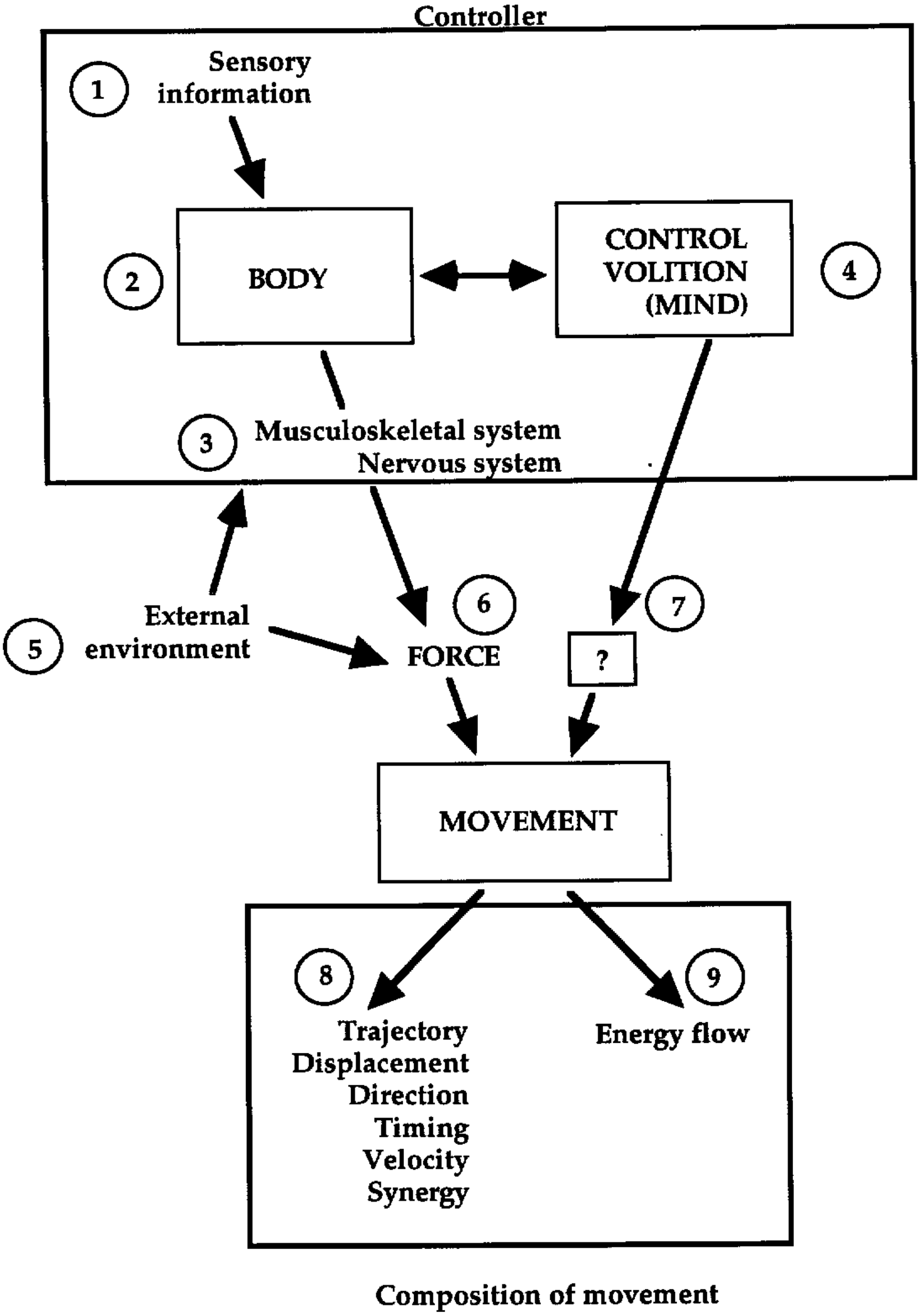


Figure 2.1 Summary diagrams of factors related to movement

can be identified. The relationships between anatomical structures and functions are important elements in basic approaches used in the study of motor control.

Structures indicated as 4 and 7 in Figure 2.1 represent another side of control which is rather abstract in form and cannot easily be defined in terms of structures. Control and volition identified in Figure 2.1 must also include the learning and practising processes which lead to skill development. The outcome of volition may affect the function of the musculoskeletal or nervous systems directly or it may affect the force produced or be responsible for other effects. For this reason, the outputs which form the abstract side of the control model in Figure 2.1 are illustrated as a black box. This aspect of control is beyond the scope of the present study.

Item 5 in Figure 2.1 represents the external environment which includes a number of factors such as information about movement and gravitational force. The external environment may directly influence movement through force or have indirect effects via the controller.

Force and composition of movement (items 6, 8, and 9) are identified as the movement variables in this review. All these components help to determine the quality of movement and to differentiate between different tasks. That is, it is obvious that reaching and throwing or walking and running are not the same movements. On the abstract side (item 9) of Figure 2.1, there is a flow of energy and force during movement, which may not be observable during movement despite the fact that the energy parameter could affect the pattern of movement. These various parameters (item 8 and 9) are considered to constitute the components of movement.

Classification of motor control theories in the present study has been derived from Kelso's (1982) comment. Motor control models are possibly divided into three classes.

a) Motor control theories based on neurophysiology.

b) Motor control theories based on outcome of performance including kinematics and kinetics of human movement. Outcome of movement, kinematics and kinetics of movement are termed movement variables in the present review.

c) Motor control theories based on the integration of all information related to movement.

2.1.1 Motor control theories based on neurophysiology

Explanation of movement control in this class is based mainly on consideration of the structures and functions of body systems. Motor control theories in this class, including, the reflex model, the hierarchical model, the closed loop model, the open loop model and motor program, originated earlier than those in other classes. Studies of neuroanatomical structures related to movement control and sensory information processing are also included in this class. Concepts and models developed to describe the production of human motion within this theoretical framework may not be able to adequately explain all aspects of movement due to task constraint problems described by Newell (1989). However, they are still useful to the understanding of motor control. Some of these data may provide clues for the development of other models, an example being how knowledge of movement time during a fast movement has resulted in the development of the open loop model of motor control (Schmidt, 1988).

2.1.1.1 Neuroanatomical structures and movement control

The attempt to understand human motion and behaviour probably started from knowledge about human anatomy and function. This information provided a general outline with which to predict the outcome performance and explained a number of human behaviours. However, complete insight into movement cannot be gained simply from an understanding of complex structures. This point is clearly confirmed by the findings about the dynamic function of the brain in which Merzenich and Kaas (1982) have demonstrated functional plasticity and reorganisation of topographic maps in the adult mammalian somatosensory system. For the purpose of the present study, which does not focus on neuroanatomical structures, only findings about the central nervous system related to movement control are presented.

Functions of the motor cortex which are associated with movement have been known for a long time. Anatomical relationships are known to be of importance in motor control. Scientists have identified and mapped the area of the cerebral cortex which appears to provide control to different parts of the body and the representations of body segments in the cortex are considered to be flexible (Anson, Hyland, & Wickens, 1992). The evidence of reorganisation of mammalian somatosensory cortex after peripheral nerve injury was also recorded by Merzenich and Kaas (1982). Thus the brain is seen as being composed of a dynamic group of neural assemblies (Wickens, Hyland, & Anson, 1994). These facts imply that there is variability and adaptability of the cortex for the purposes of controlling movement.

The connections between neurones in the motor cortex and the spinal cord are substantial and complicated, particularly with respect to motor neurones supplying muscles of the hand and forearm (Anson, et al., 1992). The complex network suggests that activation is unlikely to create a stimulus which is directed toward a single neurone. Any group of neurones which work together is termed a cell assembly (Anson, et al., 1992; Wickens, et al., 1994). Activation of a cell assembly will cause a synergy action (Anson, et al., 1992). This finding explains the synergistic pattern of movements and suggests that a synergy is defined by the controlling structures.

Arising from the theory of cortical cell assemblies is the suggestion that motor control is based on the concept of the motor program (Wickens, et al., 1994). A motor program is defined as an abstract representation of a movement sequence which is stored in memory and contains variant and invariant features (Schmidt, 1989). The motor program is hypothesised to be stored in the form of synaptic connections between appropriate groups of cortical neurones (Wickens, et al., 1994). In addition, Denier van der Gon, Coolem, Erkelens, and Jonker (1990) have described neural networks as the anatomical pattern representing a motor program.

Well-defined neural networks which contribute to many patterns of movement (mostly invertebrate) have been named according to the activities they control (Schöner & Kelso, 1988c). Examples include the swimming central pattern generator (CPG), flight CPG, and locomotor

CPG. These patterns are reproducible and stationary over a certain amount of time and can be characterised well enough to differentiate them from other neural patterns generated by the same network (Schöner & Kelso, 1988c). These data provide support for the concept of the motor program and indicate synergy in movement control.

2.1.1.2 Reflex model and hierarchical model

The reflex model has been originated from the work of Sir Charles Sherrington, a neurophysiologist in the late 1800s and early 1900s (Shumway-Cook & Woollacott, 1995). Sherrington proposed that reflexes were the building blocks which sequentially worked to achieve a complex movement (Sherrington, 1947). For example, Sherrington described a frog capturing and eating a fly as a consequence of reflexes activation. That is, the reflex protusion of the tongue to capture the fly is activated by visual stimulus, the contact of the fly on the tongue causes reflex closure of the mouth, which finally results in reflex swallowing. Thus, the reflex model depends on the connections (anatomical structures) among the inputs, centre and outputs. Furthermore, this model proposed that afferent sensory pathway are a necessary for the execution of voluntary movement (Brunnstrom, 1970). Even though, the reflex model can explain some aspects of motor behaviour, it has a number of limitations. For example, the reflex model cannot explain the spontaneous and voluntary movement because an external stimulus is required to activate the behaviour and the limitation for explanation fast movements which occur faster than the process of sensory feedback from the preceding movement to activate the next movement behaviour (Horak & Dow, 1991; Shumway-Cook & Woollacott, 1995).

The hierarchical model was proposed by Sir Hughlings Jackson (Walsche, 1961). The model separates movement control according to the level of neuroanatomical structures. The spinal cord, the motor cortex, and the higher association areas of cortex are organised hierarchically as the lowest level, the intermediate level, and the highest level of control, respectively (Foerster, 1977). The reflexive movement will dominate if the higher centre is injured. The dominance of the primitive reflexes is attributed to a lack of higher level control over lower levels (Horak and Dow, 1991). An explanation of normal motor development in infants has also been proposed from the corticalisation of the CNS in which the higher levels of control can overcome lower level reflexes (McGraw, 1945). However, the hierarchical model cannot explain the movement which originated from the lower level spinal cord, such as, the withdrawal reflex to pain (Horak & Dow, 1991). In addition, Grillner (1975) has demonstrated that paraplegic cats in which the spinal cord is partially transected and the dorsal roots are also severed can still walk on treadmills (Grillner, 1975).

Although the limitations of the reflex and hierarchical theory have been notified, the concepts of these theories still have influences in clinical practices, such as therapists try to reduce flexor spasticity in patients with hemiplegia in which they assume that this clinical strategies should enhance normal movement ability (Shumway-Cook & Woollacott, 1995). In addition, stimulation of the desired reflexes, such as righting and equilibrium reflexes and inhibition of the undesired reflex, that is, tonic neck reflex was also used as a concept in physical therapy intervention (Bobath, 1966).

2.1.1.3 Open and closed-loop model

The closed-loop theory has been developed by Adams (1971). The theory proposed from the concept that peripheral receptors (feedback) are necessary for the control of coordinated movement (Stelmach, 1982). A number of studies have demonstrated evidences for a closed-loop theory. For example, the relationship between vision and movement of hand can be disturbed by delaying visual feedback (Smith, 1972). and mechanical vibration applied to a tendon or muscle belly could produce an illusion of limb movement (Goodwin, McCloskey, & Matthews, 1972). These studies implied that stimulation of a peripheral receptor could override the higher centres of the CNS (Stelmach, 1982).

The idea of feedback leads to the examination of the information related to movement time and the time required to process sensory input and prepare motor output within the nervous system. Thus movement requiring feedback tends to be performed slowly, or to be either a new task in which some skill is needed for execution, or a complex movement which requires some degree of accuracy (Schmidt, 1988).

Rapid movement has been identified as being performed with feedforward or open loop control (Schmidt, 1988). The open loop theory suggested that movement is regulated by central rather than peripheral sources (Stelmach, 1982). In addition, experiments in deafferented animals have suggested that feedback from the moving limb may not be essential for actions to occur (Schmidt, 1988).

Open loop theory leads to the concept of programming of movement and also the problem of degrees of freedom which will be discussed in the following sections. Detailed descriptions of open and closed-loop models have been reported in motor control text books such as Kelso (1982) and Schmidt (1988).

2.1.1.4 Generalised motor program and a motor program

A motor program has been defined by Keele (1968) as a set of muscle commands that are structured before a movement sequence begins, and that allows the sequence to be carried out uninfluenced by peripheral feedback. The definition, however, has been modified from a set of motor commands for movement to an abstract representation of a sequence of motion stored in memory (Schmidt, 1988). Evidences for the existence of motor program arises from a number of researches. For example, movement can be executed in a deafferented man (Rothwell, Traub, Day, Obeso, Thomas, & Marsden, 1982). The idea of motor program, therefore, agrees with the concept of the open loop theory which proposed that sequences of movement could be prepared in advance and executed without feedback (Stelmach, 1982). Furthermore, a motor program theory can also explain the control of rapid movement in which the movement time is faster than the peripheral feedback processes. The finding of central pattern generators is also supported the concepts of motor program (Delcomyn, 1975).

Additionally, the theory of motor programs has also derived from the notion that movements are produced as a result of the organisation and maturational processes of the nervous system. However, Giuliani (1991) has reported that changes in the musculoskeletal system might also affect the motor pattern. For example, changes in the length of a limb segment may affect coordination of movement even if the nervous system function remains the same. Thus not all changes in motor coordination can be explained by the organisation and maturation of the nervous system.

The characteristics of a movement do not depend on the joint or the segment of limb performing the movement. For example, writing on a piece of paper and on the black-board have subject-specific characteristics even though the tasks are quite different. Furthermore, the problems of storage space requirements and the need for revision of motor programs for slightly different motions has led to the concept of the generalised motor program (Schmidt, 1988). Other evidence that supports the generalised motor program relates to the finding of similar patterns of movement at differing loads and speeds. The generalised motor program theory implies that the general pattern of muscle activation is the same, but some parameters such as the intensity and duration vary depending on the amplitude and duration, of the planned movement, while the selection of the muscles required to perform the movement depends on the movement direction (Schmidt, 1988). However, the observation of some types of movement has contradicted this proposition. For example, Gielen, van den Heuvel, and Denier van der Gon (1984) found that muscle activation patterns of fast goal-directed movements are preprogrammed, but they can be modified during the movement. For a complete discussion of motor programs see Schmidt (1988).

2.1.2 Motor control theories based on movement variables

Schmidt (1988) has stated that the nervous system may control movement not muscles. This thought supports the perception that it is the goal or the movement pattern which seem to be what the performer is controlled of rather than the particular muscles or motor units involved. The study of the movement variables such as, movement time, displacement, velocity or forces has provided information about a number of models or concepts which have aimed to elucidate the complexity in the control of movement. For example, concepts about invariant and variant features, the control of end point model, the maximum smoothness theory, the mass spring model, and the inverse and forward dynamic methods.

2.1.2.1 Invariant and variant features

A number of movement variables have been identified as invariant features in a movement. They include such things as trajectory (Soechting & Lacquaniti, 1981), movement velocity (Atkeson &

Hollerbach, 1985; Soechting & Lacquaniti, 1981), and relative timing (Schmidt, 1988). Identification of invariant parameters supports the concept of motor programs. That is, the motor program may contain both the invariant and variant features (Wallace & Weeks, 1988). The invariant features are the parameters that remain constant across changes in a particular movement and are viewed as a sequence of activation or a motor program (Wallace & Weeks, 1988). The invariant features help to separate one program from another whereas the variant features produce different movement characteristics within the same program. An infinite number of movements which are in the same class can be performed by a single generalised motor program (Schmidt, 1988). Thus only one program need to be stored rather than an infinite number of related programs (Schmidt, 1988).

Relative timing has been proposed as one of the invariant features in a movement (Schmidt, 1991). Generally, changes in movement time will lead to the alteration of other parameters of motion, for example, force, duration of contractions, speed and distances the limbs travel. Any variable of the movement which remains invariant or constant is termed an invariance (Schmidt, 1991). If the whole movement is speeded up uniformly, the constant is a variable called relative timing (Schmidt, 1991). Therefore, relative timing is independent of the overall speed or amplitude and is the fundamental temporal structure or rhythm of a movement pattern (Schmidt, 1991). Relative timing may also refer to the constant ratios of the durations of several intervals within the movement. Movements which have the same relative-timing are arranged into the same class. Relative timing is not the same between different classes of motion, for example throwing and punching (Schmidt, 1991) .

Schmidt (1991) used throwing as an example in his explanation of relative timing. He has stated that different types of throwing could be represented by a single generalised motor program. The basic features of the variety of these throwing motions such as a fast versus a slow throw, throwing a light versus a heavy object, throwing overarm versus sidearm were that they contained the same relative timing. If someone has an established throwing pattern, it is very difficult to change or adapt a small part of the motion of that style because the relative-timing is invariant. The motor system prefers to operate the task as a whole rather than as a segment of the movement. However, these are simply assumptions have not been verified by experimental data.

The invariance of the timing of the temporal events has also been reported in fastball and curveball pitches (Sakurai, Ikegami, Okamoto, Yabe, & Toyoshima, 1993). These results imply the consistency of temporal events in the overarm throw over different distances thrown. This suggestion supports the assumption of Schmidt (1991)that there is invariant relative timing in different trajectories of throwing. However, the throwing distance in both pitching styles is very long and may not be readily compared with studies in which the distance thrown is much shorter.

2.1.2.2 Mass spring theory

The mass-spring theory uses physical properties of springs to model how limbs move to specific positions when the initial conditions change or the feedback process is not available (Kelso, 1982). The theory proposes that a muscle-tendon unit is mechanically analogous to a spring (Schmidt, 1988). This assumption is supported by information about the length-tension properties in muscle. This information indicates that a muscle is comparable to the fundamental mechanical principle which applies to springs. The control of a spring in order to produce different positions, can be accomplished by adjusting certain parameters such as the stiffness and mass. Thus, the nervous system may define the resting length by adjusting the length-tension relationship of both agonist and antagonist muscles. An active tension of muscles develops, if the actual length of the muscle is longer than the resting length. On the other hand, the muscle is relaxed, if the muscle length is shorter than the set resting length (Kelso & Holt, 1980).

Kelso and Holt (1980) have described the following advantages of the mass-spring model.

1) The desired movement is independent of initial conditions.

2) The defined position is based on the law of mechanics. These advantages suggest that regulation does not require a feedback mechanism.

3) The speed of motion can be controlled by specifying stiffness which can be regulated independently of resting length. Muscle stiffness is dependent on muscle length, the degree of activation and the configuration of the limb (Bizzi, Accornero, Chapple, & Hogan, 1984; Flash, 1990)

4) By defining the equilibrium point, repetitive movements can be produced by the natural oscillations of a spring system.

5) Spring parameters of all muscles involved could be temporarily coupled to accomplish the desired position. For example, the task of pointing a finger to a target requires the temporary coupling of the trunk, shoulder, elbow, and wrist.

The concept of mass spring model is based on the assumption that muscles in bodies can demonstrate as a single spring which might be an oversimplification according to Latash and Zatsiorsky (1993). A number of factors, that is, the type of the muscle, level of muscle activation, operating length of the muscle-tendon complex, parameters of external perturbation, and resistance to perturbation determined the compliance contribution from the tendon and muscle fibers (Latash & Zatsiorsky, 1993). However, stiffness measurement which is one of the properties of spring could be performed in passive movement of biological tissues (Latash & Zatsiorsky, 1993).

A detailed discussion of the mass-spring model can be found in Schmidt (1988) , Kelso (1982), and Latash and Zatsiorsky (1993).

2.1.2.3 Control of end point position

A number of studies have suggested the control hypothesis which is referred to as final position control (Bizzi, et al., 1984; Kelso, 1977; Kelso & Holt, 1980; Schmidt & McGown, 1980). According to the mass-spring model, the final resting length of a spring will be the same regardless of the initial length of that spring. That is, a mass-spring system will always attain an invariant final position or equilibrium point, despite any alteration of the initial joint conditions (Kelso, 1982). This notion was confirmed by Kelso and Holt (1980) who tested the efficacy of a vibratory systems analysis of finger localisation. They found that the motion to end points needed no moment-to-moment intervention by central control mechanisms and that the starting position and brief perturbation had no effect on the end points reached.

The idea of movement control as proposed in the mass-spring model led to the notion of control of end point position, a proposition which can be explained from the perspective of there being an equilibrium point to the movement. The central nervous system may maintain a joint position by simultaneous activation of agonist and antagonist muscles (Bizzi, et al., 1984; Schmidt, 1988). That is increasing or decreasing the stiffness of either agonist or antagonist muscles has the effect of shifting the equilibrium point.

The theory of control of end point position suggests that the central nervous system controls simple large movements by specifying only the final equilibrium point of the movement while the details of movement trajectory are determined by the inherent inertial and viscoelastic properties of the limb and the muscles (Bizzi, et al., 1984). The shift in equilibrium point may be more abrupt for very fast movements, whereas the trajectories of multijoint movements may also be generated by a gradual shift in the equilibrium point (Bizzi, et al., 1984).

However, Feldman (1986) and Latash and Zatsiorsky (1993) have rejected the concept of muscle stiffness as the controlled variable. Latash and Zatsiorsky (1993) stated that the muscle-tendon complex cannot be considered as a single spring and therefore, cannot be determined a value of stiffness. Furthermore, in the control of end point concept (Bizzi et al., 1984), the muscle characteristics start from a point at which the muscle is relaxed. This model does not provide regulation of muscle length and force in the muscle's physiological range (Feldman, 1986). Feldman (1986) also argued that a load close to zero cannot be lifted at all despite intensive variations of muscle stiffness. This argument is in comparison with the insignificant changes of stiffness in a spring when the load is small. For a detailed discussion see Feldman (1986).

Calculation of how the endpoint of a system will be displaced when certain torques are applied, is known as the forward dynamics problem (Rosenbaum, 1991). In contrast, the inverse dynamics problem is the problem of determining the torques that should be applied to the system given that the endpoint of the lever is supposed to traverse some path

(Rosenbaum, 1991). If the forward dynamics problem is applied, then the patterns of joint angles would be simple but the profiles of the hand trajectory would be complicated. If the motor system uses the inverse dynamics approach, the direct hand path and the regulating system would calculate the muscle torques required to generate that movement. This would lead to a simple hand trajectory but complex joint angle patterns (Rosenbaum, 1991).

The trajectory of the movement is always a result not only of the active muscle contractions affecting the joint, but of passive forces as well (Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990). The combination of active and passive forces is highly complex, task-dependent, and likely nonlinear, because the interactions between muscles and joints are different at different levels of activation and different locations in the work space (Schneider, et al., 1990). Only the muscle forces are actively controlled by the CNS. However, there may be no need to use muscle contraction when the trajectory of movement can be accomplished by gravity, inertial forces from movements of other parts of the body, or from the inherent elasticity of muscle and tendons (Schneider, et al., 1990). No one-to-one correspondence exists between muscle activation patterns and the resulting time-space behaviour of the limbs, because the forces that move the limbs do not originate from muscles only (Schneider, et al., 1990).

Movement of multiple segment limbs requires production of appropriate joint torques. These torques arise from dynamic interactions among the moving segments and from external forces such as gravity (Hollerbach & Flash, 1982). The interaction torques are not necessarily important during normal arm movements (Hollerbach & Flash, 1982). For example, during sufficiently slow movements, the effect of gravity will dominate all other dynamic torques, that is, the interaction torques between moving segments. However, during most human arm movements the gravity contribution represents only a small fraction of the shoulder torque. Hollerbach and Flash (1982) have studied the dynamic interactions between limb segments during planar arm movement. Their results suggest that the interaction torques are significant for a two joint arm movement over a range of movement speeds and movement paths. They concluded that there must exist control strategies which compensate for the presence of interaction torques during multiple joint movement.

For movement along different straight line paths, the torque profiles are quite different. This means that there is no simple way to adapt a torque program for movement along one path to generate a movement along a different path. The authors postulated that computation or compensation for the dynamic interactions must already have occurred in the motor preprogram because delays from the proprioceptors make feedback correction unlikely (Hollerbach & Flash, 1982). The methods of constructing motor programs including provisions for interaction torques might have been considered. For a detailed explanation see Hollerbach and Flash (1982).

2.1.2.4 The maximum-smoothness theory for arm movements

The observation of smooth and graceful movements in humans has led to the theory of maximum-smoothness. This theory postulated that voluntary movements can be made as smooth as possible under particular circumstances (Flash, 1990). Rate of change of hand acceleration or the third derivative of position was used to determine a degree of smoothness (Flash, 1990).

The smoothness and variability of individual joint motions have been measured in the study of the coordination of squat-lifting (Scholz, 1993b). One of the experimental goals was to determine whether movement planning of the lifting task takes place at the individual joints or at the crate/ hand (end-effector) (Scholz, 1993b). Comparison of the jerk-cost or the smoothness of the crate/hand, knee, lumbar spine, and shoulder joints suggested that the control of squat-lifting occurs in terms of end-effector spatial trajectory rather than individual joint trajectories.

Even though this theory can explain some of the movement patterns, it is difficult to prove that hand jerk is actually sensed or that the minimum-jerk trajectories are computationally derived by the nervous system (Flash, 1990).

2.1.2.5 Single-joint and multi-joint movement

It is now widely recognised that the dynamics of multiple-degree-of-freedom movements are different from those pertaining to one degree of freedom movements (Hollerbach & Flash, 1982). This is because the motion at each joint depends not only on the muscular torques acting about that joint, but also on dynamic interactions with the other joints. These dynamic interactions are due mainly to the inertia of the limb segments (Hollerbach & Flash, 1982).

The musculoskeletal system involved in a multiarticular motion is a highly nonlinear system (Zajac & Winters, 1990). Thus the net motion of the body segments is not equal to the sum of the motions that would occur if individual muscles acted in isolation. Zajac and Winters (1990) described three fundamental sources of nonlinear properties:

a) the musculotendon dynamics,

b) the static transformation between musculotendon force to joint torque and musculotendon velocity to angular velocity, and

c) intersegmental dynamics and gravitational influences.

For simple, in single-joint tasks the input-output pattern may be linear. However, the output behaviour may change drastically if the system is perturbed. One explanation which can be considered uses the Hill nonlinear model (Zajac & Winters, 1990). That is, when muscle force increases, muscle impedance, the force-velocity slopes of the elastic components and the tension-length slope all increase. Therefore, the action of muscles is dependent on the initial conditions and type of perturbation (Zajac & Winters, 1990).

The differences between the concept of Zajac and Winters (1990) and the concept of mass spring theory (Kelso & Holt, 1980) may be due to the underlying assumptions. The mass spring theory could be applied only to a specific condition such as in passive muscle, whereas in active muscle-tendon unit under perturbation, the mass spring theory failed to be true (Latash & Zatsiorsky, 1993).

Kelso, Putman, and Goodman (1983) have examined the concept of coordination of limbs as a unitary structure. Subjects were asked to move both hands to perform an easy and a hard task using an obstacle in the path of one limb, but not the other. The results suggested that the multijoint limb motions function as a single unit (Kelso, et al., 1983).

2.1.3 Motor control theories based on the integration of all information related to movement

For the last class of motor control theories, all components related to movement production and outcome performance are considered as a pattern. This concept is supported by Kelso and Schöner (1988) who have stated that the study of complex biological systems and behavioural complexity should be undertaken using organisation principles rather than mechanisms. One of the reasons they propose for this suggestion is that biological systems generate ordered behaviour in a flexible (eg., changing according to environmental demands) as well as stable fashion (eg., persisting for a certain amount of time under varying environmental conditions) (Kelso & Schöner, 1988). The multifunctional features of biological structures in which the same set of anatomical components can be used for different behavioural functions or different components to perform the same function also offer support for this idea Kelso and Schöner (1988) and Kelso (1995).

Dynamic pattern theory is an example of a motor control model in this class. Apart from the basic concept of organisation of system components, the dynamic pattern theory is also concerned with the effect of intention or mind on movement coordination (Schöner & Kelso, 1988a).

2.1.3.1 Dynamic pattern theory

The dynamic pattern theory or the dynamic system theory has been developed by Kelso (1984) and Schöner, Haken, and Kelso (1986). This theory is based on the problem presented by the issue of degrees of freedom. One of the solutions to the degrees of freedom problem is to organise muscles to function as synergies or coordinated structures. A synergy is a group of muscles that is constrained to act as a single functional unit (Heriza, 1991a). In dynamic systems theory instead of the assumption that sequencing and timing of movement require motor programs, it has been proposed that such coordinated motion may be described in terms of self-organisation (Heriza, 1991a).

In the dynamic pattern theory, the central nervous system is viewed as one subsystem that dynamically interacts to produce movement. The theory is based on the principle of the non-equilibrium phenomenon in physics (Heriza, 1991a). It provides a new way of conceptualising motor control. The theory deals with the dynamic concepts of self-organisation, stability, phase shifts, and attractors. The CNS is seen as a necessary but not sufficient component to explain movement. Other factors such as biomechanical, musculoskeletal, psychological, and social environments are all important (Heriza, 1991a). Dynamic pattern theory is discussed in detail later in this chapter.

2.1.4 Summary

There are many theories of motor control. The oldest one is based on the idea of reflex control as the basis for simple movement. The evolution of the various theories in motor control have not served to prove that previous theories were useless. Instead examination of various theories appears to have increased the understanding of movement in particular conditions. Despite the fact that some theories do not hold in all cases, they can still explain the nature of motor control in certain conditions. So far, expanding the knowledge of how movement is controlled is still one of the most difficult challenges of research.

The concepts of motor control theories have evolved in two directions:

a) from the basic aim of analysis at the anatomical or structures and function level to the consideration of composition of movements and

b) from concrete to abstract parameters.

The present review has described motor control theories with respect to the approaching concepts of a particular theory. That is: a) Motor control theories based on the neurophysiology point of view which provided some basic backgrounds, such as a knowledge about a reflex control of movement and a feedback control system. However, the information provided by such theories is not sufficient to explain complex movements which involve many degrees of freedom; b) Motor control theories based on examination of movement variables. This perspective is specific to a movement parameter and does not investigate the effect of abstract components, such as the intention of performance on the learning effects; and c) Motor control theories based on the integration of neurophysiological components and movement variables approach. Dynamic pattern theory is located on this type of approach.

2.2 Dynamic Pattern Theory

A dynamical system can be explained as a system that changes over time (Walter, Swinnen, & Franz, 1993). In dynamic pattern theory, movement patterns spontaneously arise from the organisation of sub-systems related to that particular motor behaviour (Kelso, 1995). Schöner, Zanone, and Kelso (1992) have stated that the CNS provides not only for a particular pattern but for its entire dynamic environment. Flexibility and spatiotemporal stability are an essential property of a coordination pattern. Flexibility allows the coordinated pattern to adjust to a variety of environmental demands (Heriza, 1991a). Stability of the movement pattern can be indicated by order parameters, which can describe the characteristics of motor behaviour, and can be measured by the ability to return to the pattern after a small perturbation. Loss of stability leads to a pattern alteration and increase in the variance of order parameters (Schöner, et al., 1986).

2.2.1 Concept

Dynamic pattern theory is based on the concept of pattern formation which has to handle two problems (Kelso, 1995):

1) a very large number of components required for pattern formation;

2) production of many patterns to accommodate different environmental conditions.

To explain the mechanisms underlying pattern formation, some generalisations must be considered.

2.2.1.1 Self-organisation

The dynamic pattern theory assumes that behavioural patterns may arise from the interaction of a large number of sub-systems (Schöner & Kelso, 1988c). Trajectories of movement in space will converge on an attractor, if it is given sufficient time. An attractor is a preferred state of a particular movement in certain conditions (Heriza, 1991a). Changes in control parameters produce a new pattern. Control parameters are known as parameters which cause qualitative changes in a movement pattern (Schöner & Kelso, 1988c). A pattern is referred to as self-organised because it emerges as a result of the dynamic of the interactions between components of the network under the influence of inputs, without any specific ordering influence from the external components such as, the central and the peripheral nervous system and the network's specific anatomical structure (Scholz, 1990; Schöner & Kelso, 1988c).

2.2.1.2 Attractor

The coordinative movement patterns have preferred frequencies and amplitudes of oscillation. These patterns are the preferred state and are termed dynamic attractors (Heriza, 1991a). When the system is perturbed it tends to return to the preferred movement pattern. Dynamic attractors occupy the state space and evolve over time. State space is an hypothetical space which can be defined any number of variables. For example, the attractors of kicking or stepping may be detected from the pilot of the joint angle of a moving limb against another joint angle of the same limb (angle-angle plot) or the joint angle of a limb against a joint velocity of the same limb (phase plane plot) (Heriza, 1991a).

Attractors are one of the crucial properties for systems because they imply that the system has a low-dimensional asymptotic form in spite of high-dimensional complexity. For biological systems, the forms of organs or organisms are attractors of their (embryological) development dynamics (Garfinkel, 1983).

Three types of attractors have been defined, a point (equilibrium) attractor, a periodic (limit cycle) attractor, and a chaotic (mixing) attractor (Heriza, 1991a). A point attractor is an attractor in which the trajectory converges from arbitrary initial conditions onto a single state, or a point. Point attractors have the property that a transient perturbation applied during movement does not affect achievement of the equilibrium point because the short perturbation is equivalent to a resetting of initial conditions, such as position and velocity (Kay, Saltzman, & Kelso, 1991). The movement of a single limb to a target or the damped linear mass-spring, describable by a second-order linear differential equation is considered qualitatively as a point attractor (Kay, et al., 1991).

A periodic attractor, or limit cycle attractor, is one in which the trajectory forms a closed ring. Most of the lower extremity motions are considered to be a limit cycle, that is, kicking, walking, running, hopping, galloping, and skipping. For the oscillatory task, the attractor is the limit cycle (Walter & Swinnen, 1990). Physiological functions of the body are oscillatory, such as heart beat, respiration, the neuromuscular system. Regulation in the body is carried out by means of the fundamentally oscillatory structure of physiological activities. Thus, the preferred mode of operation of the information-carrying systems of physiology is oscillatory in nature (Garfinkel, 1983). Various pathologies are associated with irregular oscillation. For example, various arrhythmias and fibrillation of the heart, irregular breathing and apnoeas affect the lungs, various types of epileptic seizures disrupt central nervous system physiology, and various forms of dyskinesias affect the neuromuscular system (Garfinkel, 1983). Oscillating biological systems are not an ideal limit cycle. They are never exactly periodic when plotted on the phase plane but appear as a band around some average closed curve (Kay, et al., 1991). Point and periodic attractors can be seen in the two-dimensional plane, despite all the degrees of freedom involved in these movements (Garfinkel, 1983). The equations described point and limit cycle attractor dynamics can be seen in Kay, Saltzman, and Kelso (1991).

The chaotic attractor, so-called strange attractor, is an attractor in which trajectories are mixed in state space. It appears that chaotic attractors represent part of the future of dynamics in physiology (Garfinkel, 1983).

These preferred movement patterns can be represented graphically by plotting the joint angle of a moving limb against another joint angle of the same limb (angle-angle plot) (Heriza, 1991b). Moreover, the presence of an attractor can be tested by comparing kinematic variables such as frequency and amplitude before and after intervention of a transient mechanical perturbation (Kay, et al., 1991).

2.2.1.3 Stability of the system

Newell and Corcos (1993) have stated that it is difficult to define stability. More than one variable is required to characterise the stability of a system. Schöner and Kelso (1988c) has proposed methods to measure the stability of the system. The first method is by calculating the standard deviation or coefficient of variability of the collective parameters of the system. The measurement of variability or the inherent noise in a system by this technique has been generally used to assess variability. The more stable the attractor, the smaller the standard deviation from the attractor state. Another method of measuring variability is to measure the relaxation time which the system requires to return from an unstable to a stable state (Giuliani, 1991; Schöner & Kelso, 1988c). The relaxation time is defined as the time from the onset of the perturbation until the pattern existing prior to the perturbation is reestablished (Scholz, 1990). The smaller the relaxation time is, the more stable is the attractor. A relaxation time approaching infinity indicates a loss of stability (Schöner & Kelso, 1988c). For more details about relaxation time see Scholz (1990) and Schöner and Kelso (1988c).

Loss of stability of a previous movement pattern prior to a transition has been used as evidence for self-organisation of movement coordination (Scholz & Kelso, 1989). In addition, instability also leads to alteration of the movement pattern.

Multistability systems

Pattern alteration may be observed in a system with a fixed parameter set and a fixed architecture. That is, several different patterns can be performed within the same task and in the presence of the same environmental information (Thompson & Stewart, 1986). Such changes are the result of multiple stabilities in the state dynamics of the system, but not of system bifurcation (Thompson & Stewart, 1986). An externally driven force is required to push the multistable system from one stable pattern to the other (Saltzman & Munhall, 1992).

In a multistable system, several attractors with different basins of attraction may coexist (Schöner & Kelso, 1988c). Biological systems often demonstrate multiple behaviour, for example, in neural networks, this property is known as multifunctionality (Schöner & Kelso, 1988c).

The concept of multistable state systems is consistent with "motor equivalence" in which the same action can be performed by different means depending upon the conditions of execution (Darling & Stephenson, 1993; Paulignan, MacKenzie, Mateniuk, & Jeannerod, 1990). Paulignan and coworkers (1990) have investigated the coupling of arm and finger movements during prehension by measuring two-dimensional motion of the index, thumb, wrist, elbow, and shoulder joints. Subjects were asked to reach, grasp, and lift a dowel as accurately and rapidly as possible. They found that reorientation of the hand to the new object position is likely to be achieved by different patterns of movement, such as, combining rotation of the shoulder and elbow joints, increasing the motion of thumb and index finger, and rotation of the wrist.

2.2.1.4 Phase transition

Discontinuous pattern change accompanied by a systematic change in a control parameter is called phase transition. This change generally occurs because the old pattern has become unstable. The stability of the previous pattern decreases just prior to the pattern alteration while the new pattern is becoming more stable (Scholz & Kelso, 1989). Phase shift in biological systems is based on nonequilibrium phase transition. That is, alteration from one qualitative coordinated pattern to another is nonlinear or discontinuous, for example, the shift from walking to a trotting gait in a horse (Vilensky, Njock Libii, & Moore, 1991). This concept has been known to be the core of pattern transformation in open physical (Hakens, 1975), chemical systems (Ross, Müller, & Vidal, 1988). A main idea of the theory of nonequilibrium phase transitions is the reduction in the number of degrees of freedom that occurs near critical points where patterns form or change spontaneously (Kelso, Scholz, & Schöner, 1988).

Transition of a pattern occurs from a state with relative phase (ø)

$$ø = \pm\pi$$

(referred to as the antisymmetric mode) to another state with relative phase

$$ø = 0$$

(referred to as the symmetric mode) (Schöner, et al., 1986). Below the transitional point, the system is bistable whereas beyond the critical point only the symmetric mode persists (Schöner, et al., 1986). This generalisation of the preferred direction of transition may only apply to the tasks that have been studied. It did not imply for all motor behaviours.

If two stable solutions coexist, phase shift occurs at the bifurcation point. This phase transition is also known as the bifurcation phenomenon. A bifurcation phenomenon in human movement involves quantitative differences among a set of similarly topological patterns of a system

(Saltzman & Munhall, 1992). The best known example of a bifurcation phenomenon in human movement is the bimanual rhythmic movements in which subjects oscillate their fingers or hands at the same frequency in an out-of-phase manner. The frequency of oscillation is then increased over the course of the trial. The out-of-phase coordination abruptly shifts to an in-phase coordination when the frequency passes a critical value. A comparable shift does not happen as the frequency increases when subjects start with an in-phase coordination (Kelso, 1984).

The phenomenon in which phase transition occurs when the system is in an out-of-phase pattern, but does not happen when the system is in an in-phase pattern is called the hysteresis phenomenon (Kelso, 1995). That is, the alteration of pattern is dependent on the direction of parameter change or the presence of a control parameters along which changes occurs in one direction but not in the reversal or at a different value of the control parameter upon reversal. Hysteresis is also involved in perception because perception depends on the direction of stimulus change and also its rate of change (Kelso, 1995).

Not all behavioural changes are phase transitions (Schöner & Kelso, 1988c). Phase transitions are characterised by a period of increased variability, a period of slower restoration to a stable state, and points at which new behaviour is observed (Giuliani, 1991).

A review of the issues relevant to bifurcation can be seen in Kelso (1995), Saltzman and Munhall (1992), and Thompson and Stewart (1986).

a) Energy utilisation and phase transition

Kelso (1984) proposed that the "new" stable mode is energetically more favourable at a given frequency than the previous one. The relationship between energy expenditure and behavioural pattern has been reported in studies of gait in quadrupeds (Hoyt & Taylor, 1981; van Emmerik, 1992; Vilensky, et al., 1991).

Vilensky et al. (1991) reviewed studies on the trot-gallop gait transitions in quadrupeds. They proposed that running, trotting, and galloping involve a spring-like mechanism for minimising energy expenditure. As animals switch to galloping, they change from smaller, stiffer springs to longer, more complaint springs. This change in energy storage mechanisms is hypothesised to occur at the trot-gallop transition. As speed increases within a gait in a horse, the amount of oxygen consumption used to travel a particular distance is illustrated as a reverse bell-shaped curve. Within each gait, there is a speed at which maximum efficiency (minimum oxygen consumption) is achieved. Thus transitions between gaits normally occur at speeds where the curves intersect and oxygen consumption is the same for the two gait styles. However, shifts in locomotory modes are not hard wired or deterministic (except perhaps at the very limits of stability). Horses can trot at speeds at which they would normally gallop or walk, but it consumes more metabolic energy (Kelso, 1984).

b) Variability in phase transition

Phase transition cannot always be accurately predicted. Changes in control parameters or energy expenditure are not the only things which explain phase shifting, other factors are also involved. Vilensky et al. (1991) have discussed variability that probably causes divergence from the predicted trot-gallop transition values in quadrupeds, that is cats, dogs, and monkeys. They proposed that the psychological state of the animal, the animal's level of fatigue and social implications are associated with each gait.

2.2.1.5 Recruitment and annihilation of task components

Kelso (1995) noticed a new bifurcation while increasing the cycling frequency in the study of repetitive bimanual motion in the x-y plane. Typically the phase transition occurs from an antiphase to an in-phase pattern in the horizontal (x) plane. However, Kelso and Scholz (1985) discovered another transition emerging, that is, from the horizontal to the vertical (y) plane, as the frequency of movement was increased further. He stated that the process of spontaneous recruitment and annihilation of degrees of freedom provides the stability required for systems at a particular condition. In addition, the new pattern may still have the same topology as the previous one, for example, both may be limit cycles (Kelso, 1995). Recruitment of the previous quiescent degrees of freedom is also found in the study of gait transitions in quadrupeds. As the speed of motion increases and stance duration decreases, an animal will also recruit trunk (back) muscles. Thus, the limbs work in series with the back muscles.

2.2.1.6 Intrinsic dynamics

The intrinsic dynamics are the dynamics of collective variables which are not controlled by the system but occur spontaneously during many functional behaviours (Schöner & Kelso, 1988a). The word 'intrinsic' refers to the fact that the particular parameter is a basic one in which learning and intention or effort are not required. Nevertheless, the intrinsic dynamics are not hard-wired constraints of the physiology (Schöner & Kelso, 1988a). Schöner and Kelso (1988a) have assumed that the intrinsic dynamics depend on noise for two reasons: First, any systems which contain many degrees of freedom but are described by only a few collective variables, are subject to the influence of underlying high-dimensional dynamics. Second, noise plays a crucial role in determining the stability of the system. The influence of intentions may be understood by examination of spontaneous pattern changes which allow the identification of the intrinsic dynamics of a system (Schöner & Kelso, 1988b).

Determination of whether the desired coordination is an intrinsic pattern or whether it must be learned is useful for the intervention process (Scholz, 1990). If the particular motion is not an intrinsic one, intentional effort and feedback about movement are necessary. However, the inability of a patient to perform a desired action is not a final indicator. The defined pattern may simply not be available to the system under the current conditions. For example, if the limbs are too stiff or there is inadequate weigh shift, patients may not be able to walk (Scholz, 1990).

2.2.2 Parameters in dynamic pattern theory

2.2.2.1 Order parameters

An order parameter or collective variable is a parameter that can characterise the movement pattern. This parameter can capture the spatial and temporal order of movement so that motions, such as kicking, walking or throwing can be differentiated. An order parameter has low-dimensional components when compared with a high-dimensional behaviour which has many degrees of freedom (Heriza, 1991a). In biological systems, order parameters have to be identified through a detailed stability analysis (Kelso, et al., 1988). At a transitional point, a clear differentiation of one pattern from another and the study of stability and loss of stability can be performed.

Relative phase, phase plane plot, and angle-angle plot have been used to quantify coordinated movement (Burgess-Limerick, Abernethy, & Neal, 1993; Hurmuzlu & Basdogan, 1994). Moreover, trajectories of movement can be used to present a topology characteristic of kinematic segments. This plot, the so-called Lissajous figure is a plot of selected point coordinate data in the plane of interest.

An example of a collective variable is relative phase for rhythmic movements. Relative phase is a variable which reflect the coupling of motions in performing the task (Scholz, 1990). In other words, relative phase informs coordination or timing of one motion with respect to the other (Scholz, 1990). For the mathematical definition of relative phase see Chapter 4, Section 4.2.4. Relative phase is a commonly proposed order parameter which has been used to characterise movements both in single joint motion (Schmidt, Carello, & Turvey, 1990; Scholz & Kelso, 1989; Scholz, Kelso, & Schöner, 1987; Schöner, et al., 1986; Schöner & Kelso, 1988c; Tuller & Kelso, 1989) and in single, multijoint limb movement (Kelso, Buchanan, & Wallace, 1991). It is difficult to directly apply the concept of relative phase to a discrete task (Walter, et al., 1993) however, relative phase has also been used to describe more functionally discrete movements such as in manual squat lifting (Scholz, 1993b).

In kicking or stepping movements, the order parameters of intralimb coordination are the timing of individual movement phases such as flexion and extension, the phase lags which are defined as the time between the onset of movement of one joint with respect to another joint, and the relationships of individual joints to each other. Order parameters of the interlimb level as seen in kicking and in walking are the relative temporal and spatial phasing between the two limbs (Heriza, 1991a; Heriza, 1991b).

In addition to relative phase, phase plane plots which illustrate displacement and velocity data are quite often reported as the representative measurement of movement patterns. For example, in rhythmic movements (Kay, Kelso, Saltzman, & Schöner, 1987; Kay, et al., 1991), phase plane plots were used to observe the presence of an attractor. This displacement and velocity plot is commonly found in the study related to locomotion (Clark & Phillips, 1993; Winstein & Garfinkel, 1989), in infant kicking (Heriza, 1991b), and in standing (Riley, Benda, Gill-Body, & Krebs, 1995). The phase plane plots are also used in other types of functional movements, such as in lifting (Scholz, 1993b).

Another method for the presentation of kinematic data is angle-angle plots. Plotting in one joint angle position as a function of another joint angle position has been used to inform quantitative information in coordinated movement (Burgess-Limerick, et al., 1993). Angle-angle plots are also found in the study of qualitative dynamics of human locomotion (Winstein & Garfinkel, 1989) and in lifting (Scholz, 1993a).

Trajectory of movement or Lissajous figure is another method which has been used to observe the characteristics of movement patterns. This plot does not require any additional calculation (angular displacement or angular velocity) but uses the coordinate data (x, y or z coordinate) from the kinematic analysis. A number of studies have presented kinematic results of movement using this form (Fetters & Todd, 1987; Kelso, 1984; Kelso & Jeka, 1992; Scholz, 1993b; Soechting & Terzuolo, 1987).

2.2.2.2 Control parameters

A control parameter is a parameter which shifts the movement from one form to another. This parameter does not prescribe the characteristics of the pattern directly but it can make the system reorganise to a new pattern (Heriza, 1991a). The new pattern arises only as a result of the dynamics of the system. A control parameter that shifts the system into a new pattern at one time may not be the control parameter that is critical at a later time because the changes in the components are nonlinear (Heriza, 1991a). For example, in the transition in infant stepping, muscle strength, and balance seemed to act as control parameters at one stage, while dynamic postural control, balance, and strength function as control parameters at another stage (Heriza, 1991a).

In general, frequency is identified as a control parameter for oscillatory actions. For example, an auditory metronome pulse produced by a computer was used as a control parameter to examine the control process of intentionally switching from one pattern of coordination to another in rhythmic motion of both index fingers (Kelso, et al., 1988; Scholz & Kelso, 1990) and also to determine the dynamic approach in multijoint single limb movement (Kelso, et al., 1991).

In the case of the pattern change phase transition in horse locomotion, the control parameter is the speed of movement (Heriza, 1991a). Clark and Phillips (1993) have found that a potential control parameter in the first year of independent walking is the strength of the thigh flexors. Heriza (1991b) also found that body build affected kicking activity in infants. Infants who were fat or who became fat quickly did not have the muscle strength to kick their heavier, stockier legs.

Walter and Swinnen (1990) found that torque or stiffness is a coordinative control parameter which affects the degree of interlimb attraction emerging during discrete bimanual actions. Stiffness determines the instantaneous force exerted (and thus the acceleration generated) at each transient position throughout a limb trajectory (Walter & Swinnen, 1990). It has also been proposed as the critical coupling variable for oscillatory actions (Soechting & Lacquaniti, 1981). However, limb kinematics have been found to determine the magnitude of interlimb attraction in oscillatory motions (Kelso & Schöner, 1988). Whether the limb kinematics or the combination of the limb kinematics and kinetics are responsible for interlimb coordination is still unclear (Walter & Swinnen, 1990).

Identification of control parameters is not an easy task in the dynamical approach (Kelso & Schöner, 1988; Schöner & Kelso, 1988c). The proposed control variable has to be changed through a sufficient range to determine whether it is a control parameter, that is whether it promotes a pattern transition (Scholz, 1990).

2.2.3 Movements used in previous study

Dynamic pattern theory has been applied generally to the characterisation of transitions between patterns of rhythmic movement coordination. The repetitive movement may be a single joint unilateral movement (Wimmers, Beek, & van Wieringen, 1992), a single joint bimanual motion (Baldissera, Cavallari, Marini, & Tassone, 1991; Kay, et al., 1991; Kelso, 1984; Scholz & Kelso, 1989; Scholz & Kelso, 1990), a multijoint single limb movement (Kelso, et al., 1991) or inter-subject coordination (Schmidt, et al., 1990). Most of the alternative movements have been performed both in normal subjects as just described and also in split-brain subjects (Tuller & Kelso, 1989). This theory has also been used in the study of human locomotion both in adults and children (Clark & Phillips, 1993; Heriza, 1991b; Whitall, 1989) and in quadruped locomotion (Hoyt & Taylor, 1981; van Emmerik, 1992; Vilensky, et al., 1991) Furthermore, dynamic pattern theory has also been applied to lifting tasks (Scholz, 1993a; Scholz, 1993b) and rhythmic drawing movements (van Emmerik, 1992). Recently, the theory has been extended theoretically to discrete motor tasks (Schöner, 1990; Wallace & Weeks, 1988; Walter & Swinnen, 1990). In addition to the coordinated movements of the trunk and limbs, dynamic pattern theory has also been used in the study of speech production and perception (for review see Kelso, 1995). Only some works cited above will be reviewed.

2.2.3.1 Rhythmic movement

Rhythmic periodic movements are generally used in studies designed to examine dynamic pattern theory in terms of motor control. Two patterns, in-phase and out-of-phase, have been observed (Scholz & Kelso, 1989). If both of the limbs are moved in the same direction, that is, both flex or extend, the movement is termed in-phase. If the limbs are moved in opposite directions, that is one extends while the other flexes, the movement is termed out-of-phase. Subjects are initially asked to move their limbs in an out-of-phase mode. As the frequency of movement is gradually increased, subjects involuntarily switch to an in-phase mode. On the other hand, if subjects start from an in-phase pattern, no pattern shift seems to occur. The process underlying phase transitions from the antiphase to in-phase mode may result from the informational resolution reaching its limit during antiphase movement. The system may solve this limitation by shifting to the in-phase pattern in which the informational degree of freedom is reduced (Schmidt, et al., 1990; Wimmers, et al., 1992)

A number of studies have been reported which use rhythmic motion in single joint movement (Baldissera, et al., 1991; Tuller & Kelso, 1989; Wimmers, et al., 1992). Phase transition is generally demonstrated as the frequency of movement is increased within a person. However, Schmidt et al. (1990) have shown a phase shift in between-person coordination. Subjects were asked to watch each other's lower leg as it oscillated according to a common tempo. The results demonstrated a transition of pattern the same as that found in within-person coordination. They concluded that the transitions are independent of the neural components and the nature of the information coupling.

A phase transition in single limb multijoint movements has been reported by Kelso, Buchanan, and Wallace (1991). Subjects performed two coordination patterns between the elbow and wrist joints of the right arm, that is, flexion or extension of both joints or alternating flexion of one joint and extension of the other. Kelso, Buchanan, and Wallace (1991) found that relative phase was an adequate collective variable, successfully characterising the ordered spatiotemporal patterning between the elbow and wrist joints. Frequency can also act as a control parameter by moving the system through coordinative states. However, stable phasing patterns are dependent upon spatial orientation (whether the forearm is pronated or supinated). These authors concluded that spatial orientation is also a control parameter in this experiment system.

The effect of practice on kinematic adaptation has been studied in rhythmic movement based on dynamic pattern theory (van Emmerik, 1992). Using rhythmic drawing movements, van Emmerik (1992) manipulated the friction level between the stylus and the writing surface as a perturbation. He concluded that early in practice, the control problem was simplified by the active reduction or freezing of the degrees of freedom. Later in practice, there was a reduction of the high degree of coupling between degrees of freedom, enabling the formation of functional units in joint and segmental linkages that were flexibly adapted to the constraints imposed. Furthermore, he found that in the nondominant limb, the adjustments were anatomically specific. All joints and segments responded in a similar manner, as shown by the high cross-correlations at all four perturbation magnitudes. In the dominant limb, the adjustments to the perturbations were not anatomically specific but more task specific. The degrees of freedom adjusted in different ways to the perturbations as shown by low cross-correlation values for all perturbation magnitudes.

2.2.3.2 Locomotion and developmental study

Locomotion in humans and in quadrupeds has been commonly used in the study of motor control based on dynamic pattern theory (Hoyt & Taylor, 1981; van Emmerik, 1992; Vilensky et al., 1991). Most of the work on human locomotion has been performed in the developmental area, for example, in running and galloping (Whitall, 1989), in the first year of independent walking (Clark & Phillips, 1993) and in kicking (Heriza, 1991b).

2.2.3.3 Discrete movement

The concepts of pattern dynamics and their adaptation through behavioural information has generally developed in the context of rhythmic movement coordination. Many of the techniques used for dynamical analysis of movement oscillations, for example, phase transitions, critical fluctuations, and relaxation times are quite difficult to apply to discrete tasks (Schöner, 1990). Although phase-locking of kinematic trajectories is quite apparent for discrete as well as for oscillatory tasks (Scholz & Kelso, 1989; Schöner & Kelso, 1988c), the nature of the control parameter(s) underlying the magnitude of interlimb attraction remains unclear for discrete tasks (Walter & Swinnen, 1990). Schöner (1990) has applied the concept of dynamics to discrete movements with single and multiple components. He has described a discrete movement as follows:

1) The initial and the target positions are intrinsically stable;

2) The intention to move stabilises an attractor, a limit cycle. This attractor is stable only over a period of time, approximately a half-cycle of movement;

3) After that time, the intrinsic dynamics again dominate so that the system relaxes autonomously to the second (target) fixed point; and

4) The intention to move is expressed as behavioural information, that is, as a part of the end-effector dynamics that stabilise the intended coordination pattern and the position-velocity curve (as a piece of the limit cycle).

The pattern of discrete movement is stable but may change over the course of the movement, or at the start and end points of movement. That is, the pattern of discrete movement exists only for a time period equal to typical relaxation times. On the other hand, the degree of persistence in rhythmic movement is maintained over periods of time much greater than typical relaxation times. Therefore, pattern fluctuations can be used to measure temporal stability in the case of rhythmic movement but not in discrete movement (Schöner, 1990). Temporal stability is one of the important concepts of the dynamic theory of coordination. Schöner (1990) has proposed that interpretation of inter-trial variability of movement parameters may possibly measure the stability in discrete movements.

The same is true for using the relaxation time to measure temporal stability. It is not easy to use the relaxation time to measure stability in discrete movement except for the initial and final postural stability (Schöner, 1990). A perturbation applied to discrete movement may cause only partial relaxation, that is, the relationship between position and velocity may remain changed until the end of movement (Schöner, 1990).

Schöner (1990) has pointed out that the coordination of discrete movement can be captured in terms of relative timing. The existence of a relationship between amplitude of movement and movement time has been consistently found in discrete movement (Schöner, 1990). The attraction to relative timing corresponding to anti-phase locking leads to a tendency to perform two movements sequentially. Therefore, if two discrete movements are initiated with sufficient delay, the movement time of delayed movement increases to make the movement occur with less temporal overlap.

In line with the concepts identified by Schöner (1990), Walter et al. (1993) have also pointed out that there are at least two problems which have to be solved to identify attractors for bimanual discrete action. The first problem is the short duration of actions of interest. Thus only a little settling time is provided for attractors or the preferred coordinated state to form. The second problem is related to the appropriate variable(s) in which the system can be characterised. That is the problem of identification of the order parameter.

Walter and Swinnen, and Franz (1993) have proposed that the relative motion trajectory is the possible useful collective parameter for bimanual discrete tasks, such as plotting of a kinematics of one limb as a function of the same variable for the contra lateral limb (eg. angle-angle plots). The direct linear relationship between these two variables indicates the inphase oscillation, and an inverse linear relationship (negative sign) represents the antiphase oscillations.

Walter and Swinnen (1990) have examined the effects of independent variations in kinetic and kinematic parameters on interlimb coordination in a bimanual task. Subjects attempt to perform a unidirectional movement with the left arm while the right arm presents a three-segment reversal movement. Angular acceleration was selected as the main dependent variable in this bimanual discrete task because it has been shown to be very sensitive to changes in spatiotemporal trajectory (Swinnen & Walter, 1988). The degree of synchronisation was determined in several ways (Walter & Swinnen, 1990).

1) The magnitude of the peak acceleration was compared between the control (alone) and the experimental (paired) conditions;

2) The temporal location and magnitude of the first peak in unidirectional acceleration were compared with those of the reversed condition; and

3) Cross-correlations were calculated between unidirectional and reversal limb angular accelerations.

Movement time and kinematic variables did not show any effect on the interlimb coupling. However, the results implied that some form of kinetic variable may influence the synchronisation of spatiotemporal patterns in bimanual discrete movement.

Even though, the previously discussed studies have used discrete movement in examining the dynamic pattern theory, experimental procedures still concentrate on studies of repetitive movement. Subjects are usually required to perform oscillating tasks, for example, a study of rhythmic manual squat lifting (Scholz, 1993a; Scholz, 1993b) or a study of the control of prehensile movement in which subjects perform tasks as rapidly as possible (Wallace & Weeks, 1988). In functional terms, there are many movements that are not rhythmic and not synchronised. The present study is the first to select a non-oscillatory discrete motion, throwing, to verify the application of the dynamic pattern theory in this type of movement.

2.2.4 Intention as behavioural information

The effect of intentional changes in behaviour on coordinated movement has been studied by Schöner and Kelso (1988a). The key idea was to treat the goal of the intention to change behaviour in terms of behavioural information. Behavioural information was defined as the part of the pattern dynamics that attracts the movement variables toward the intended coordinated movement. The effect of intention on the switching between patterns of bimanual coordination has been studied by Scholz and Kelso (1990). These authors found that although intention acts to modify a coordinative pattern's intrinsic dynamics, the influence of these dynamics on the resulting behaviour is always present and is particularly strong at high movement frequencies. This means that as the frequency of movement increased, intrinsic dynamics of the system will have the stronger effect than the intention of subjects. For example, if the subjects alternately abducted and adducted left and right index fingers (out of phase motion), as the frequency of movement increased, movement of fingers in both limbs became in phase relationship. Phase transition occurred even though subjects tried to maintain the out of phase relationship (Scholz & Kelso, 1990).

2.2.5 Application

Application of the dynamic pattern theory has been discussed by many authors (Heriza, 1991a; Scholz, 1990; Smith & Thelen, 1993). The dynamic pattern theory provides a new concept in understanding the control of movement. Although, it is generally used in repetitive motions which are not functional movements, the theory can explain the change in locomotion patterns both in animals and humans. In addition to motor behaviour, it has been applied to human development (Smith & Thelen, 1993) and speech production (Kelso, 1995). Many types of dynamics have been classified. For example, Saltzman and Munhall (1992) have applied the dynamic pattern theory in the study of skill acquisition and development. They divided the dynamical systems into three types, state dynamics, parameter dynamics, and graph dynamics. Similarly, Kelso (1995) has written about intentional dynamics, learning dynamics, and perceptual dynamics in applying the dynamic pattern theory to the area of motor learning.

Each component of the dynamic pattern theory, such as stability of the system, phase transition, order and control parameters, may contribute to therapeutic knowledge. Moreover, once the patterns and their dynamics are determined, alteration of the pattern may be induced easily (Scholz & Kelso, 1990). Examples of therapeutic interventions using the dynamic pattern theory are as follows:

1) To stimulate the organisation of a new pattern, therapists should apply the dynamic pattern theory to determine a suitable time to disturb the movement coordination of the patient (Giuliani, 1991). For example, in balance training, perturbation of patients' equilibrium will facilitate their posture and learning process to produce the correct response (Giuliani, 1991).

2) To acquire voluntary skills, the concept of intrinsic dynamics can be applied (Schöner, 1989; Schöner & Kelso, 1988a; Walter & Swinnen, 1992). Walter and Swinnen (1992) facilitated motor skills in tasks that required bimanual decoupling by tuning the system dynamics using a three-step strategy: a) Identifying a parameter that affects the strength of interlimb attraction, b) initially tuning down the parameter so that the desired relative motion pattern can be acquired more easily, and c) once the pattern has been acquired, progressively tune up the parameter to the criterion level. An example of this application would be training motor skills that require different limb movements, such as tapping nonharmonic rhythms with contralateral fingers (Deutsch, 1983).

3) To enhance the ability to assess the movement coordination by identification of relevant order parameters. An order parameter once defined would help to detect any changes in the pattern of motion as treatment or development proceeds and would also determine the effect of environmental conditions on the patient's dynamics (Scholz, 1990). For example, identification of order parameters in a child with spastic diplegia would help therapists to quantitatively document the

improvement of locomotion pattern from the bunny-hops to reciprocal lower extremity pattern (Scholz, 1990).

Dynamic pattern theory introduced the measurement of movement variability. In other words, the theory facilitate the identification of transition periods and the observation of factors influencing alteration of movement pattern, such as, environmental condition of movement, period of instability, or factors that produce stability (Giuliani, 1991). Since some of therapists might have observed the transitional movement of patients after a few repetitions of a desired movement pattern to an unwanted one, applying of the dynamic theory might provided a new class in both normal and dysfunctional movement (Giuliani, 1991).

2.2.6 Summary

One of the basic advantages of dynamic pattern theory is the theory's capacity to compress a large number of variables into a few variables. Under a particular condition, a pattern will have a preferred state which is called an attractor. The parameters that capture the characteristics of the system are called order parameters or collective parameters, whereas a control parameter is able to change or reorganise the system to a new pattern. However, a control parameter does not define the emerging pattern, instead it arises from the self-organisation of the subsystems. Manipulation of control parameters to a critical point will cause a phase transition. That is, a shift of pattern from one attractor to another. This transition is characterised by the increasing variability of the order parameters and the relaxation time. Although the theory has been tested and applied to different types of movements, the application of dynamic pattern theory to functionally discrete motions has been limited.

2.3 Reaching and pointing movement

Throwing, reaching, and pointing are all functionally discrete movements and involve aiming at the end of the movement. The distance to the target is the prime difference between these three actions. Thus, the control of the hand may be different in each action. For the purposes of this review, the discussion of reaching, pointing, and throwing movements only are presented as being relevant to the present study.

A reaching motion can be divided into two phases, that is a transport phase and a grasp phase (Paulignan, et al., 1990; Rosenbaum, 1991) or the acceleration pulse and the deceleration pulse (Ailon, Langholz, & Arcan, 1984). These two phases appear to be controlled by different areas of the brain. Damage to the pyramidal tract results in impairment of fine finger control, including impairment in grasping objects. Damage to the extra pyramidal tract results in impairment of gross arm movements, including the transport prior to object manipulation. Behavioural studies also indicate that the transport phase and grasp phase are governed separately (Rosenbaum, 1991).

Ailon et al. (1984) have proposed that the control law in a reaching motion is constructed by selecting from a set of preestablished parameters (rate of acceleration and deceleration), and is then optimised (to minimise effort) subject to specific constraints. Fetters and Todd (1987) have reported a movement unit which they identified by examining the relationship of inflection points in the speed-curvature of reaching movements of five to nine month old infants. A movement unit consists of a single acceleration followed by a single deceleration, which appears to these authors to have temporal stability across subjects, age, and condition. From the perspective of dynamic pattern theory, Scholz (1990) has suggested that identification of order parameters for a multijoint behaviour such as reaching is not an easy task. He proposed that the relative timing or phase of joint motions may be an appropriate order parameter and more than one order parameter may be required to characterise the reaching pattern since the action involves more than two joints.

For pointing movements, most studies have investigated the effect of target location (Gielen, et al., 1984; Soechting, 1984; Soechting & Lacquaniti, 1983) and target size (Soechting, 1984) on the motion. Soechting and Lacquaniti (1983) found that the rapid corrections of a movement involved the production of stereotyped patterns of activity in the muscles acting at the shoulder and elbow joint in response to a change in target location during a pointing movement. Whereas, increasing the movement time as the target size decreased, resulted in closed coupling between the elbow and shoulder joints. The wrist joint was only loosely coupled to the motion at the more proximal joints and was related to the angular orientation of the target in space (Soechting, 1984). Soechting (1984) concluded that wrist motion was controlled separately from motion at the elbow and shoulder joints.

2.4 Throwing

Research on throwing movements has concentrated on sporting activities, especially in the analysis of the baseball pitch. The pattern of throwing demonstrated by baseball pitchers is different from other throwing movements. However, an understandings of the features of baseball pitching provides insights into overarm throwing in general terms.

No studies involving kinematic and kinetic parameters of an underarm throw were located during the literature search for this study. Thus, the review of throwing concentrates on the overarm throw. It commences from the developmental point of view, and then moves on to the classification and phases of throwing. Kinematic and kinetic characteristics of the overarm throw are described according to the phases of movement.

2.4.1 The development of throwing

The development of throwing demonstrates an increasing appearance of sequential segmental rotations as the mature pattern develops (Kreighbaum & Barthels, 1990). For an overarm throw, the motion of shoulder rotation seems to be a crucial point which separates the unskilled and skilled thrower. These conclusions were confirmed by Enami and Yamagami (1995). They investigated the development of overarm throwing in 119 boys three to nine years of age. Subjects were asked to throw a tennis ball as far as possible. Differences identified in the patterns of throwing between the skilled and unskilled boys included the rotation of the trunk and of the shoulder joint. The skilled boys showed a higher range of motion of rotation of the hips and external rotation of the shoulder joint than the unskilled subjects. The upper arm of the skilled thrower demonstrated rapid internal rotation of the shoulder joint at the instant of release even though the shoulder joint was still in an externally rotated position at this instant (Enami & Yamagami, 1995). External rotation of the shoulder joint is caused by the inertial lag of the forearm and hand as the more proximal segments rotate forward and appears to be due to the combined effects of the abductor and horizontal abductor (Feltner & Dapena, 1986). In addition, a rapid motion of internal rotation was found immediately after maximum external rotation had been reached in the baseball pitch. More details about the development of throwing can be seen in Kreighbaum and Barthels (1990) and Roberton (1978).

Feltner and Dapena (1986) also found a rapid motion of internal rotation immediately after reaching the position of maximum external rotation in the throwing arm during a baseball pitch. They also reported that the elbow stops short of full extension in the baseball pitch. These authors explained that the motion of internal rotation may be unavoidable, and due to the stretch of the internal rotator musculature and the inability of the abductor and horizontal adductor torques to produce a large external rotator torque when the arm is nearly straight. Whether the motion of internal rotation of the shoulder is voluntary or involuntary, the combination of this motion with a slowing down of elbow extension may help to protect the elbow joint against injury.

2.4.2 Classification of throwing movements

Kreighbaum and Barthels (1990) have classified overarm, underarm, and sidearm throws according to where the movements occur relative to the body. Atwater (1977) describes an overarm pattern as one in which the trunk laterally flexes away from the projecting arm and a sidearm pattern as one in which the trunk laterally flexes toward the projecting arm. The terms overhand and underhand technically refer to the grasping position of the hand. Underarm occurs when the forearm is in a supinated position and overarm is normally produced when the forearm is in a pronated position.

Two types of rotation in the throwing motion have been described. The lever and the wheel-axle rotation of throwing. Kreighbaum and Barthels (1990) have defined the throwlike movement in which segmental rotations occur simultaneously as the pushlike motion The throwlike and the pushlike patterns can be differentiated by:

1) The hand and the object lag behind the proximal segment in a throwlike movement, but in a pushlike pattern the distal segment is positioned behind or is pulled along with the motion;

2) In throwlike movements, segmental rotations occur sequentially to produce high velocity but in pushlike motions, the rotations occur simultaneously to produce high accuracy or force.;

3) In throwlike patterns, objects move along a curvilinear path whereas in pushlike patterns, object are directed in a rectilinear path before contact or release;

4) Throwlike motions have a predominance of wheel-axle movements, and pushlike patterns have a predominance of leverlike movement.

Even though the lever and wheel-axle system are both rotational systems, a wheel-axle system can give a greater angular acceleration for a given muscular torque when compared with a lever system (Kreighbaum & Barthels, 1990). This is due to the fact that increasing the radius of rotation in a wheel-axle system has less effect on the rotational inertia when compared with the lever system. The detail of this explanation and an example of the calculation method can be seen in Kreighbaum and Barthels (1990).

2.4.3 Sequences of joint motion and joint torques during throwing

Throwing involves the sequential movement of joints. Putnam (1993) modelled the motion of the body and the upper limb as an open-link system of rigid segments in which the distal end moves freely through space. Throwing movements are characterised by proximal to distal sequential motions of the segments. The sequence of actions are: trunk rotation, sternoclavicular protraction, medial shoulder rotation, elbow extension, then wrist, and finger flexion (Jöris, Edwards van Muyen, van Ingen Schenau, & Kemper, 1985). Normally the shoulder joint makes a large part of its movement before the elbow joint starts to extend, and then the wrist joint moves last. The sequencing of joint movements will be limited to the arm if the trunk is not involved in the throw. Many types of throwing, for example, throwing a baseball and throwing a hammer require movements of the whole body. The sequence of joint movement in such actions starts from the lower limb and progresses to the trunk and to the upper limb and then to the projectile (Alexander, 1992).

Herring and Chapman (1992) have suggested that a successful throw will show temporal sequential joint torques which develop from proximal to distal. This proximal-distal sequence can also be demonstrated using the timing of the peak joint angular velocities. Furthermore, Herring, and Chapman (1992) also found that the timing of torque development was flexible. That is, to throw with a high torque, the timing and the proximal-distal sequences are both important. However, a really successful throw is not possible if there is no proximal-distal sequence.

An explanation of proximal-to-distal sequencing has been described in detail in Putnam (1993). Calculation of joint and segmental moments were used to explain proximal-to-distal sequencing using segment interactions. However, knowledge of joint moments does not lead to the precise prediction of the joint motions, because the interactions between segments make the system non-linear (Putnam, 1993). That is, increasing a joint moment will not linearly increase the effect that joint moment has on the motion of any one segment in the system.

The differences in sequential movement patterns vary as a result of many factors (Putnam, 1993). These include the skill of the performer and the nature of the tasks each of which may require differences in speed and accuracy. Factors that are directly related to segment interactions also significantly affect the timing of segment motions (Putnam, 1993). These factors include the lengths, masses, centre of mass locations and moments of inertia of the segments. The relative angles between segments are also related to the segments interaction. The sequential actions of joints may be connected to the physiological prestretch phenomena of muscles (Jöris, et al., 1985). During the period where the hand and forearm lag that is in the last 50 ms of the movement, medial shoulder rotation and wrist flexion are prestretched. It appears that prestretch immediately preceding concentric contraction is essential to the development of power during the last 50 ms of the throw (Jöris, et al., 1985).

Nevertheless, the proximal-to-distal sequential pattern does not apply to some movements. For example, in the tennis serve internal rotation of the shoulder joint and forearm pronation which are responsible for the velocity of the racket head, show a different sequential pattern. The shoulder rotation increases as the rate of forearm pronation decreases (Deporte, Van Gheluwe, & Hebbelinck, 1990).

2.4.4 Velocity of the ball at release

In general, the performer will try to achieve high projectile velocity at the release point. The linear velocity of a point on a rotating segment is directly proportional to both its angular velocity and its radius of rotation ($V= rw$) (Putnam, 1993). The radius of rotation is defined as the perpendicular distance between the contact point of the object being projected and the axis of rotation of that segment (Putnam, 1993). The release velocity has no relation to body weight or height, upper arm or forearm length (Jöris, et al., 1985). How far a ball can travel depends on velocity at release and the angle of throwing. A projectile will go furthest if it is thrown at 45 degrees to the horizontal. The distance thrown (d) can be calculated by the equation

$$d = v^2/g,$$

where v is the speed of throwing and g is the acceleration of gravity (Alexander, 1992). Coordination of three parameters, that is, point of release relative to the target, the angle, and the velocity of release is required in order to achieve a good throw (Alexander, 1992). In tennis flat serving, Ito, Tanabe, and Fuchimoto (1995) have reported that internal rotation contributes greatly to the development of racket-head velocity, and that external rotation before internal rotation may play a role as a counter movement to increase the velocity of internal rotation.

The maximum velocity at the end point of the distal segment can be accomplished by increasing the radius of rotation. For the same amount of muscle torque, the wheel-axle mechanism will give a higher end-point velocity than the lever system (Kreighbaum & Barthels, 1990). This is due to the fact that increasing the radius of rotation also means increasing the radius of gyration in the lever system. The squared increment of the radius of gyration will have a squared effect on the resistance or rotational inertia of the movement. On the other hand, the lengthening radius of rotation in the wheel-axle system does not amplify the resistance of rotation to the same degree as the lever system (Kreighbaum & Barthels, 1990).

The maximum speed at release of the distal end of a linked system can be explained in two ways. The first involves the principle of optimal coordination of partial moments (Jöris, et al., 1985). This principle states that the maximum speed at the distal end will be achieved, if all segments reach a maximum value at the same time (Deporte, et al., 1990). The second explanation relies on the proximal-to-distal sequential pattern which is observed in most throwing actions (Putnam, 1993). This principle is based on the notion that the speed of the distal end is the sum of the individual speeds of all involved segments. A number of throwing parameters are used to describe the summation of speed principle, for example, joint angular velocity, segment angular velocity, resultant linear velocities of segment endpoints and components of the linear velocities of segment endpoints in the direction of throwing. Each parameter has been reviewed in detail by Putnam (1993). In summary, joint angular velocity appears to give the clearest description of the proximal-to-distal model.

The contribution of each body segment velocity to the velocity of the projectile has been determined by several studies. Kulig, Nowacki, and Bober (1983) created a kinematic and dynamic model for a throwing task. They reported that at ball release, the contribution of the arm is 3%, forearm 90%, and hand 7%. Elliott, Grove, Gibson, and Thurston (1986) analysed fastball and curveball pitches in baseball. They reported that the horizontal segment end point velocity at release resulted from the action of shoulder joint (19.4%), elbow joint (8.8%), wrist joint (35%), and hand (26.5%) in the fastball pitch. The roles of these joints for the curveball were different at the elbow joint (6.4%), wrist joint (38%), and hand (31.8%). Miyanishi, Fujii, Ae, Kunugi, and Okada (1995) studied the contribution of the torso and upper limb to ball velocity in a baseball throw. They reported that the horizontal velocity of the ball (HVB) during the late releasing phase was due to the horizontal velocities obtained from the rotation of the upper torso, extension of the forearm, internal-rotation of the upper arm and the palmar-flexion of the hand. Miyanishi and coworkers (1995) concluded that the HVB at the releasing point was generated from the internal rotation of the upper arm (31.5%), the extension of the forearm (18.1%), the palmar flexion of the hand (16.4%), and the rotation of the upper torso (9.4%).

In the studies reported by Elliott and colleges (1986), Kulig et al. (1983), and Miyanishi and coworkers (1995) percentile contribution were presented for different components, that is, segments, joints, and actions of the body. Furthermore, Kulig and coworkers (1983) used a dynamic model for their study whereas Elliott et al. (1986) and Miyanishi et al. (1995) examined the baseball pitch. Therefore, it is difficult to make general conclusions about the contributory factors involved in projectile velocity. However, Putnam (1993) has stated that the shoulder moment contributes only a small proportion of the acceleration of the upper limb. Most of the acceleration is produced by the interaction moment resulting from forearm rotation. Furthermore, it has been reported by Feltner and Dapena (1986) that only a small amount of elbow extension torque is required in the baseball pitch (Feltner & Dapena, 1986). This finding suggests that the acceleration of the ball may not be due to the elbow extensors. Thus, the rotation component seems to play the major role in releasing velocity.

2.4.5 Factors affecting the pattern of throwing

Generally, the throwing pattern is dependent on many constraints, such as, the mass of the implement (a racket), the mass of the object to be projected (a projectile), the size of the target, the size of the environment or playing area and the strength and the ability of the performer (Kreighbaum & Barthels, 1990). A weak or immature performer tends to show a more simultaneous movement than a sequential action of joint angles during throwing (Kreighbaum & Barthels, 1990). Moreover, Feltner and Dapena (1986) reported that only a small amount of elbow extension torque is required in the baseball pitch. This suggests that the acceleration of the ball may not be due to the elbow extensors. In fact, a three-dimensional study in baseball pitching also found that the rapid elbow extension mainly resulted from the counterclockwise (top view) angular velocity of the upper arm and trunk that took place during the pitch (Feltner, 1989).

The force exerted on the ball can be calculated by multiplying ball acceleration and ball mass (Jöris, et al., 1985). The product of force and velocity produces the energy flow to the ball (power of the ball). The energy flow equals the change of kinetic energy of the ball (Jöris, et al., 1985). Variations in potential energy during the throw appear to be negligible when compared with the increase in kinetic energy. Furthermore, the major part (73%) of the work on the ball appears to be done in the last 50 ms of the throw particularly in female handball players (Jöris, et al., 1985). Approximately 30% of the total work done on the ball in this period is delivered by muscles involved in wrist and finger flexion. The remaining part is caused by a flow of energy from proximal to distal segments, mainly at the expense of the kinetic energy of the more proximal segments. Jöris and coworkers (1985) have concluded that high segmental velocities and the action of wrist and finger flexors are responsible for a large flow of energy from the lower arm to the hand and ball to gain a large power output at the end of the throw.

To get some picture of kinetic energy used during throwing, examples of some type of throwing were presented. For a 7.26 kg shot, if it is released at a speed of about 14 metres per second, its kinetic energy is equal 711 joules and for a 145 g baseball which is released at 45 metres per second, its kinetic energy is equal 147 joules (Alexander, 1992).

McDonald, van Emmerik, and Newell (1989) have found that with practice the nondominant limb showed a synergy pattern which reduced the degrees of freedom. In contrast, with practice the dominant limb began to increase the degrees of freedom as demonstrated by the decreasing cross-correlations of angular displacement in the wrist-elbow and wrist-shoulder correlations. These findings suggest that the effects of practice can be seen in the coordination mode and the decrease of variability of various parameters of limb motion.

2.4.6 Summary

Most of the research on throwing motions has examined an overarm pattern. This may be due to the fact that the overarm throw is commonly used in sport activities. Thus the present review has focused on the overarm throw. Sequences of joint motion seem to be an essential characteristic of the throwing movement. Sequential motion of segments start proximally and move distally. An immature or an unskilled thrower appear to employ the simultaneous action of all joint angles rather than using a sequential action. Among actions of the joints of the upper extremity, the rotation component is likely to play the crucial role in releasing velocity. Characteristics of a projectile, conditions of the environment, the strength and the skills of the performer all affect the pattern of throwing.

2.5 Quantitative measurement in movement coordination

2.5.1 Three dimensional motion analysis

There are three main types of 3-D motion analysis systems, that is, cinematography (Miller, Shapiro, & McLaughlin, 1980), optoelectric systems (Scholz, 1989), and video (Vander Linden, Carlson, & Hubbard, 1992). A cinematographic system records a movement onto film, then the operator has to manually digitise coordinate data by projecting the film from each camera on to a screen for each frame. This system is time consuming and expensive when compared with other techniques. The optoelectric system requires subjects to wear special infrared lights on each desired anatomical landmark (Winter, 1990). Wires used to carry an electric signal to each active marker may cause interference with the subjects movement pattern. Thus, more careful attention to subject setup is required (Scholz, 1989).

Two types of video motion analysis systems with differing methods of digitisation of marker position have been introduced in motion analysis studies. The Motion Analysis Corporation System uses a special processing unit to digitise the video images on-line whereas the Peak Performance Technologies Motion Measurement System records the images to videotape before using a frame-grabber to capture the images to a computer and then digitise images based on user-defined thresholds (Scholz & Millford, 1993). These systems use passive reflective markers which result in a relatively simple subject setup and less marker interference for the subjects (Scholz, 1989).

In video and optoelectric systems, joint centres are digitised automatically, which would result in smaller errors than the manual digitisation used in cinematography (Vander Linden, et al., 1992). However, errors associated with calculating joint angles or joint centres are still introduced (Vander Linden, et al., 1992). For example, errors can occur from the marker attachment method, that is, from the non-rigid base of the marker and from movement between the skin and the bone (Ronsky & Nigg, 1991). Generally, spherical shaped markers have been used in 3-D analysis. Bauman, Plamondon, and Gagnon (1995) have compared three different types of marker sets for the determination of the joint centres of rotation. These were, a) wide fluorescent elastic bands which encircle the joint (band method), b) two fluorescent spheres placed on the either side of the joint (ball method), and c) three spheres placed on the segment near the joint (coordinate system). They found that the band method could be used as an alternative method to other commonly used marker sets because it had a low incidence of missing points, especially when complex movements were being studied.

Three-dimensional analysis using the Peak Performance Technologies system is of specific interest to the present study. Characteristics of the Peak system have been described in detail by Scheirman and Cheetham (1990). However, some of the operational parameters and the results of testing system precision (calibration error) are reported in Chapter 3, Section 3.7, 3.8, 3.9.5, 3.10.5, and 3.11.5.

2.5.1.1 Reliability of measurement

Accuracy and precision of the PEAK Performance Technologies Motion Measurement System has been reported in the literature. Scheirman and Cheetham (1990) reported acceptable accuracy and precision of the PEAK system in two-dimensional calculation. Scheirman and Cheetham (1990) compared the lengths in between 16 markers which were measured using the Peak and measured by hand. The results showed the consistency among repeated observations made under the same conditions (precision) and agreement between the Peak measurements and conventional hand measurement (accuracy) (Scheirman & Cheetham, 1990). Scholz and Milford (1993) measured the validity and reliability of angular displacement in three-dimensional motion. A bar with 18 markers in which the positions of the markers had been measured was set to allow a free swing which was recorded by two video cameras. The angles calculated using trigonometric methods were compared with angles computed from the Peak system. Intraclass correlation coefficients between trials within each pendulum orientation and between random selected trials and actual angles were greater than .99. The authors concluded that the PEAK system could provide accurate and reliable angular measurements.

2.5.1.2 Angular displacement calculation

Three dimensional joint angles can be measured by recording the spatial positions of surface markers placed on each body segment. Three-dimensional rigid body orientation can be calculated using several methods including: projected angles, Euler angles, the Joint Coordinate System (JCS), and the helical or screw axis method (Cole, Nigg, Ronsky, & Yeadon, 1993). The helical parameters are more sensitive to the definition of embedded axes than Euler angles but are difficult to interpret clinically. Thus, it may be less useful in describing joint kinematics (Ramakrishnan & Kadaba, 1991). Mathematical discussion of each method has been reviewed by many authors, such as Cole, Nigg, Ronsky, and Yeadon (1993), Grood and Suntay (1983), and Woltring (1991). Projected angles are planar representations of 3-D angular variables. This method has often been used as an estimation of clinical components in two-dimensional studies. With appropriately defined local segment coordinate systems, the projections of the local coordinate axes onto the xy, yz, and zx planes are interpreted as segment angles with respect to the Cartesian coordinate system. Joint angles are defined as the differences between corresponding, distal and proximal segment angles (Woltring, 1991). Projected angles are defined in a manner consistent with conventional physiotherapy measurement of joint angles. However, the angle calculated contains errors due to projection distortion (Cole, et al., 1993). Woltring (1991) has stated that the use of projected angles should be completely avoided. Thus, the projected angle method of calculation was rejected for the purposes of the study.

Euler angles is one of the popular methods used for a 3-D clinical representation of human movement (Woltring, 1991). The order of calculated joint angles is specific and determines the outcome (Grood & Suntay, 1983; Woltring, 1991). Despite the fact that Euler's method requires definition of joint rotations inconsistent with those used in physiotherapy, it was selected for the present research for a variety of reasons. This method gives the correct value of joint angle and is well accepted. The angular displacements of the joint in each plane which were calculated using Euler's method could be traced back to the three dimensional position. A detailed description of Euler angles is provided in Grood and Suntay (1983) and Woltring (1991).

Hollerbach and Hollister (1995) have stated that if Euler angles are used to represent joint rotations, proper alignment of the coordinate reference frame with the joint mechanism is essential. The range of errors in joint motion introduced by the uncertainties in the definition of embedded axes in gait using the Euler and helical models has been determined by Ramakrishnan and Kadaba (1991). These authors indicated that reliable estimation of joint angular motion depends on the accurate definition and construction of embedded axes within each body segment. Error in defining the embedded reference may come from many sources (Ramakrishnan & Kadaba, 1991). In the direct measurement system, the goniometer axes are usually found to deviate from the true axes of joint rotation. Errors of up to ±10° in the orientation of the embedded axes can be easily introduced by a goniometer. In indirect measurement systems, such as video motion analysis, it is necessary to define only two of the embedded axes accurately as the third axis can be determined based on orthogonality. In practice, the first selected axes should be the one that is subjected to the least error in its orientation, for example, the vertical or the mediolateral axes are easier to define than the anteroposterior axis. Ramakrishnan and Kadaba (1991) have examined the effect of uncertainties in the definition and construction of embedded axes on joint angles of the lower extremity during gait using the Euler model. The results demonstrated that the magnitude of errors in abduction/adduction and rotation angles are a function of the flexion angle. The errors for the abduction/adduction angles increase with increasing flexion angle and errors for the rotation angle, decrease with increasing flexion angle, whereas flexion angles are relatively unaffected.

2.5.2 Measurement in coordination

Qualitative dynamics is a branch of mathematics that uses topology to study the forms of behaviour that are exhibited by solution of differential equations (Garfinkel, 1983). In the topological view, only breaks and discontinuities are meaningful; two figures, such as the ellipse and the circle, which can be smoothly deformed into each other without discontinuities, are equivalent. However, the circle and the line are not equivalent, because the circle must be broken somewhere to map it smoothly one-to-one onto the line (Garfinkel, 1983). For qualitative dynamics, the shapes of the curves are more important than the exact numerical predictions. The concepts of qualitative form are suited to biology because while, people come in a variety of sizes, all share the same form. Winstein and Garfinkel (1989) have investigated the qualitative dynamics approach and concluded that this method, together with electromyography and force dynamics, may allow the characterisation of movement disorders. The two commonly used trajectory spaces in a qualitative approach are phase plane and angle-angle space.

Phase plane portraits are used to visualise dynamics in a special way, based either upon point set topology (being closed or open) or differential topology (having bumps, kinks, or cusps) (Garfinkel, 1983). It also used to define the preferred frequencies and amplitudes of the coordinative movement pattern, the attractor (Kay, et al., 1991). A number of studies have been used phase plane plots, angle-angle plots and relative phase plots to demonstrate coordinative movements as has been reviewed in Section 2.2.2.1.

The disadvantages of the phase plane plot and angle-angle plot are that time is omitted from an explicit representation. This can be solved by using tick marks on the trajectory at constant time intervals (Winstein & Garfinkel, 1989).

Based on this information it would seem appropriate to use phase plane plots, angle-angle plots, and relative phase plots to illustrate the relationship between the movement of the upper limb segments during throwing.

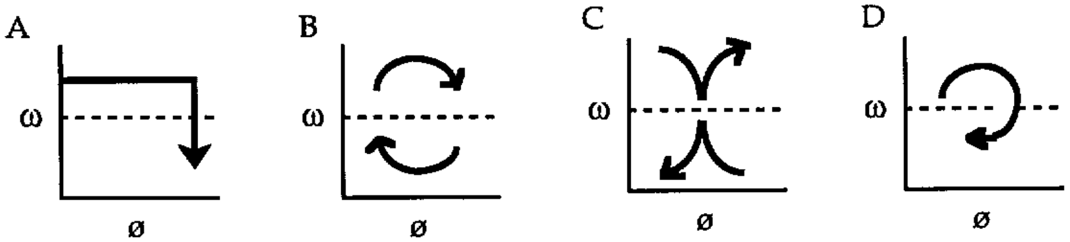


Figure 2.2 Selected shapes of trajectory segments in phase plane space. The dotted line indicates zero velocity. w = angular velocity, ø = angular displacement, From Winstein and Garfinkel (1989)

2.5.2.1 Phase plane plot

The phase plane plot is a plot of joint angular velocity against joint angle for a single joint. This technique has been used in many studies for example Burgess-Limerick, Abernethy, and Neal (1993) and Hurmuzlu, Basdogan, and Carollo (1994). A phase plane plot shows a graphical summary of the relationship between velocity and position, and has the advantage that only one plot is required. In contrast while the same information can be derived from a combination of angle-time and velocity-time plots, these plots must be used in combination. A phase plane plot is a picture of the resultant action of the control mechanisms (Winstein & Garfinkel, 1989). It is a picture of the displacement versus rate of change in state relationship. If the picture has a recognisable shape, it can be compared with the shapes seen in dynamical systems for which the underlying control processes are known. Examples of shapes of trajectory segments (Figure 2.2) and their associated types of control mechanisms are shown below (Winstein & Garfinkel, 1989).

Nearly vertical segments (Figure 2.2 A) with sharp corners indicates that control is sharply focused at the extremes of movement, indicative of ballistic control or rapidly decelerating motion. In other words, the control mechanism produces accelerations that are concentrated at the extreme value of displacement or angle and exert their effect over very short ranges. An example of a simple ballistic dynamical system is a tennis ball volleyed back and forth without hitting the ground. The flat horizontal segments are the periods when the ball is in free flight at constant velocity, between players, whereas the vertical sides represent the impulsive changes in the ball's velocity produced by the impact of the rackets. Flat horizontal segments represent constant velocity where the net acceleration is zero thus the net force being applied is zero.

Convex segments (Figure 2.2 B) represent smooth accelerations and deceleration; reversals occur only at movement extremes. For example, phase plane of shoulder flexion and extension in reaching task.

Cusps pointing toward zero velocity (Figure 2.2 C) are associated with movement interruptions; sudden cessation of forces opposing motion and/or sudden resumption of motion. If cusps cross the zero velocity line, they become loops. Loops indicate movement reversals.

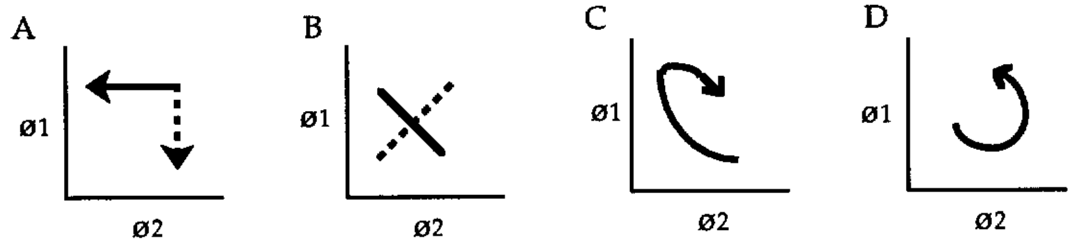


Figure 2.3 Selected shapes of trajectory segments in angle-angle space. From Winstein and Garfinkel (1989)

Smoothly rounded segments (Figure 2.2 D), that is those in which the radius of curvature is pointed inward, represent position-dependent forces opposing the motion, as occurs in springs or the oscillation of a pendulum.

The use of angular position and velocity information to describe joint movement on a phase plane is advantageous on theoretical grounds because the afferent information available from muscle receptors is provided effectively in terms of joint position and velocity (McCloskey, 1978). The representation of movement on a phase plane plot may be meaningfully equated with the information available from afferent receptors (Burgess-Limerick, et al., 1993).

2.5.2.2 Angle-angle plots

Angle-angle plots are plots of one joint angle against the simultaneous value of another joint angle. This plot gives insight into intersegmental coordination, demonstrating changes in spatial and temporal relationships between limb segments. This plot has been used to quantitatively describe multijoint coordination during complex task by a number of investigators, for example Burgess-Limerick, Abernethy, and Neal (1993), Sparrow (1992). Angle-angle plots show aspects of intersegmental coordination that are difficult to see in other representations. Examples of the curves (Figure 2.3) and their dynamical interpretations have been described by Winstein and Garfinkel (1989).

Horizontal or vertical segments (Figure 2.3 A) represent changing range of motion of one joint angle while the other is held constant.

A diagonally oriented straight line (Figure 2.3 B) with either a negative or positive slope, indicates two joints angles coordinated out of phase or in phase respectively. The rates of change of the two joint angles occur at a constant ratio.

If both joints reach their end ranges and switch simultaneously, the turning point is synchronised and there is said to exist an intersegmental coordination at the switching point (Figure 2.3 C).

A rounded trajectory (Figure 2.3 D) represents phase offset and decoupled coordination since the rate of change in each joint angle is not consistent.

2.5.2.3 Relative phase

The relative phase of motion between movement components represented by ø have been identified as a collective variable for bimanual movement coordination, four-limb coordination, and intralimb coordination in humans (Kelso, 1984; Kelso, et al., 1991) and also in the rhythmic flexion and extension of both index fingers (Scholz & Kelso, 1989). Burgess-Limerick, Abernethy, and Neal (1993) have used relative phase to quantify coordinated motion expressed on a phase plane. They proposed that the relative phase angle may provide a measure which is sensitive to the effects of environmental changes, learning, and other independent variables affecting movement coordination.

A theoretical treatment of relative phase as a measure of coordination can be found in Schöner and coworkers (1986). Relative phase is defined mathematically as the difference between the movement phase of each individual joint for a pair of joints, obtained at each data sample (Scholz, 1993b).

Schöner, Haken, and Kelso (1986) have concluded that relative phase reflects the evolutionary design of rhythmical activity. From the invertebrates, in which many groups use a large number of propulsive structures (eg., limbs, tube feet, cilia) for swimming and locomotion, to the vertebrates that use one, two, three, or four pairs of legs. In addition, phase has been observed to be an essential parameter in many voluntary activities of a less cyclical kind, ranging from handwriting to speech (eg., Kelso, 1995, for review).

2.5.2.4 Cross-correlation

Determination of equivalence or similarity between movement patterns has been performed using the chain encoding method (Whiting & Zernicke, 1982). This method was originally proposed by Freeman in 1961 (Whiting & Zernicke, 1982). Chain encoding is suitable for two-dimensional, line drawing such as angle-angle diagrams or parameter plots against time. Encoding is performed using grid lines which transform a trajectory (analog data) into digital data by approximating the curve (by superimposing a grid overlay onto the curve) and then connecting successive grid intersects to form a chain. A measure of coherence between two patterns is determined by the recognition coefficient (R) which is defined as a peak value of a cross-correlation function. When two figures or shapes have exactly the same pattern, they have an R equal to 1. Grid density can be increased or decreased according to the desired degree of resolution. Although the potential of the chain-encoded method has been demonstrated for the quantification of limb segments, further refinement and statistical standardisation of the method is still needed (Whiting & Zernicke, 1982).

Sparrow, Donovan, van Emmerik, and Bary (1987) have reviewed a number of quantitative methods for determining changes in relative motion plots. These authors derived a formula to measure the cross-correlation which they used to determine the degree of correspondence between angle-angle diagrams. This cross-correlation formula can distinguish any differences in shape, size, and orientation. Only identical plots would give a maximum cross-correlation function of unity. Size, shape, orientation, and pattern centre can vary independently in angle-angle diagrams. Change in any of these parameters causes a degree of dissimilarity in the coordination patterns being compared. Sparrow et al.

(1987) suggest that this method can be used to assess changes in both intra-limb and inter-limb coordination.

The problem of finding a valid statistic, at least for testing the statistical significance of the cross-correlation function still remains (Sparrow, et al., 1987). There have been some attempts to use Fisher's Z-transformation to evaluate the sample cross-correlation coefficients, such as in the study of effect of practice on limb kinematics in a throwing task (McDonald, et al., 1989). Sparrow and coworkers (1987) argue that this procedure violates the assumption appropriate to the use of Fisher's Z-transformation. Fisher's procedure is based on the assumption that the sample data are independent and are drawn from populations of normally distributed variables, whereas data sampled from a time-dependent series are dependent unless the series is white noise or a similarly random variable, and it is not safe to assume that they are normally distributed (Sparrow, et al., 1987).

Burgess-Limerick, Abernethy, and Neal (1991) have proposed that directional statistics are more appropriate than conventional statistics in testing the invariance of movement using phase plane models. Conventional statistics are designed for scalar-valued variables to which the principles of arithmetic and the natural number system apply. Phase plane data deals with directional vectors to which geometric principles apply, with extension to trigonometry and vector algebra.

The application of cross-correlation to determine the degree of coupling has been reported. For example, Walter and Swinnen (1990) used the cross-correlation of the angular acceleration of two testing conditions to determine structural coupling, that is the similarity of the acceleration trajectories independent of magnitude. Furthermore, it has been suggested that the size of the cross correlations can be taken as an index of dependent or independent control of the joints or segments of the arm (van Emmerik, 1992). A high positive correlation indicates that the joints or segments are phase locked and not controlled independently. The more independent the motion of the joints or segments, the closer the correlation coefficient causes to zero. A high negative correlation indicates locking with a 180° phase shift.

2.6 Summary

Many different models have been proposed to explain movement control. These models have evolved from the concepts of structural and functional relationships to the more abstract ideas of the motor program. More recently, research then has concentrated on the study of movement components as developments in technology have provided more detailed information. However, a limited level of understanding has been attained as a result of the assumptions of motor control theories.

Dynamic pattern theory is one concept in motor control theory which approaches movement analysis at the macroscopic level. It suggests that a particular movement behaviour arises from the self-organisation of sub-systems. Alteration of a control parameter which is a variable of the system environment will lead to a phase transition. A new pattern will then emerge under the new environmental conditions as a result of instability of the previous movement pattern. The reduction in energy used has been proposed as one of the reasons for phase shifting. Dynamic pattern theory has been mainly applied to locomotion and non functional repetitive movements. The application of this theory to functionally discrete movements is limited. The present review has described the concepts of dynamic pattern theory and its application in various types of movements. The review has also emphasised the mechanics of the overarm throw which may provide some basis for understanding alteration in throwing styles such as are considered likely to occur in any study of throwing patterns.

From the dynamic pattern theory perspective, identification of order parameters which characterise the movement pattern appears to be an essential task. Kinematic measurements have been described using three dimensional motion analysis. Angular displacement has been reported to be a fundamental parameter used for describing movement. In addition motion analysis and joint angle calculation methods and the reliability of such calculations have been presented. Measurements of coordination reported by previous researchers were also reviewed. Phase plane plots, angle-angle plots, relative phase, and cross-correlation and the contribution they can make to understanding motor control have also been presented.

Given the lack of information about the application of dynamic pattern theory in functionally discrete movements, it would seem to be appropriate to undertake a study of such a movement. Accordingly, throwing movements have been selected as a model for the present study. Generally, previous research has concentrated on throwing styles used in sports such as baseball. Sequences of joint motion appear to be the important characteristic of the skilled throw. Overarm throws have been examined mainly and no analyses of the underarm throw has been published.

The proposed study will include a kinematic analysis of throwing styles in a set task in which several independent variables will be manipulated to investigate their effects on the throwing action. The data will then be examined in terms of the invariant and variant characteristics in an effort to examine the extent to which dynamic pattern theory can provide a model for understanding throwing actions.

Chapter 3
Methodology

> *Theory is a good thing but a good experiment lasts forever.*
>
> *- Peter Leonidovich Kapitsa*

To investigate the issues raised in Chapter 2 and achieve the objectives outlined in Chapter 1, a three stage study was designed. The principal objective was the identification of the control and order parameters as proposed by the dynamic pattern theory which might be essential to the control of the upper limb movement in a throwing action.

To satisfy this objective the study was divided into three stages. Stage One included the identification of the upper extremity task and verification of the repeatability of the angular displacement between different trials for the same subject. This stage also involved the data reduction process which consisted of writing programs for the calculation of kinematic parameters.

Stage Two aimed to establish a suitable protocol for data collection in subsequent stages. The testing procedure and independent parameters were adjusted and modified based on information derived from the first experiment. The results were analysed to identify potential problems and to set up a suitable procedure for the final stage.

Stage Three (the Principal Study) involved the careful examination of data generated from the task selected in Stage Two and also relied upon the reliability established in Stage One. This stage aimed to identify the control and order parameters for the movement.

Hypotheses for the present study are described separately for each stage of the study. Experimental protocols including the results and discussion of Stage Two and Stage Three are explained in detail in this chapter.

3.1 Hypotheses

3.1.1 Stage One

1) Performance on three trials of the criterion task for each subject will not be significantly different.

2) Variation in distance thrown, weight of the projectile, and area of the target will all influence the pattern of throwing.

3.1.2 Stage Two

No specific hypotheses were tested at this stage. Stage Two was designed to consolidate the experimental protocol used in Stage Three.

3.1.3 Stage Three

Hypothesis 1: Calculated joint angles and clinical joint angles

Angular displacement measured using three-dimensional motion analysis employed in the study will show no significant difference when compares to the angle measured by the standard clinical method.

Hypotheses 2: Number of throwing patterns

a) Subjects, given a choice, will demonstrate more than one style in executing the defined throwing task.

b) At least two throwing patterns, the overarm and the underarm throw, will be demonstrated when subjects freely selected throwing patterns.

Hypotheses 3: Phase transition

a) A phase transition will be demonstrated by changes in proposed order parameters as the distance thrown increases.

b) Changes in the throwing pattern in individual subjects may occur in the direction of the overarm throw or in direction of the underarm throw.

Hypotheses 4: Relative timing

In the present study, relative timing was defined as the ratios of movement durations, that is, the preparation phase (Prep) and the releasing phase (Rel) over the total movement time (TMT). That is the ratios of the Prep/TMT, Rel/TMT, and Rel/Prep.

a) There will be no significant differences in the relative timing of the overarm throw and the underarm throw as the distance thrown of a projectile increases.

b) There will be no significant difference in the relative timing between the overarm and the underarm throw at the same distance thrown.

Hypotheses 5: Angular displacement

a) Each throwing pattern can be defined by the changing of angular displacement over time of all joint angles of the throwing limb.

b) The range of joint angles will be greater when throwing to the longer distance.

c) Limitation of the elbow joint angle using an orthosis will force a change in throwing styles as the distance thrown increases.

Hypotheses 6: Releasing joint angle

a) There will be no significant difference in the releasing joint angles of the overarm and the underarm throw as the distance thrown increases.

b) There will be no significant difference in the releasing joint angles between the overarm and the underarm throw for the same distance thrown.

Hypotheses 7: Angular velocity

a) Angular velocity of all joint angles at the releasing point will be greater when throwing to the longer distances.

b) Both the overarm and the underarm throw will show a sequential peak angular velocity which is clearly shown at the longest distance thrown.

Hypotheses 8: Order parameter

a) More than one order parameter is required to characterise the throwing pattern.

b) Trajectories of movement can differentiate throwing patterns as the distance thrown increases for the overarm and the underarm throw.

c) Trajectories of movement can differentiate the throwing pattern between the overarm and the underarm throw.

d) Relationships between angular displacement and angular velocity or between angular displacement of one joint related to another joint as illustrated in phase plane plots, angle-angle plots, and relative phase plots can act as order parameters for the throwing movement.

Hypothesis 9: Measurement of coordination

Visual comparison and cross-correlation provide the same information when used to measure patterns of coordinated movement, phase plane plots and angle-angle plots, as the distance thrown increases.

3.2 Research design

A cross-sectional study was used to specify suitable control and order parameters for the throwing movement in a sample of volunteer female subjects.

The independent variables were controlled by reducing the extent of the movement possible and so limiting the variability of the pattern of the selected functional movement. This control also aimed to facilitate the shifting of the form of motion from one phase to the next when any selected variable of interest changed. In Stage One of the study, right handed adult female subjects were observed in a set environment performing a throwing task. The distance thrown, weight of the object, and area of the target at which the throw was aimed were manipulated to test the effects on the movement pattern.

The dependent variables were the variables that describe the pattern of movement, for example the trajectories of the movement. To identify these variables, all the kinematic parameters were calculated and carefully examined. Only the angular displacement of each joint of the upper limb was tested for reliability and validity because this was the basic factor for calculation of all other parameters of interest.

3.3 Ethical considerations

All normal subjects were volunteers. Informed and written consent was obtained from all subjects. Measurement of the three-dimensional movement was recorded using a video motion analysis system. The data were used only for the purposes of this study by the principal investigator. However, as the data are a valuable resource, they will be retained for at least twelve months after the project has been completed. All video tapes were preserved in a secure format and will be maintained by the School of Physiotherapy at the end of research. Access to the data for other purposes will require additional permission from the original subjects.

Confidentiality of records was maintained by restricting access to data stored on computer and by appropriately storing other hard copy materials. Subject anonymity was ensured by using a number to identify the subject in the video. Name and identifying features were removed from all data prior to analysis, presentation and publication.

3.4 Selection of the functional movement of the upper extremity

A complex motion of the upper limb was chosen to test the application of the dynamic pattern theory of motor control. In order to observe factors associated with the induction of pattern transition in a movement, it was essential to select a movement pattern which could be dependent on a variety of factors likely to induce a change in the movement. Changes of the movement scheme in shifting from placing to throwing an object and in the throwing styles required for different distances are generally seen. There are a number of factors responsible for these changes, such as the distance thrown, the weight of the object being thrown, whether accuracy to a target or simply distance thrown is the objective, speed of action and starting position of the thrower. Given these possibilities, the throwing activity was chosen as a coordinated model for the present study. The variations of the activity were confined by the protocol and the nature of the data collection protocol. For example, the starting position allowed only movement of the upper limbs and the testing procedures were conducted in a laboratory environment.

3.5 Task

Subjects were asked to throw or place an object from a seated position in all study protocols. The movement of the trunk was limited by fixing the subjects' body to the back rest of a chair. The independent variables eg. the distance throw, the weight of the object and the accuracy of the throw differed for each stage of the study. The details relevant to each testing procedure for each stage are described in separate sections.

3.6 Subjects

The sample population consisted of twenty-two right handed female subjects. The age range of all subjects was 18-35 years (25.73 ± 5.41). They were naive to the study. None had any limitation or musculoskeletal injuries or diseases of the joints of the right upper limb or any previous injuries or diseases of the nervous system.

Subjects dressed in comfortable clothes. They were asked to use a sleeveless dark coloured top to provide better contrast between markers and the background. Subjects also worn a pair of sun glasses to protect their eyes from the spotlight used for filming.

Stage One examined four subjects aged between 26-35 years (31.25 ± 4.11). Stage Two involved two subjects aged between 25-32 years (28.5 ± 4.95). Sixteen subjects aged between 18-35 years (24.00 ± 4.86) participated in the principal study. All subjects participated in the study neither had a special training in throwing nor were athletes in sport involved the throwing skill employed in the study. Table 3.1 shows the details of the subject characteristics.

Table 3.1 Characteristics of subjects Stage One, Two and Three

	Range	Mean	SD
Characteristics of subjects: Stage One (n=4)			
Age (yrs)	26 to 35	31.25	4.11
Upper limb length (cm)	60 to 68	63.75	3.86
Characteristics of subjects: Stage Two (n=2)			
Age (yrs)	25 to 32	28.50	4.95
Upper limb length (cm)	73 to 74	73.50	0.71
Characteristics of subjects: Stage Three (n=16)			
Age (yrs)	18 to 35	24.00	4.86
Upper limb length (cm)	67 to 78	72.03	3.19
Height (cm)	150.5 to 178.3	164.24	7.76
Body weight (kg)	45 to 77.4	57.6	9.27

3.7 Measurement of the kinematic parameters

All measures were performed during the day in the motion analysis laboratory. Testing for each subject took about 30-45 minutes. Three-dimensional motions were filmed using three video cameras (JVC Super VHS Colour, KY-17-E and Panasonic F15) and later analysed using the Peak motion analysis system (software version 5.0, 1992). The system used reflective markers placed upon the bony landmarks of the body from which three dimensional coordinates could be established by digitisation of the three cameras views. The Peak 5 System uses the Direct Linear Transformation (DLT) method to calculate the coordinates of the markers. The coordinate data of each marker attached to bony landmarks of the right upper limb were calculated. These coordinates were used to calculate other kinematic parameters such as angular displacement, the angular velocity, and the angular acceleration of the limb segments, using macro sheets in

Microsoft Excel on a Macintosh IIci computer. All data reduction processing such as normalisation were also performed using a Macintosh IIci computer.

3.7.1 Calibration procedure

The filming space was calibrated by filming a calibration frame provided by the Peak Performance Technology (Peak). There are 24 markers on the frame (Figure 3.1). The coordinate value in the x, y, and z dimension of each point is provided by the system in millimetres (mm). At least six non coplanar markers on the calibration frame must be digitised for three-dimensional motion analysis. The calibration frame was positioned at the centre of the recording area. The camera lenses were zoomed in so that points on the frame filled the field of view. The calibration frame was filmed either before or after the testing period for every subject. Details pertaining to calibration in each of the stages of the study will be presented subsequently.

3.7.2 Camera set up

Three cameras (JVC Super VHS Colour, KY-17-E and Panasonic F15) were mounted on tripods and placed in different planes to ensure the best view of all markers. They were positioned so that the optical axes of the lenses intersected at approximately the centre of the filming space. The second and the third cameras were genlocked to the master camera. The cursor light from the synchronising unit was used to synchronise the video frames of the three cameras. All cameras had a frame rate of 25 Hz and shutter speed of 1/500 seconds. The white balance was set prior to other adjustment after the cameras had been turned on. The opening of the iris was adjusted to ensure a high contrast between the subject and background and the markers. After positioning and focusing the three cameras, they were not moved or adjusted until the recording process for both the movements and the calibration frame were completed. Three Panasonic VCRs were used to record the output of the three cameras. Halogen spotlights of 800 watts were placed beside each camera. The ray of light was focused at the subjects. As the study evolved the position of cameras was altered for subsequent stages. These camera positions will be described in detail with each of the studies.

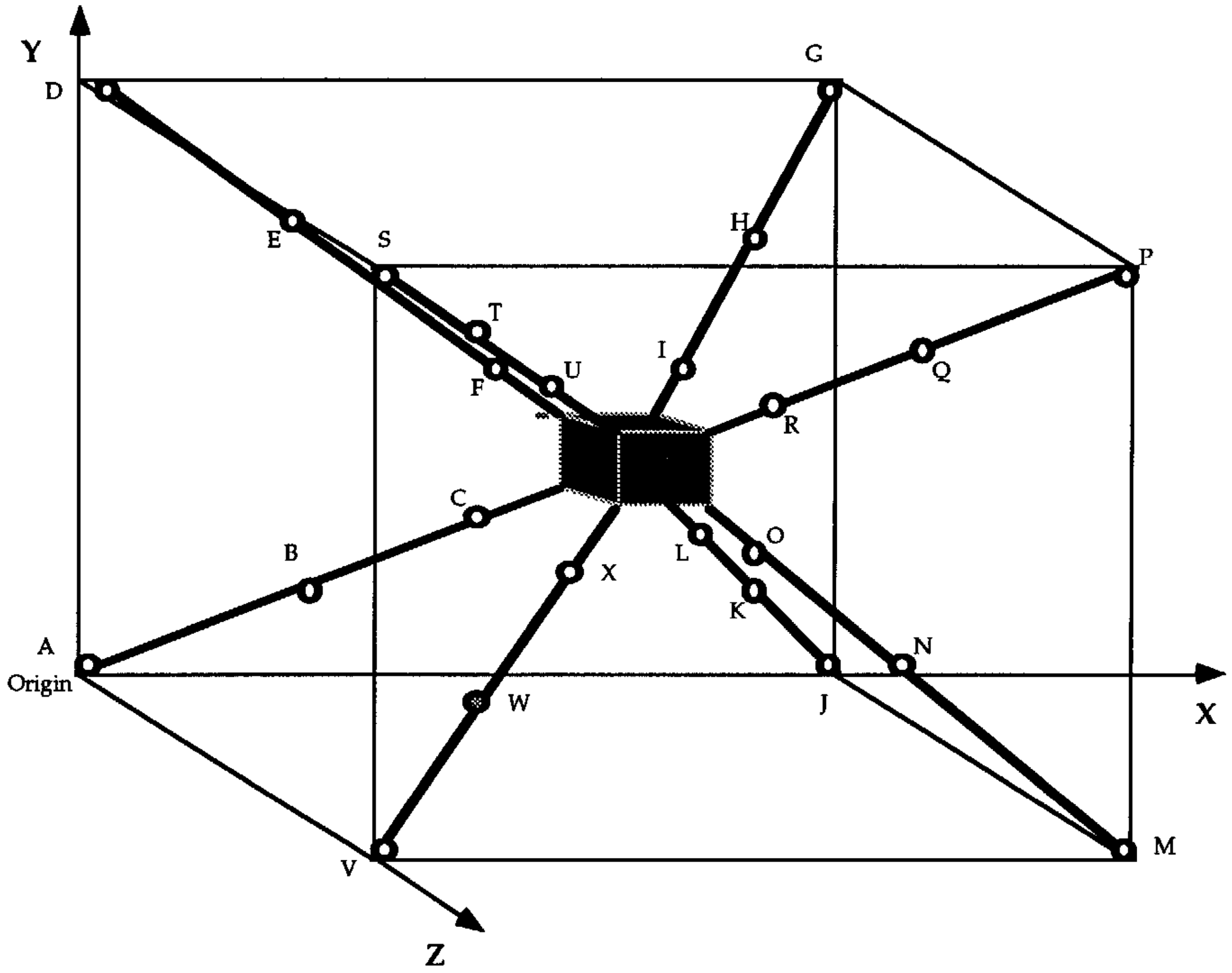


Figure 3.1 Peak calibration frame diagram shows the position of 24 markers

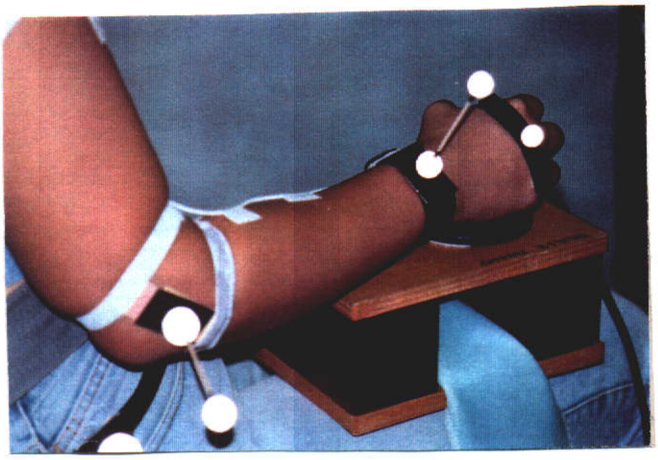


Figure 3.2 Rod markers attached to the elbow and wrist joints and the technique used to secure the markers onto the skin

3.7.3 Markers

Markers were made from styrofoam balls or wooden beads which were covered with reflective tape (Scotch 3M brand). Various sizes of markers were used according to the joint position to be tracked.

Markers were located on: the right and left acromion processes of the shoulder joints, lateral epicondyle of the right humerus, the middle of the dorsal surface of the right wrist joint, the head of the third metacarpal bone of the right hand, and the tubercle of the right iliac crest. In the first two stages of the study, markers were also attached at the tip of the thumb and index finger.

A rod marker, one which had markers at both ends, was used at the elbow and the wrist joints (Figure 3.2). The position of each rod marker for each subject was relatively the same. However, the angle between a rod and the axis of the body segment was not equal to 90 degrees. These rod markers were used as reference points for the rotational axes which are explained later in Chapter 4, Section 4.1. Ten markers were used for each subject in the first two studies but only eight were used in the main study.

To secure markers to the skin, the surface area of marker contact with the skin was increased. Markers on the shoulder joints and hand were attached to a small piece of felt. Markers with the felt base were then attached to the skin using double sided adhesive tape (3M).

For the rod marker at the elbow joint, a piece of hard leather was used to provide the strong base required to support the length of the extension rod and also to give enough flexibility to accommodate the non smooth contour and mobile area around the lateral epicondyle of the elbow joint. Two elastic tapes located at each end of the piece of leather were used to fix the marker at the elbow joint. These were attached around the arm and the forearm (Figure 3.2) on either side of the joint.

For the wrist joint, the marker was placed on the dorsal surface of the wrist, a rather smooth and non mobile surface. A piece of hard plastic was fastened to the wrist marker to form a firm base. The marker at the wrist joint was attached to the body using Velcro. The marker for the tubercle of the iliac crest was also placed on the body using the same technique as for the maker for the wrist joint. All the materials used as the base for markers were black or of a dark colour to enhance the contrast of the markers.

3.8 Analysis of data

3.8.1 Encoding and Digitising

In Stage One, the videotapes were encoded by an audio dubbing method. In Stage Two and the principal study, the videotapes were encoded using a time code generator method. All trials were digitised using the automatic digitising module of the Peak5 System. When the marker was obscured and not visible in at least two camera views, the manual digitising technique was used so that all markers were digitised from at least two camera views in every frame. All marker trajectory paths in all camera views were examined and edited before the calculation of coordinates was performed.

3.8.2 Filtering

The coordinate data were smoothed using the software of the Peak System which applies a fourth order, zero-lag Butterworth digital filter. The optimal cut-off frequency was determined in detail for every trial in the Stage One using the available function of the Peak software. Most of the optimal cut-off frequency calculated by Peak were 5 Hz, thus this frequency was chosen to filter all the coordinate data in the Stage Two and Three. Subsequently, the smoothed data were used to calculate other parameters.

3.9 Stage One

This stage was designed to examine a throwing activity, identify the components of the activity and any limitations to the data collection process for the task chosen. It also offered the opportunity to examine the parameters of the movement to be tested in the next step. The distance over which the subjects were asked to throw, the weight of the object thrown, and the area of the target were each manipulated. The repeatability of the angular displacement curves between trials for each subject was also evaluated in this stage of the study.

3.9.1 Hypotheses

1) Performance on three trials of the criterion task for each subject will not be significantly different.

2) Variation in distance thrown, weight of the projectile, and area of the target will all influence the pattern of throwing.

3.9.2 Equipment set up

An adjustable chair and an hydraulic adjustable table were used. The table was 102 cm wide, 195 cm long and covered with blue felt. A small marker wrapped with reflective tape was attached to the table to give the subjects a starting position on which to place their hand. This marker could be seen only when subjects raised their hand. It was used to define the starting point of the movement.

The projectile was made from soft leather in a non-rigid cube shape, so it could mould to the palm of the hand like a ball. The dimensions of the ball were 8 ¥ 8 ¥ 8 cm. It was modified to provide two different weights. The heavy ball was filled with the lead shot and weighed 1500 g. The light ball weighed 15 g. All balls were wrapped with Velcro so that they would adhere to the material covering the table at the end point of the throw. Figure 3.3 shows a cubic projectile used in the study.

Figure 3.3 A photograph shows cubic projectiles (a) which were used in Stage One; balls with three copper plates (b); two copper plates for the index and middle fingers which functioned as a switch (c); and the external circuit with the flat pneumatic button (d). The equipment marked in b, c and d were used in Stage Three of the study.

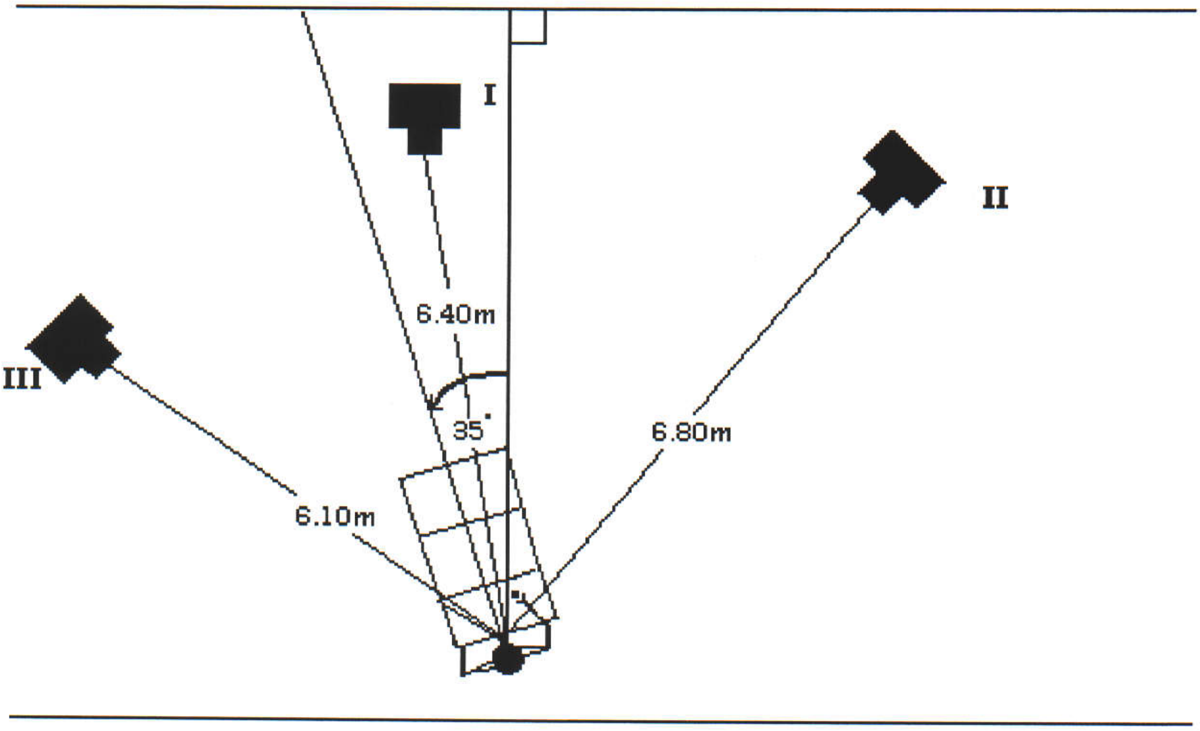


Figure 3.4 The set up of cameras and adjustable table used in data collection in Stage One

Three cameras which were adjusted as described in Section 3.7.2 were set on tripods. The first or master camera (JVC Super VHS Colour, KY-17-E) was placed 6.40 metres in front of the subject. The second camera (Panasonic F15) was set on the right hand side of the subject at a distance of 6.80 metres. The third camera (Panasonic F15) was placed on the left side of the subject 6.10 metres away. The height of these three cameras from the floor to the lower rim of lens was 1.26, 1.17 and 1.68 metres respectively. Figure 3.4 illustrates the set up of the three cameras. These three cameras were positioned to focus on the same area of filming space and were placed as far as possible from subjects to prevent lens distortion. Thus the distances and height of these three cameras were not necessary be the same.

3.9.3 Task

Each subject was seated on the adjustable chair at the adjustable table. Each subject performed two patterns of placing and two of throwing using a heavy and a light projectile. Each projectile was thrown to three different distances. These distances were proportional to the length of the upper extremity of each subject. To establish the subjects' most preferred style, they were not initially told that the objective was to have them perform the task using two different patterns. Subjects were asked to throw the projectile using a different pattern of movement once they had performed the first task. All elements of the protocol were followed for each throwing pattern.

3.9.4 Protocol

Testing procedures for the study were explained to all subjects. Ten markers were attached to the defined bony points over the joints as described in Section 3.7.3. The chair and table were adjusted so that the height of the table was at the same level as the elbow joint when the arm was at rest beside the body with the elbow joint flexed to 90 degrees. The torso of the subject was strapped to the back rest of the chair. In the seated position subjects were asked to maintain the throwing arm in 90 degrees of shoulder flexion with full elbow, wrist and finger extension. In this position the length of the subject's arm was measured from the acromion process to the tip of the thumb. The distances equal to 1, 1.5, and 2 times the length of the arm were marked on the table and the area between each target was divided by a line of Velcro attached to the surface of the table. Two size of target was defined on the table, 12.5 cm^2 and about 6,600 to 7,000 cm^2.

All subjects assumed the same starting position, with the right shoulder joint in the neutral position, the radioulnar joint in a semipronated position. The right hand holding the ball rested on the table at the marked starting point. Subjects practised placing and throwing at the three different distances using both the heavy and the light balls, with ten practice trials for each condition.

Then subjects were asked to perform the activities with three trials for each condition. There were three independent variables, that is, the distance thrown, the weight of the projectile and the size of the target. The distance thrown had three levels whereas the weight of a projectile and the size of the target each had two levels. Thus there were 12 conditions for each part of the first stage of the study. The sequences in which each condition was completed were ordered randomly. After completion of the task for all conditions, subjects were asked to repeat the experiment using a different style of throwing. The protocol for data collecting and recording was identical to that used for the first movement pattern.

3.9.5 Data management

Each video tape was encoded and digitised as explained in Section 3.8.1. In the first study, the beginning and the end of every trial was estimated. The starting point of the activity was defined from the first picture in which the marker on the table could be seen. The finishing point was set at the first picture which showed the ball leaving the subject's hand. The digitisation process started two pictures before the starting point and finished 10 pictures after the finishing point. The coordinate data were calculated in millimetres. The filming space was calibrated using eight points of the calibration frame (B, C, K, L, N, O, W, X see Figure 3.1). Calibration error for this study ranged from 0.359-1.359 mm in the x dimension, 1.064-1.416 mm in the y dimension, and 0.423-1.105 mm in the z dimension. The maximum RMS error for the calibration process as calculated by the Peak Motion Analysis Software was 1.403-2.110 mm.

There were 284 trials in Stage One of the study. Four trials were lost because the marker at the wrist joint fell off during the trials. All trials were digitised and analysed.

The analysis consisted of calculation of the angular displacement and normalisation. Seven movements of the upper limb, shoulder flexion and extension, shoulder adduction and abduction, shoulder rotation, elbow flexion and extension, forearm rotation, wrist flexion and extension and wrist ulnar and radial deviation were calculated as described in Chapter 4 Section 4.1.2.

The trajectories of markers at the shoulder, elbow and wrist joints for each of the different conditions were also inspected. The smooth coordinate data from the Peak software were used to translate and rotate axes to standardise the axes and planes of the movements for each subject as described in Chapter 4, Section 4.2.1.

3.9.6 Results

The first stage of the study investigated the repeatability of the performance of each subject and the variation in the specified placing and throwing movements under different conditions. The distance thrown, the weight of a projectile, and the size of a target were manipulated. Subjects were asked to perform the task twice using their own styles as indicated in the protocol (Section 3.9.4). As reported in Chapter 4, Section 4.3.1 all four subjects were found to be able to perform the task consistently under the same conditions. Therefore, Hypothesis One for Stage One of the study could be accepted.

The effects of the independent variables on the pattern of movement and the angular displacement were investigated next.

3.9.6.1 Statistical procedures

The differences in the shape of the angular displacement curves were compared visually. In addition, the maximum and the minimum values of all joint angles in each condition were examined for statistical significance.

Even though Stage One of the study was a 3 ¥ 2 ¥ 2 factorial experiment, the significance of each factor was computed as for an analysis of the single-factor design. To investigate the interaction effects of these variables on the seven joint angles required a sufficient number of subjects. The sample size of four used in Stage One of the study was not appropriate for testing the combined effects using multivariate analysis of variance. Thus the data were grouped according to the independent variable of interest for each subject and treated as a single independent variable.

Paired t-tests were used to determine the significance of the means of the maximum and the minimum values of the seven joint angles for each of the different weights of the projectile and each of the different sizes of the target.

One-way analysis of variance (ANOVA) for related designs was used to test for any significant differences in the maximum and the minimum values of the seven joint angles for all three distances. The Scheffé multiple range test was used to specify the statistical position between variables. The Scheffé test was applied for each joint angle when the ANOVA test showed an overall significant difference.

The statistical analysis was performed using the software Statview version 4.02 for the Macintosh computer. A probability level of 5% ($p<.05$) was selected as the significance level for all statistical calculations.

3.9.6.2 Patterns of the movements

The trajectories of the markers on the xz or sagittal plane were used to classify the pattern of the selected tasks (Figure 3.5). Three patterns of movement were identified. The first was an overarm pattern, the second an underarm pattern and the final pattern was identified as a rotation pattern. This last title was chosen because the movement started from a position of internal rotation of the shoulder joint with flexion of the elbow joint and moved to external rotation of the shoulder joint and extension of the elbow joint with the release of the projectile and could be described as similar to the action used in dealing cards.

All four subjects chose the overarm pattern for their first style. That is all subjects threw a projectile in the same way for the first pattern. When subjects were asked to perform another style of placing and throwing, two of them had some difficulty in selecting different patterns and chose a pattern that was very similar to the overarm pattern. The other two subjects chose the underarm or rotation pattern. Thus subjects used different styles of throwing in choosing their second pattern.

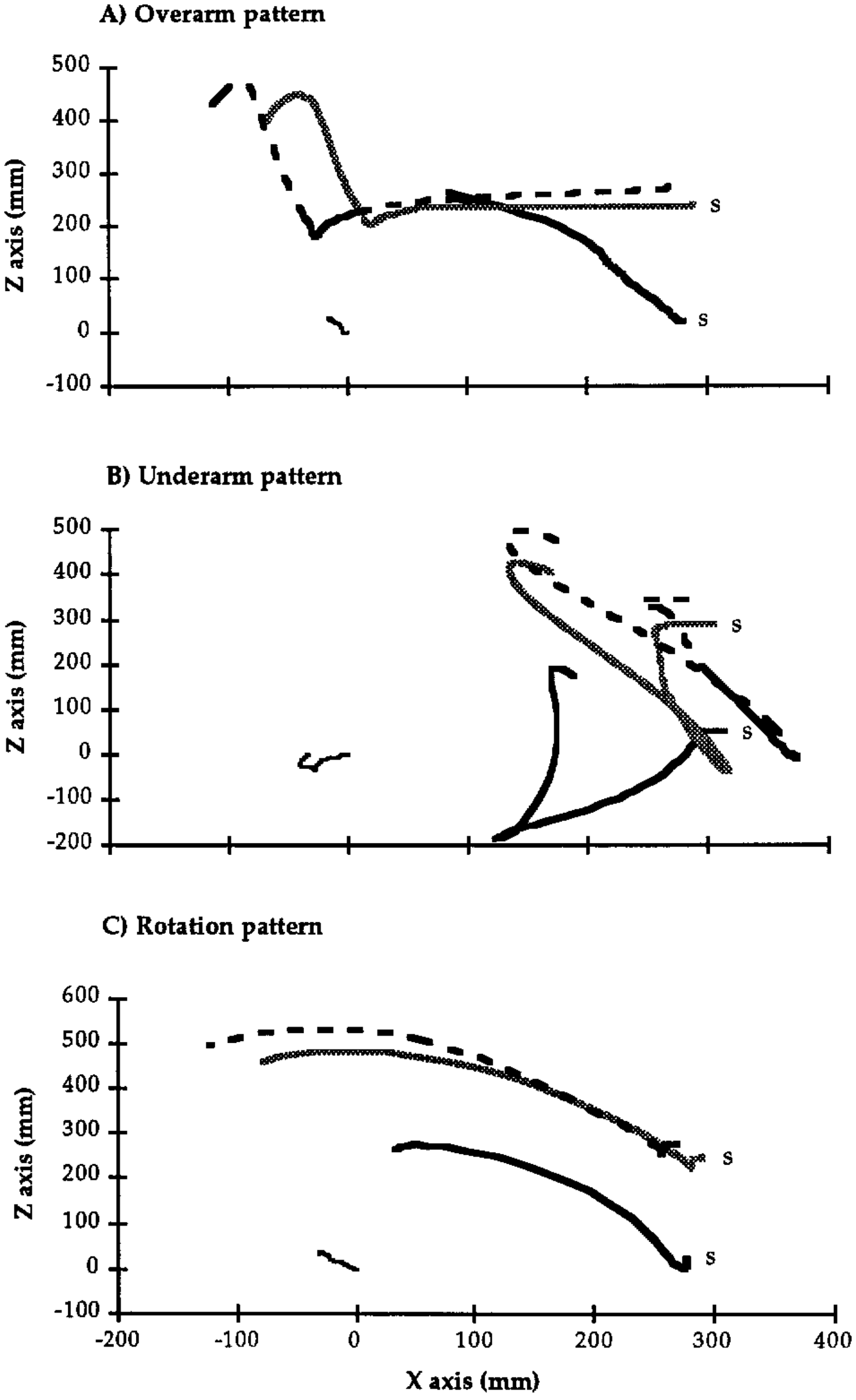


Figure 3.5 Trajectories of the throwing movement in the sagittal plane. **A)** overarm pattern, **B)** underarm pattern, **C)** rotation pattern. ——— = shoulder joint, ▬▬▬ = elbow joint, ▒▒▒ = wrist joint, ▬ ▬ ▬ ▬ = hand. s = starting point

3.9.6.3 The effect of the distance thrown, the weight of the projectile and the size of the target on the angular displacement

In the first stage of the study, the angular displacement of the joints of the upper limb were the main parameters to be evaluated. The range of motion of each joint angle was averaged according to each of the conditions (ie. distance thrown, weight of the projectile and size of the target).

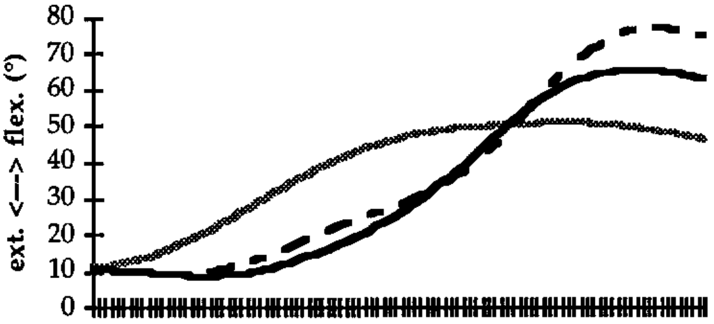
To illustrate the effect of the independent variables on the angular displacement of the upper limb in the throwing activity, only the data from the first pattern of the Stage One of the study were chosen for analysis because all four subjects used the same styles of throwing. The joint angle data from the second pattern demonstrated a high degree of variation due to the different patterns used. Thus these data were not suitable for use in determining the statistical significance of any changes identified. However, throwing forms of the first and the second pattern were used in the protocol for the next stage of the study.

a) The effect of the distance thrown on angular displacement

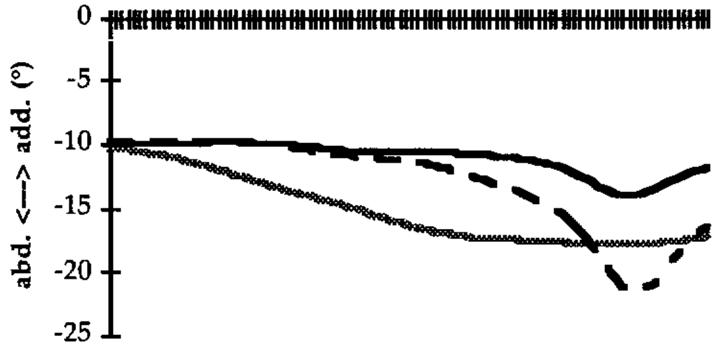
The angular displacement of the joints of the upper limb at each distance thrown was averaged. The means and standard deviations of the forty seven trials of four subjects for each joint angle were plotted against time. The shape of the joint motion curves were visually compared between the distance A, B and C. There was no difference in the profile of the curves of each joint angle as the distance thrown increased (Figure 3.6). However, the minimum and the maximum values of each joint angle were statistically examined.

The average values of the minimum and the maximum joint angles for each subject were calculated. Differences among the minimum or the maximum values as the distance thrown increased were compared using a factorial ANOVA. The minimum values of all joint angles were not significantly different as the distance thrown increased (Table 3.2). Only the maximum values of flexion and extension of the shoulder and elbow joints differed significantly ($F_{(2,9)} = 6.670$, $p = .0167$ and $F_{(2,9)} = 7.358$, $p = .0128$ respectively) (Table 3.3). Amongst the three distances thrown, only the

A) Shoulder flexion/extension



B) Shoulder adduction/abduction



C) Shoulder internal/external rotation

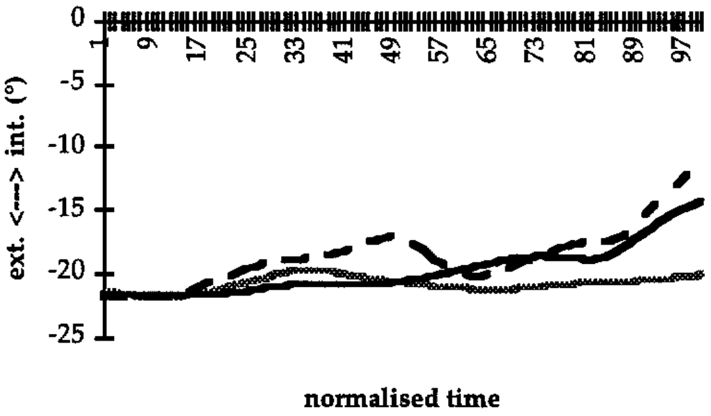
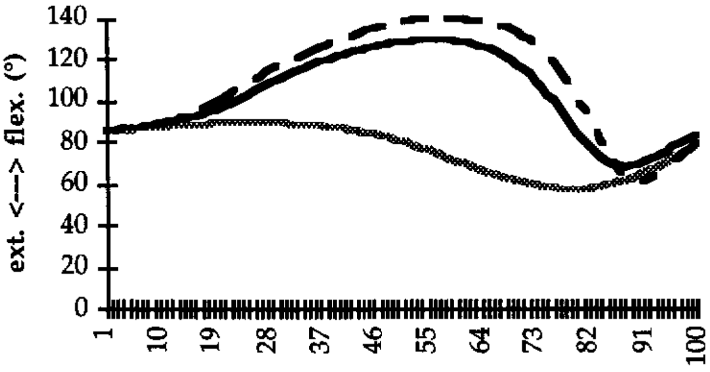


Figure 3.6 Mean values of angular displacement of the shoulder joint as the distance thrown increased (n=47 trials for each distance) ········ = 1 arm's length, ——— = 1.5 arm's length, - - - - = 2 arm's length

D) Elbow flexion/extension



E) Forearm pronation/supination

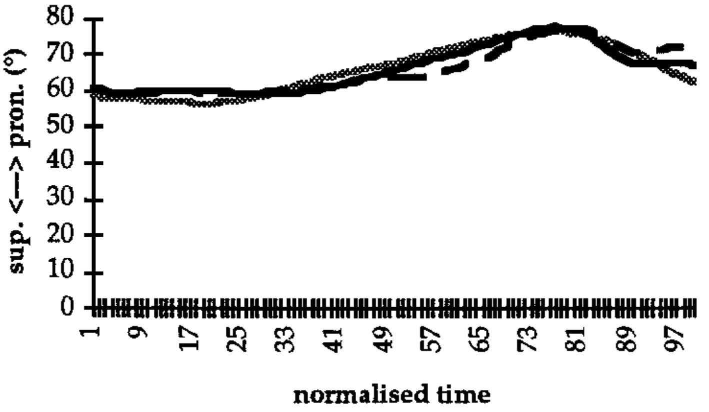
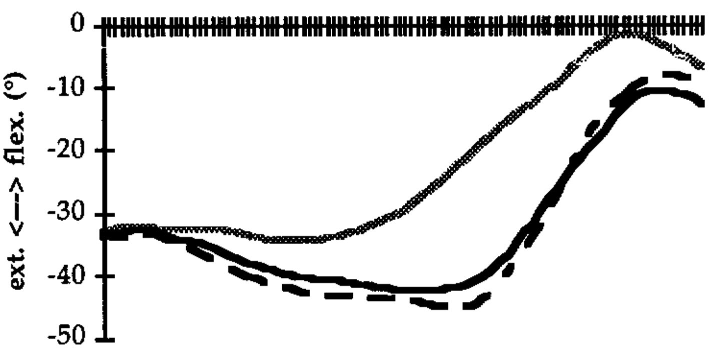
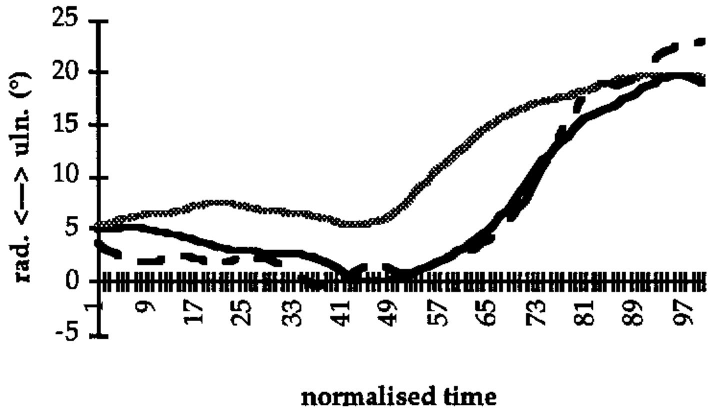


Figure 3.6 (continued) Mean values of angular displacement of the elbow and radioulnar joint as the distance thrown increased (n=47 trials for each distance) ▨▨▨ = 1 arm's length, ━━━ = 1.5 arm's length, ▬ ▬ ▬ = 2 arm's length



F) Wrist flexion/extension



G) Wrist ulnar/radial deviation

Figure 3.6 (continued) Mean values of angular displacement of the wrist joint as the distance thrown increased (n=47 trials for each distance) ▒▒▒ = 1 arm's length, ▬▬▬ = 1.5 arm's length, ▬ ▬ = 2 arm's length

Table 3.2 Summary of one-factor ANOVA of the minimum values of joint angles with distance thrown as the independent variable

Dependent variable	df	SS	MS	F	p
Shoulder flexion/extension	2	20.04	10.02	0.74	0.50
Residual	9	121.40	13.49		
Shoulder adduction/abduction	2	535.39	267.70	1.35	0.31
Residual	9	1791.16	199.02		
Shoulder rotation	2	7.87	3.93	0.05	0.95
Residual	9	744.72	82.75		
Elbow flexion/extension	2	268.27	134.13	0.49	0.63
Residual	9	2479.54	275.50		
Forearm rotation	2	33.83	16.92	0.30	0.75
Residual	9	515.01	57.22		
Wrist flexion/extension	2	437.24	218.62	4.22	0.51
Residual	9	466.31	51.81		
Wrist ulnar/radial deviation	2	295.87	147.93	1.34	0.31
Residual	9	997.57	110.84		

Table 3.3 Summary of one-factor ANOVA of the maximum values of joint angles with distance thrown as the independent variable

Dependent variable	df	SS	MS	F	p
Shoulder flexion/extension	2	1029.96	514.98	6.67	0.02*
Residual	9	694.91	77.21		
Shoulder adduction/abduction	2	5.00	2.50	0.18	0.84
Residual	9	127.92	14.21		
Shoulder rotation	2	38.87	19.43	0.26	0.78
Residual	9	677.94	75.33		
Elbow flexion/extension	2	3666.13	1833.07	7.36	0.01*
Residual	9	2242.07	249.12		
Forearm rotation	2	151.13	75.57	0.50	0.62
Residual	9	1370.54	152.28		
Wrist flexion/extension	2	67.87	33.94	0.19	0.83
Residual	9	1572.64	174.74		
Wrist ulnar/radial deviation	2	23.80	11.90	0.07	0.93
Residual	9	1549.91	172.21		

Table 3.4 Mean difference, critical difference and p-value of the Scheffé test for the maximum values of joint angles

Dependent variable	Source	Mean Diff.	Crit. Diff.	p-value
Shoulder flexion/extension	Distance A and B	-10.35	18.13	0.30
	Distance A and C	-22.67	18.13	0.02*
	Distance B and C	-12.32	18.13	0.20
Elbow flexion/extension	Distance A and B	-29.31	32.56	0.08
	Distance A and C	-41.68	32.56	0.01*
	Distance B and C	-12.37	32.56	0.56

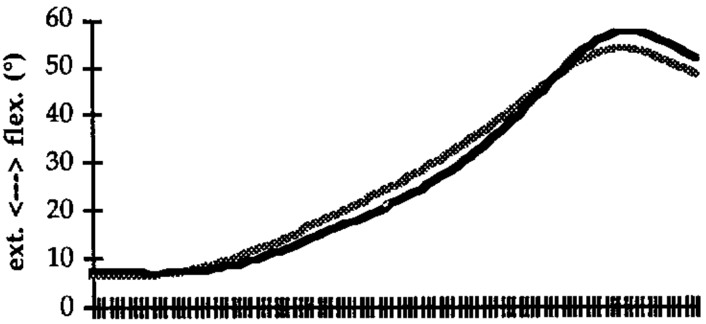
maximum values of the distance A and C showed a significant difference in flexion and extension of the shoulder and elbow joints (p=.0168 and .0128 respectively, Table 3.4). Other joint angles, ie. shoulder adduction and abduction, shoulder rotation, forearm rotation and wrist motion showed no significant change in the range of motion as the distance increased. The increasing range of the shoulder and elbow flexion as the distance thrown increased suggested the possible function of the distance as a control parameter. Thus Hypothesis Two for Stage One of the study could be accepted for the independent variable distance thrown.

b) The effect of the weight of a projectile on the angular displacement

All the angular displacement files in which a heavy or a light projectile was used were averaged. The means and standard deviations of 18 trials of these joint angles files for each subject were determined. The curve of the average value for each joint angle using a heavy projectile were compared with the curve of the data using a light projectile. A visual comparison of the results showed that there were no differences in the angular displacement profiles of any joints when subjects used a projectile of different weights (Figure 3.7).

A two tailed paired t-test was used to determine differences in the minimum and the maximum values of each joint angle as the weight of the projectile increased. The maximum values of all joint angles in the heavy projectile condition were not significantly different when compared with the data in the light projectile condition (Table 3.5). However, the maximum value of abduction of the shoulder joint and maximum supination of the radioulnar joint showed a significant difference between a heavy and a light projectile ($t_{(3)}$=-3.864, p=0.0307 and $t_{(3)}$=-3.603, p=.0367 respectively) (Table 3.6). The significant difference of supination of the radioulnar joint implies that increasing weight of the projectile may affect the throwing pattern. Thus the Hypothesis Two for Stage One of the study could be accepted for the independent variable weight of the projectile for selected joint angles.

A) Shoulder flexion/extension



B) Shoulder adduction/abduction

C) Shoulder internal/external rotation

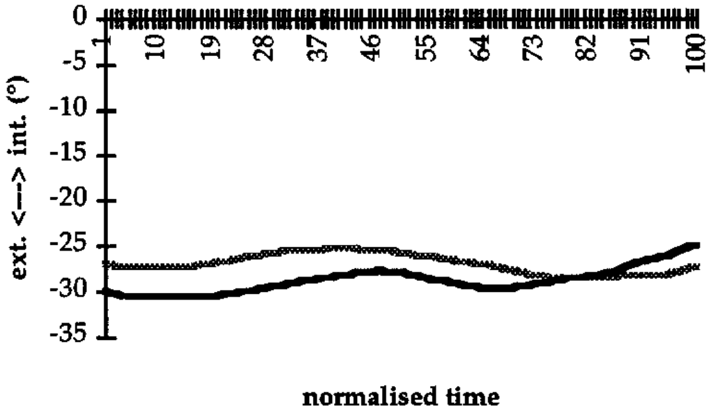


Figure 3.7 Mean values of angular displacement of the shoulder joint under light and heavy projectile conditions (n=18 trials each) ▒▒▒ = light projectile, ▬▬▬ = heavy projectile

Table 3.5 Means and standard deviations, t and p values for the minimum angular displacements of the upper limb under heavy and light projectile conditions

			Heavy projectile		Light projectile			
	Variable	df	Mean	SD	Mean	SD	t	p
Minimum value	Shoulder flexion/extension	3	5.14	3.39	4.85	3.72	0.37	0.74
	Shoulder adduction/abduction	3	-35.87	14.98	-27.35	11.04	-3.86	0.03*
	Shoulder rotation	3	-34.13	10.03	-32.38	8.06	-1.36	0.27
	Elbow flexion/extension	3	45.03	13.40	45.37	15.84	-0.23	0.83
	Forearm rotation	3	32.30	6.63	48.55	10.12	-3.60	0.04*
	Wrist flexion/extension	3	-52.32	8.48	-48.28	4.16	-1.66	0.20
	Wrist deviation	3	-18.19	11.00	-12.36	8.81	-1.43	0.25

Table 3.6 Means and standard deviations, t and p values for the maximum angular displacements of the upper limb under heavy and light projectile conditions

			Heavy projectile		Light projectile			
	Variable	df	Mean	SD	Mean	SD	t	p
Maximum value	Shoulder flexion	3	58.71	8.37	55.22	7.04	2.96	0.06
	Shoulder adduction/abduction	3	-13.06	3.68	-13.07	3.64	0.02	0.99
	Shoulder rotation	3	-22.01	9.67	-22.18	7.75	0.10	0.93
	Elbow flexion/extension	3	108.61	14.02	103.32	11.03	1.82	0.17
	Forearm rotation	3	65.06	12.35	69.38	11.76	-2.77	0.07
	Wrist flexion/extension	3	-16.64	13.76	-20.68	11.60	2.08	0.13
	Wrist deviation	3	9.72	13.68	9.55	12.33	0.13	0.90

c) The effect of the size of the target on the angular displacement

A similar examination to that used to review the effect of the weight of the projectile was employed to examine the effect of target size on the task. Throwing to a large target was compared with throwing to a small target area. The means and standard deviations of the joint angle files (18 trials) for each subject were determined. The curve of the average values for each joint angle during throwing to the large target were compared with the curve of the data for throwing to a small target. The profiles of the angular displacement of all joints were similar for both small and large target conditions.

A two tailed paired t-test was used to determine differences in the minimum and the maximum values of each joint angle as the size of the target increased. The maximum values of all joint angles in the large target condition were not significantly different from those obtained for the small target condition (Table 3.7). Only the maximum value of abduction of the shoulder joint showed a significant difference as the size of the target increased ($t_{(3)}$ =4.708, p=.0181) (Table 3.8). Thus Hypothesis Two for Stage One of the study with respect to target and size could not be supported and was therefore rejected for this particular independent variable.

Table 3.7 Means and standard deviations, t and p values for the minimum angular displacements of the upper limb under small and large area conditions

			Small target		Large target			
	Variable	df	Mean	SD	Mean	SD	t	p
Minimum value	Shoulder flexion/extension	3	4.91	2.72	5.10	4.22	-0.25	0.82
	Shoulder adduction/abduction	3	-29.96	12.63	-33.30	13.27	4.71	0.02*
	Shoulder rotation	3	-32.99	8.34	-33.52	9.71	0.57	0.61
	Elbow flexion/extension	3	45.70	15.01	44.79	14.24	0.80	0.48
	Forearm rotation	3	39.69	5.32	40.83	9.78	-0.34	0.75
	Wrist flexion/extension	3	-50.31	7.08	-50.24	5.44	-0.08	0.94
	Wrist deviation	3	-16.86	7.91	-14.02	10.09	-2.02	0.14

Table 3.8 Means and standard deviations, t and p values for the maximum angular displacements of the upper limb under small and large area conditions

			Small target		Large target			
	Variable	df	Mean	SD	Mean	SD	t	p
Maximum value	Shoulder flexion/extension	3	56.17	7.50	57.73	7.81	-6.88	0.01*
	Shoulder adduction/abduction	3	-12.57	4.34	-13.54	3.21	0.91	0.43
	Shoulder rotation	3	-22.51	8.27	-21.77	8.97	-0.75	0.51
	Elbow flexion/extension	3	104.86	13.09	107.07	11.55	-1.68	0.19
	Forearm rotation	3	67.10	12.60	67.24	11.39	-0.14	0.90
	Wrist flexion/extension	3	-18.98	12.84	-18.34	12.55	-0.37	0.74
	Wrist deviation	3	9.84	13.75	9.58	12.30	0.26	0.81

3.9.7 Discussion

3.9.7.1 Patterns of the movements

In the laboratory environment, all subjects used an overarm pattern to accomplish the task on the first series of trials. Thus an overarm throw appears to be the most natural movement for all subjects under these experimental conditions. Other evidence which supports this idea is the appearance of difficulties which some subjects experienced in trying to think of a different style of throwing for the second pattern and the fact that two subjects chose a throwing form which was very similar to an overarm throw as their second pattern.

Use of the overarm throw as the first pattern by all subjects may have been a result of the experimental environment. The position of the table and the position of the subject could have been limiting factors. The table was placed directly in front of the subjects and in the required sitting position, movement of the trunk was limited. The free space in the experimental set up may have specifically facilitated movement of the upper limb in the overarm pattern and the rotation patterns rather than the underarm pattern. In addition, because an adjustable table was placed in front of subjects in Stage One of the study to facilitate the completion of the placing task, the subject who performed the underarm pattern used an increased range of elbow flexion to avoid hitting the table. However, all three patterns were used by at least one subject and were chosen for further examination in Stage Two of the study.

3.9.7.2 The effect of the distance thrown, the weight of the projectile and the size of the target on the pattern of throwing

The results of the first stage of the study showed that the shapes of the angular displacement curves were the same despite the changes in parameters such as weight of the projectile, distance thrown and the size of the target. This may have been the result of a number of factors. For example, subjects were asked to use a consistent pattern of movement through each set of trials of the task. Subjects were also asked to change the style of movement only when they performed another set of trials of the task. Both of these instructions could have influenced the subjects performance. Another reason might be that the changes in the proposed parameters were not sufficient to cause any variation in the pattern.

Even though the profiles of the joint motion curves were consistent under the different conditions, the maximum and the minimum values of some joint angles were shown to differ significantly as the independent variables were modified.

The distance thrown did not cause any significant differences in the minimum values of the joint angles. The effects of the distance thrown were shown only in the maximum values of flexion and extension of the shoulder and elbow joints. The step increase in flexion of the shoulder and elbow joints occurred between distance A to C. The non significant differences between the distance A and B and the distance B and C may be a result of the fact that the extent of each distance (which was in proportion to a subject's arm length) was insufficient to show differences. Since the increased range of flexion of the shoulder and elbow joints occurred during the throwing period, it appears that these two joints might be responsible for changing the movement pattern when the distance to be thrown is increased.

Neither the weight of the projectile nor the size of the target had a significant effect on the maximum values of the joint angles. But these two independent variables could be seen to contribute to the significant differences in the minimum values of the joint angles. For the effect of the size of the target, only abduction of the shoulder joint showed a significant difference. For the effect of the weight of the projectile, abduction of the shoulder joint and rotation of the radioulnar joint were both significantly different. The significant differences in shoulder abduction in both conditions occurred at the end of the task. Thus the weight of the projectile and the size of the target might not have any effect on the movement of the shoulder during the throwing period but simply influence the end position of the extremity on completion of the throw. In contrast, the effect of the weight of the projectile on the rotation of the forearm occurred at the beginning of the movement. Subjects supinated the forearm when they threw the heavy projectile more than when throwing the light projectile. This increase in the range of supination in the heavy projectile condition may be explained by the action of the biceps brachii muscle which is an important flexor muscle of the elbow joint. This muscle functions well when there is supination of the forearm and may have been recruited more strongly to counter the increasing weight. Therefore, weight of the projectile was still manipulated in the next stage of the study.

Another point to consider is the area of the target used in Stage One of the study. The small target had an area of 12.5 cm^2 and the large target had an area about 6,600 to 7,000 cm^2. Thus subjects had to be more careful in controlling their movement when they threw to the small target than when they threw to the large target. The success of throwing to the small target is also related to the amount of practice time. In Stage One of the study, subjects were allowed to practice so that they became familiar with the equipment and accustomed to the markers attached to the upper limb. The practice period was not designed to improve the precision of throwing because they allowed to throw a projectile tem times to their choices of targets. The number of rehearsal was not enough to gain a skill to throw to the small size of target accurately. Inclusion of different sizes of target in this study was aimed at examining the immediate effect of the intention together with any intended adjustment of the movement in response to the different requirements of the movement. It was not planned to measure the accuracy of the throw. Therefore, all trials in which subjects were asked to throw the projectile to hit the specific target area were included in the examination of the results, even though that throw may have failed to hit the target.

The results from this stage of the study showed no significant effects of target size on the joint motions. Despite the fact that the degree of shoulder abduction were significantly different, the point at which the significant angle occurred was always at the end of the movement. To clearly demonstrate the effects of the size of the target required a period of practising and since this was not a central element of the study, target size was excluded from the protocol for the next stage of the study.

3.9.7.3 Position of the cameras

Loss of some markers, especially markers attached on the index and middle fingers was demonstrated during the digitising. A view from at least two cameras is required for calculation of coordinate data in three-dimensional analysis. Suitable positioning of the cameras was therefore one of the aims identified for Stage Two of the study.

3.9.8 Summary

Three different patterns of throwing were used by subjects. That is patterns which can be described as overarm, underarm and rotation.

The distance from the starting point to the target had some effect on the angular displacement of the upper limb. However, it appeared that the longest distance chosen for use in the first stage of the study was not sufficient to cause a clear change in the pattern of throwing. Furthermore, of the seven joint angles of the upper extremity that were measured, only flexion and extension of the shoulder and elbow showed the step increment in displacement as the distance thrown increased.

On the other hand, neither the weight of the projectile nor the area of the target caused significant changes in the joint motions. Nevertheless, the significant difference in supination of the forearm caused by the increasing weight of the projectile suggests that there is a potential effect of the weight of an object on the joint angles. For this reason the distance thrown and the weight of the projectile were selected to manipulate more extensively in Stage Two of the study.

3.10 Stage Two

Stage Two of the experiment was designed to explore and solve some of technical problems that may occur when independent variables were manipulated in a greater range compared with Stage One of the study. These problems included the most appropriate projectile, the length of the distance thrown, suitable positioning of the cameras, and the security of the markers.

3.10.1 Hypotheses

Stage two was not designed to test any hypotheses. It was intended to develop solutions for technical problems such as the position of the cameras and the security of the marker on the skin as subjects used the maximum throwing effort. Furthermore, during this stage it was also planned to test and adjust the protocol derived from the results of Stage One so that a suitable procedure for the Stage Three could be developed.

3.10.2 Equipment set up

An adjustable chair and six separate small tables were used in this stage. Each table was 50 ¥ 90 cm and was set as a target. The tables were placed at distances of 0.5, 1.0, 2.0, 3.0, 4.5 and 6.0 m from the subjects. A pneumatic button was connected to a synchronising unit and placed on the first table at the identified starting position for the task. As the subjects started to move the hand for the throw the trigger light was automatically illuminated and displayed on the monitor. This light was used to synchronise the video frames and to define the starting point of the movement. The projectiles used in this test were the same as those in the first stage.

Three cameras (Panasonic F15) were again used and adjusted as described in Section 3.7.2. The master camera was positioned at right angles above the subjects 5.20 metres from the floor. The second camera was placed in front of the subjects slightly toward the right hand side at 7.20 metres away. The third camera was set behind and slightly toward the right hand side of the subjects at a distance of 6.80 metres (Figure 3.8). The height of the second and the third cameras from the floor to the lower rim of the lens was 1.22 metres for both cameras.

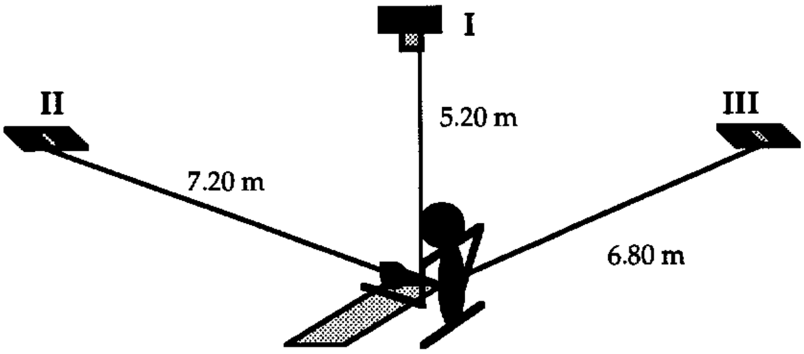


Figure 3.8 The set up of cameras used in data collection in Stage Two

3.10.3 Task

Unlike the first stage of the study, the secondary stage defined the patterns of throwing for the subject. Subjects were asked to throw a heavy (1500 g) or a light (15 g) projectile as described in Stage One in three different patterns to six distances. The first pattern was an overarm pattern. The second pattern was an underarm pattern. The last pattern was the rotation pattern (ie., similar to that used in dealing cards).

3.10.4 Protocol

Subjects were seated on an adjustable chair. Ten markers were placed on the subjects as described in Section 3.7.3. Because all of the lower bars in the calibration frame were obscured in the overhead camera view, the frame needed to be tilted to provide a clear view of all markers on the frame. Since the reference planes were defined from the calibration frame, three additional markers were placed on the table to identify the horizontal plane.

The starting position was the same as in the first stage. Subjects were informed of the requirements of the protocol and the defined pattern of movement was demonstrated. They were allowed ten practice throws. Then they were asked to throw the projectile to the six different distances assigned in random order. For every distance, subjects were allowed to throw at least three times and not more than five attempts were permitted. The projectile had to land within the defined area to be counted as a successful attempt. The same protocol was applied for each pattern of throwing. The styles and the projectiles used were randomly selected.

3.10.5 Data management

The digitising process was completed as delineated in Section 3.8.1. In this stage, the beginning of each trial was judged from the cursor light shown on the screen but the end of a trial was estimated as for the first stage. The starting point was defined as a first picture in which the cursor light appeared on the screen. The digitisation process started 10 pictures before the starting point and finished 20 pictures after the finishing point. The calculation of the coordinates data was based on the twelve markers (B, C, F, I, K, L, N, O, R, U, W, X see Figure 3.1) on the calibration frame. Calibration error for this study ranged from 1.058-2.062, 1.687-2.764, 2.367-2.497 mm in the x, y, and z dimensions respectively. The maximum RMS error for the calibration process was 3.093-4.257 mm.

In Stage Two of the study, the first successful throw for each throwing distance was selected to be digitised and analysed. Sixty-eight trials were selected from 235 trials.

Seven angular displacements of the upper limb were calculated. Trajectory and joint angles at the releasing point were determined and were compared between the three different patterns.

3.10.6 Results

The second stage of the study was planned to examine the different styles of throwing identified from Stage One under different conditions. The original independent variable, the distance thrown was modified as a result of study one.

The range of the distance thrown was increased from twice the length of the upper limb (which was about 1.40 m) to a maximum distance of 6.0 metres from the subject. This distance was defined because it seemed to require the maximum effort of female throwers as have been tested with a few girls (not included as subjects). In addition, the maximum distance was also limited by the space of the laboratory room.

Weight of the projectile was limited by its size. The selected size had an optimal diameter which allowed subjects to hold it comfortably in their hand. The maximum weight of lead shot that it could contain was 1500 g. Therefore it was not possible to further manipulate this independent variable. Thus the same weight of projectile was used in the second stage as was used in the first stage of the study.

Because the method of digitising and computation of the large volume of data required a significant amount of time to process, the results of Stage Two were used to adjust and reduce unnecessary procedures required for the main experiment. Stage Two of the study was designed to allow selection of the most suitable pattern of throwing and most useful independent variables for the principal study.

Trajectories of the movement were used to detect the changing style of throwing as the distance thrown and the weight of the projectile increased. Two subjects were examined in Stage Two of the study. Therefore only descriptive results are presented.

3.10.6.1 Movement trajectories

The smooth coordinates data from the Peak motion analysis system was used to calculate the movement trajectories as described in Chapter 4. Section 4.2.1. The xz or sagittal plane served as the perspective view for the movement trajectories. For the trajectories of the overarm and the rotation throw, the starting point is at the right end of the curves. For the underarm throw, the starting point is at the left end of the shorter profiles.

The trajectories of the throw at the distances thrown of 1, 2, 3, and 4.5 metres for the heavy and light weight of the projectile are shown in Figures 3.9 to 3.14. Three types of trajectories of the throwing movement are shown, that is, an overarm, an underarm and a rotation pattern. The trajectories of the movement as the distance thrown increased reflected the increment in the range of motion rather than the alteration of the pattern. For all styles of throwing in both subjects, the trajectories for the light and the heavy weight of the projectile at the same distance thrown, showed similar trends. However, in some cases the trajectories of a throw when the heavy projectile was used demonstrated a greater range of movement than those throws in which the light projectile was thrown over the same distance. For example see Figure 3.9 and 3.10 which shows the overarm throw at a distance of 3 and 4.5 metres.

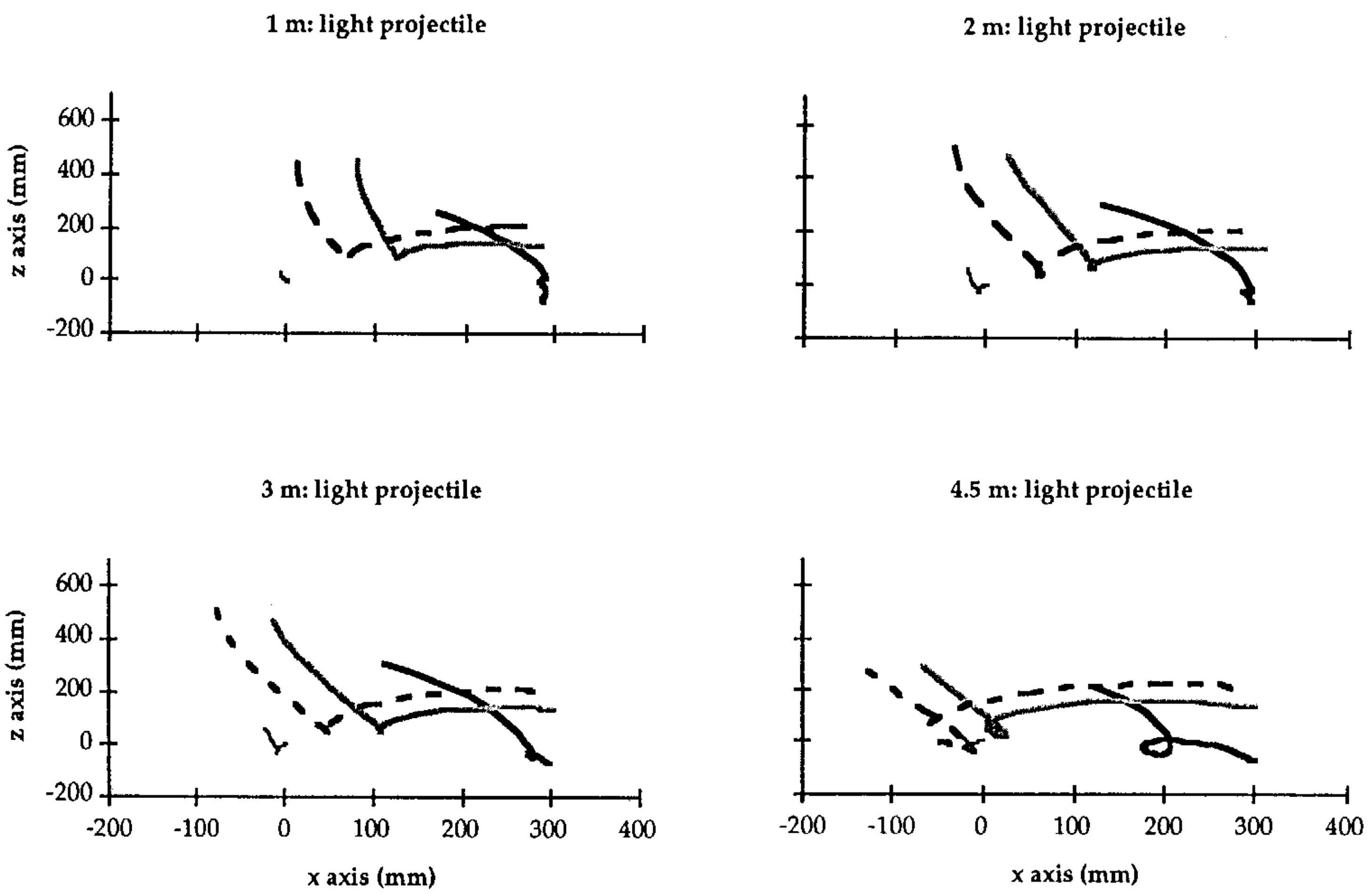


Figure 3.9 Trajectories of an overarm throw in the sagittal plane using a light projectile over different distances ____ = Shoulder joint, ____ = Elbow joint, ____ = Wrist joint, - - - - = 3rd Metacapophalangeal joint

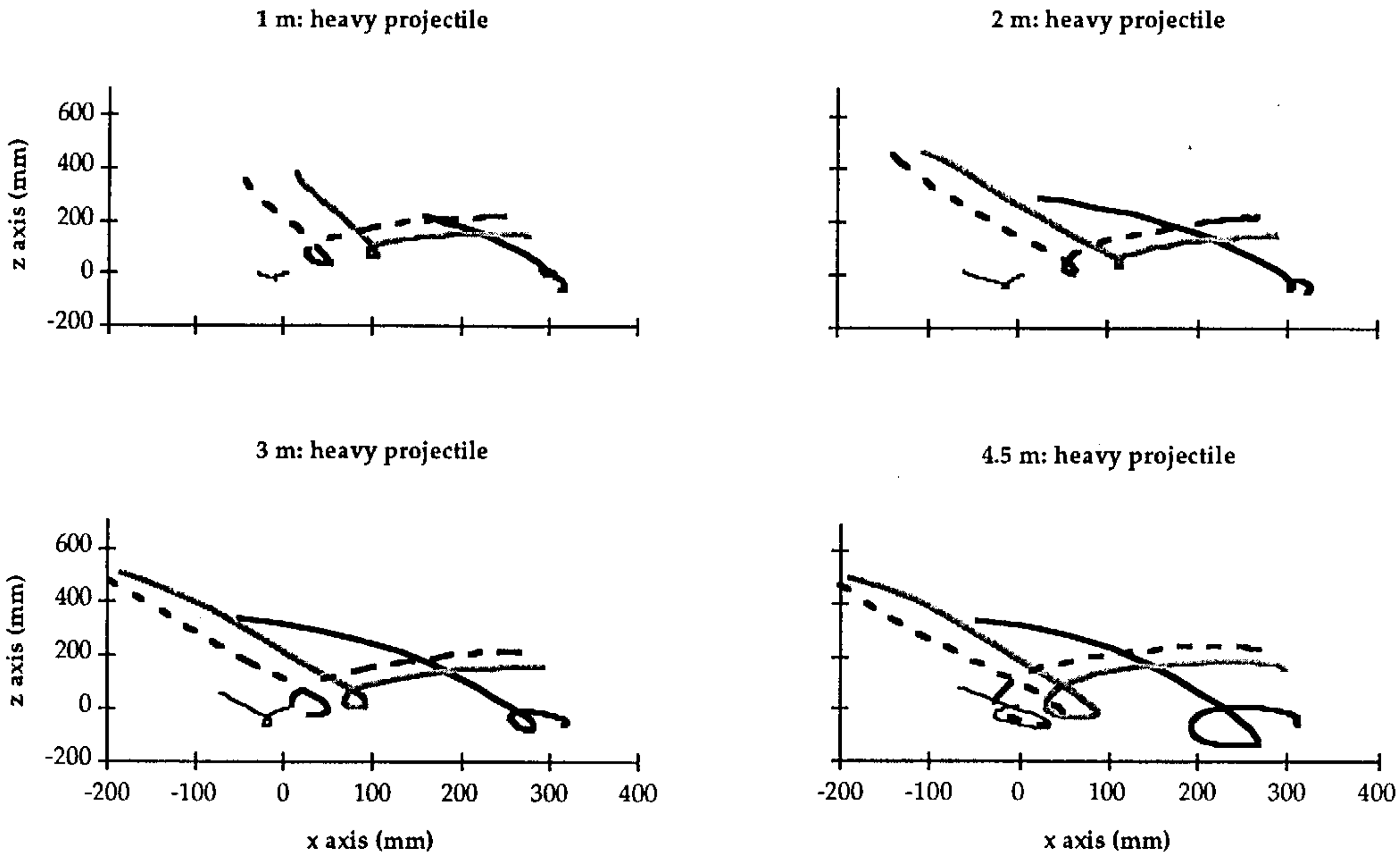


Figure 3.10 Trajectories of an overarm throw in the sagittal plane using a heavy projectile over different distances
____ = Shoulder joint, ——— = Elbow joint, ——— = Wrist joint, ---- = 3rd Metacapophalangeal joint

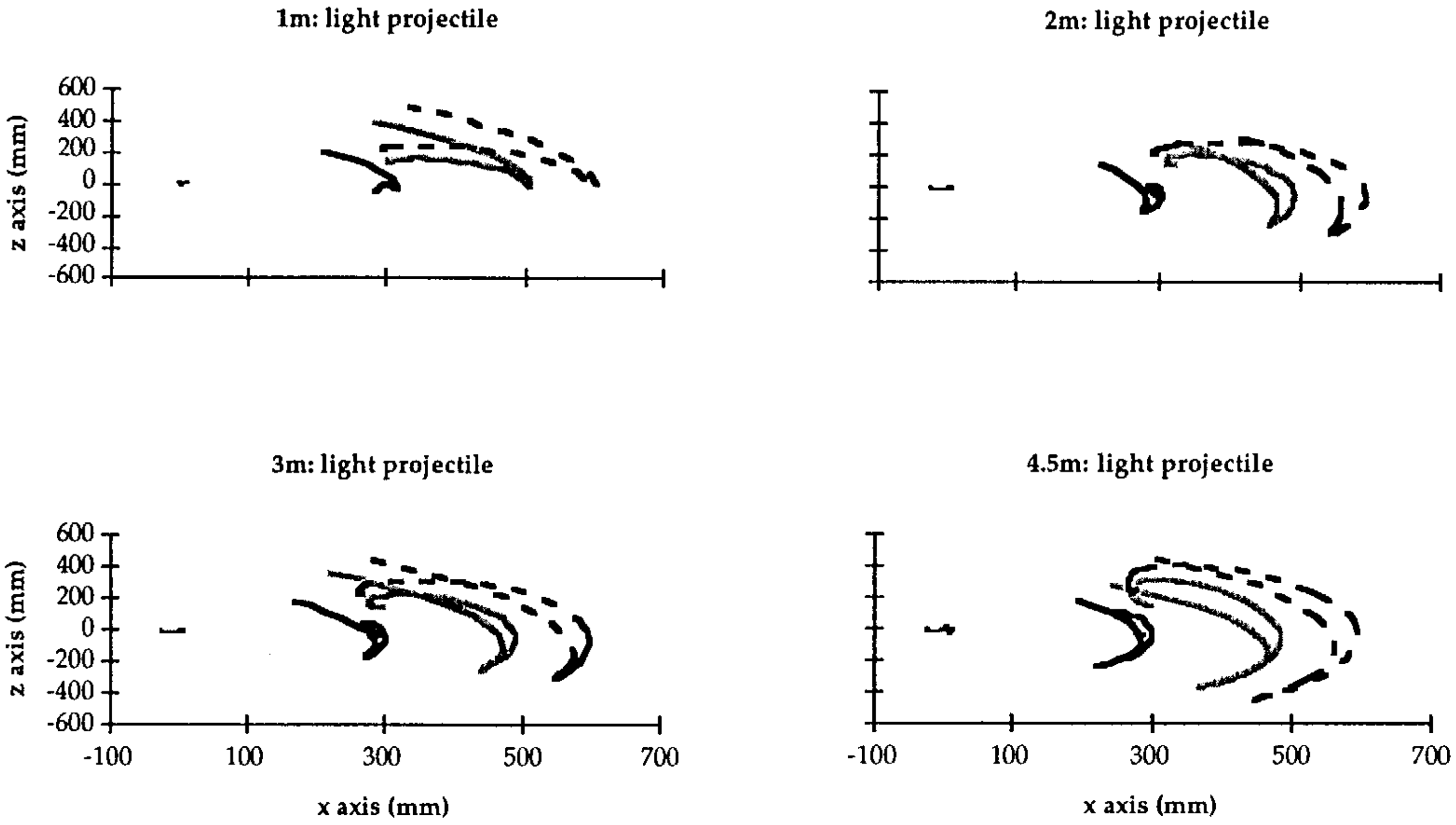


Figure 3.11 Trajectories of an underarm throw in the sagittal plane using a light projectile over different distances
____ = Shoulder joint, ▬▬ = Elbow joint, ―― = Wrist joint, - - - - = 3rd Metacapophalangeal joint

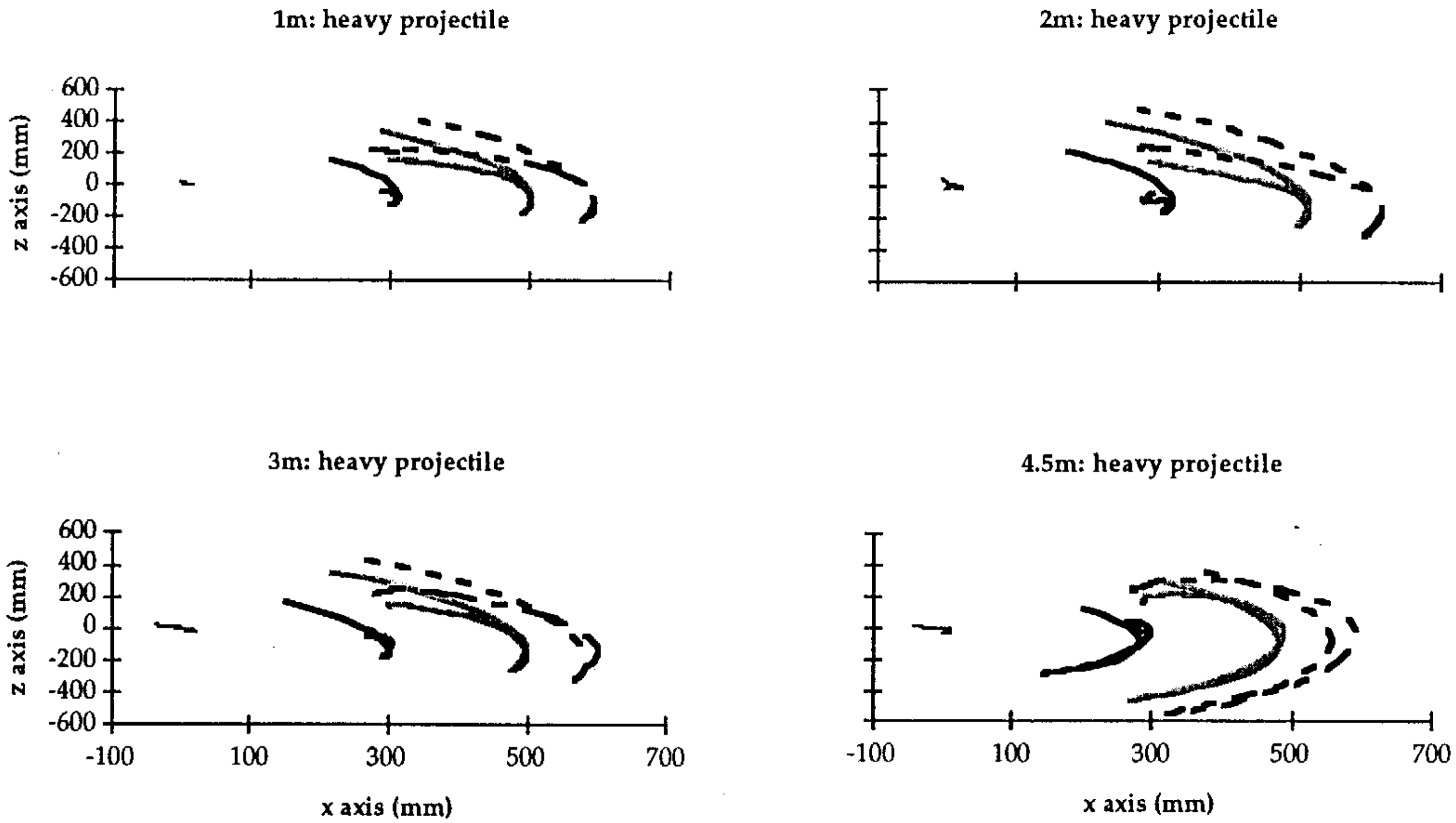


Figure 3.12 Trajectories of an underarm throw in the sagittal plane using a heavy projectile over different distances ——— = Shoulder joint, ——— = Elbow joint, ——— = Wrist joint, - - - - = 3rd Metacapophalangeal joint

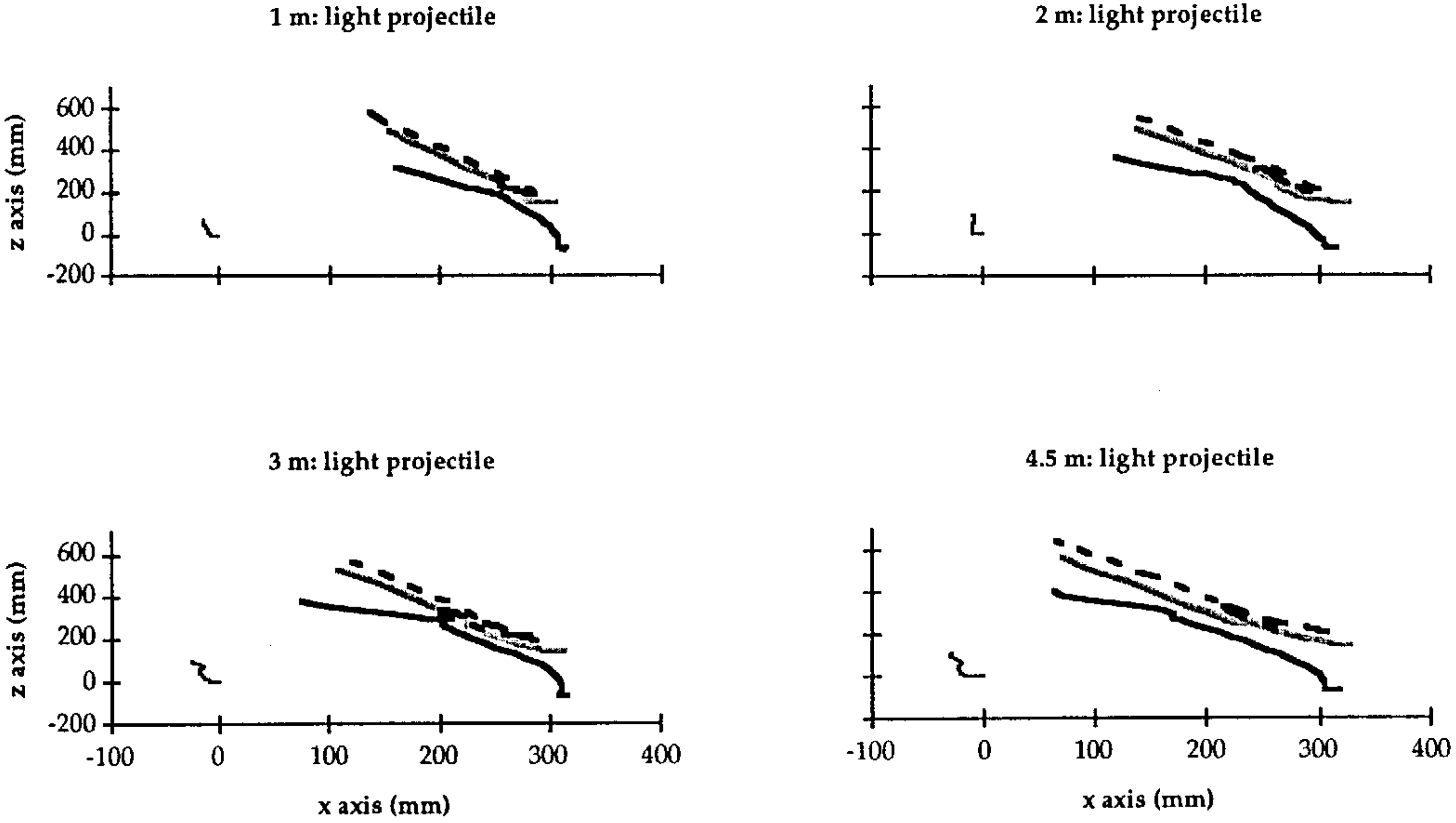


Figure 3.13 Trajectories of a rotation throw in the sagittal plane using a light projectile over different distances —— = Shoulder joint, —— = Elbow joint, —— = Wrist joint, - - - - = 3rd Metacapophalangeal joint

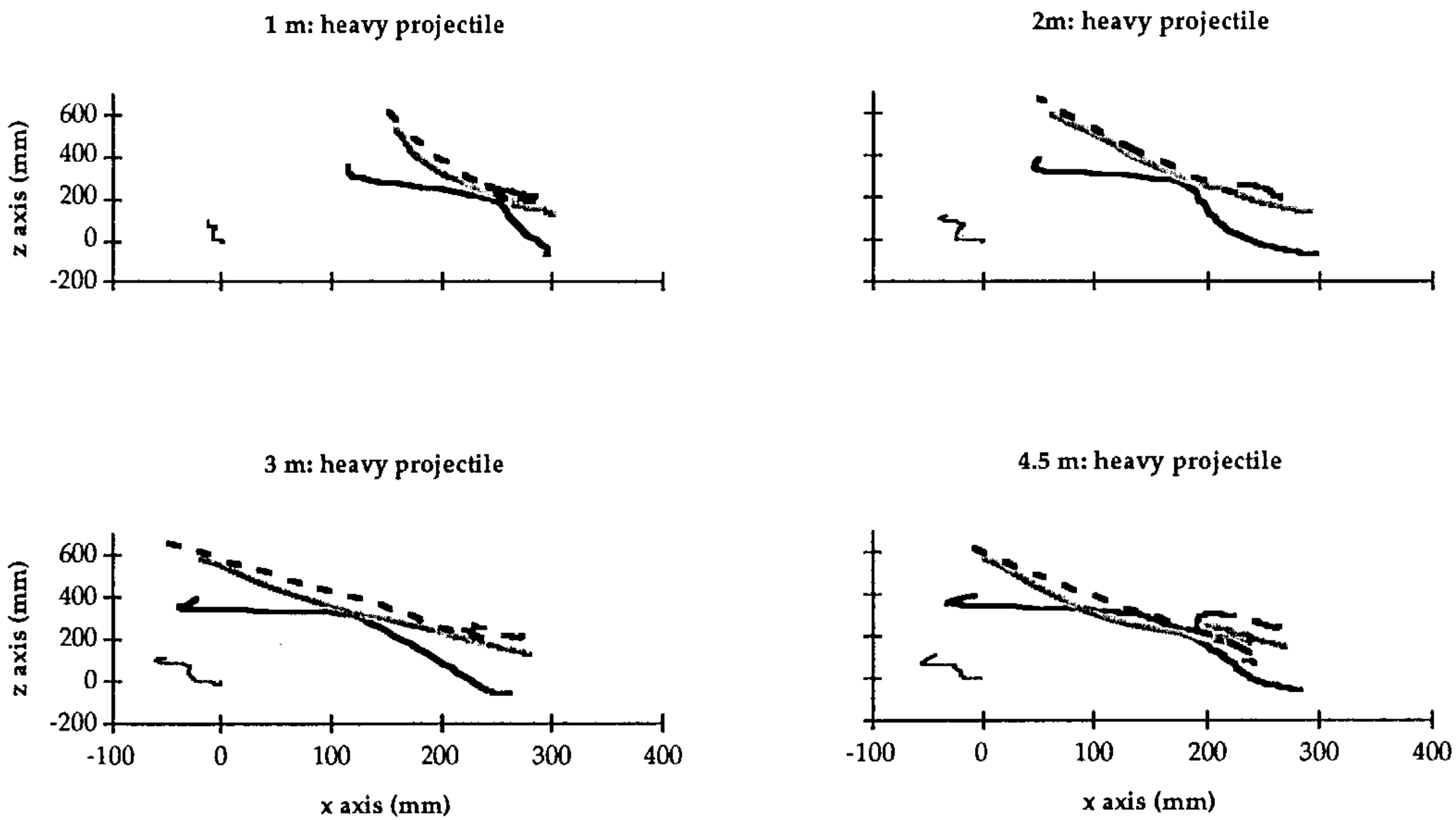


Figure 3.14 Trajectories of a rotation throw in the sagittal plane using a heavy projectile over different distances

____ = Shoulder joint, ____ = Elbow joint, ____ = Wrist joint, ---- = 3rd Metacapophalangeal joint

By using visual comparison, the trajectories suggest that as the distance thrown increased, the range of motion increased. The trajectories of the overarm throw imply that a heavy projectile required a large angular motion when compared with a light projectile thrown over the same distance. Despite the fact that Stage Two of the study was not designed to test hypotheses, the results obtained suggest that the Hypotheses Two for Stage One of the study which predict that variation in distance thrown, weight of the projectile, and area of the target will all influence the pattern of throwing could be supported.

3.10.6.2 Position of cameras and markers and instructions to subjects

The maximum number of cameras which could be used in the study was three. Thus the position of the cameras was an important component of the data collection process. The overhead camera was introduced into Stage Two of the study. It was intended to solve the problem of missing markers at the wrist, hand and fingers when subjects chose a throw involving rotation. Despite the fact that the overhead camera could detect these markers on the upper limb for almost every frame, some markers were still only able to be viewed by one camera for a number of frames. The detection of markers at the wrist, hand and fingers in some phases of an overarm and underarm throw was compromised because even with the overhead camera in place, only two camera views were available for digitisation in Stage Two of the study. Markers were generally lost because some parts of the body obscured the view of the cameras. Markers at the tip of the index finger and thumb were most frequently missed.

Markers falling off was another problem. This occurred when subjects threw strongly over greater distances. Most commonly markers at the elbow and the wrist joints were affected because they were mounted on an extension rod at these locations.

This second stage of the study demonstrated that the use of only three cameras was insufficient for the detection of all markers in at least two camera views for each of the types of throwing movement used, that is, the overarm, underarm and rotation throws.

Instruction about the throwing patterns was still given to subjects in Stage Two because this stage did not aim to test the effect of changes in patterns of throwing as an independent variable. However, alteration of throwing styles was not demonstrated in either subjects, despite of the fact that the distances thrown were greater than those in Stage One.

3.10.7 Discussion

3.10.7.1 Movement trajectories

The pattern of throwing as delineated by the trajectories shown in Figures 3.9 to 3.14 did not change as the distance thrown increased. These results were true for both the heavy and the light projectile conditions. This may be explained in several ways. The manipulation of the independent variable distance was insufficient to cause an alteration in the throwing pattern, that is the distance thrown was too short. Secondly the instruction given to subjects might limit a changing pattern as the distance thrown increased. Subjects were asked to use the same style of throwing over all of the distances thrown. These two problems were identified as essential elements for further investigation in the main study.

However, the heavy projectile demonstrated a wider range of motion than the light weight projectile in some patterns at the greatest distance. These results suggest that a heavy projectile is more likely to facilitate the alteration of the pattern of movement than a light projectile. Therefore only the heavy projectile was chosen for further examination in the main study. Weight of the projectile was not manipulated as an independent variable in Stage Three because it was difficult to increase the load without changing its size. Furthermore, leather balls filled with lead shot used in Stage One and Two of the study were sometimes broken during the recording period. Thus, a plastic ball was employed in Stage Three and the weight was reduced to 500 g. Moreover, plastic balls also proved to be suitable for making a switch which could be used in the hand to ensure the precise temporal position of the starting position for each throw which assured that the releasing event could be defined. This plastic ball was about the same size as a tennis ball, except that it was heavier. Thus, it should not cause an unfamiliar feeling when subjects held it.

3.10.7.2 Position of cameras and markers and instructions to subjects

The overhead camera was introduced to the study because markers at the fingers, hand, and wrist joint could be seen for any pattern of throwing. In spite of these facts, the top view camera presented the problem of separation of markers when most of markers were lined up in the same view. For example, when the elbow joint flexed in the overarm throw and when the arm is swung with extension of the elbow joint in the underarm throw.

Thus to eliminate the problem of missing markers at the wrist, hand and fingers and to get a good view of markers which were essential for the calculation of the joint angles of interest, the following changes were identified as important for the final stage of the study. These changes also included the problem of instruction which was implied from the results of Stage One.

a) Markers at the tip of the first and the second fingers were removed for the main study. Thus all cameras could be set at the right side of subjects which improved the view of all other markers. Thus the top view camera was not employed in Stage Three of the study.

b) Contact glue was used to fix the extension stick to the base marker to make those markers on a rod extension more secure. For the elbow joint two elastic tapes were also used to fasten the marker to the lateral epicondyle.

c) Instructions given to subjects emphasised the free choice of throwing styles. Detail of the instructions given to subjects in the principle study have been described in Section 3.11.4.

The emphasis of the Stage Three of the study was on the movement of all joints of the upper extremity except the joints of the fingers in both the overarm and underarm throwing patterns.

3.10.8 Summary

Completion of the Stage Two of the study led to modification for the protocol of the main study. Only the distance thrown was manipulated as an independent variable or a proposed control parameter. The conclusion of the position of cameras and markers has been discussed. Improvement of the marker stability and instructions to subjects have been examined and defined for the main study.

3.11 Stage Three, the Principal Study

3.11.1 Hypotheses

Hypothesis 1: Calculated joint angles and clinical joint angles

Angular displacement measured using three-dimensional motion analysis employed in the study will show no significant difference when compares to the angle measured by the standard clinical method.

Hypotheses 2: Number of throwing patterns

a) Subjects, given a choice, will demonstrate more than one style in executing the defined throwing task.

b) At least two throwing patterns, the overarm and the underarm throw, will be demonstrated when subjects freely selected throwing patterns.

Hypotheses 3: Phase transition

a) A phase transition will be demonstrated by changes in proposed order parameters as the distance thrown increases.

b) Changes in the throwing pattern in individual subjects may occur in the direction of the overarm throw or in direction of the underarm throw.

Hypotheses 4: Relative timing

In the present study, relative timing was defined as the ratios of movement durations, that is, the preparation phase (Prep) and the releasing phase (Rel) over the total movement time (TMT). That is the ratios of the Prep/TMT, Rel/TMT, and Rel/Prep.

a) There will be no significant differences in the relative timing of the overarm throw and the underarm throw as the distance thrown of a projectile increases.

b) There will be no significant difference in the relative timing between the overarm and the underarm throw at the same distance thrown.

Hypotheses 5: Angular displacement

a) Each throwing pattern can be defined by the changing of angular displacement over time of all joint angles of the throwing limb.

b) The range of joint angles will be greater when throwing to the longer distance.

c) Limitation of the elbow joint angle using an orthosis will force a change in throwing styles as the distance thrown increases.

Hypotheses 6: Releasing joint angle

a) There will be no significant difference in the releasing joint angles of the overarm and the underarm throw as the distance thrown increases.

b) There will be no significant difference in the releasing joint angles between the overarm and the underarm throw for the same distance thrown.

Hypotheses 7: Angular velocity

a) Angular velocity of all joint angles at the releasing point will be greater when throwing to the longer distances.

b) Both the overarm and the underarm throw will show a sequential peak angular velocity which is clearly shown at the longest distance thrown.

Hypotheses 8: Order parameter

a) More than one order parameter is required to characterise the throwing pattern.

b) Trajectories of movement can differentiate throwing patterns as the distance thrown increases for the overarm and the underarm throw.

c) Trajectories of movement can differentiate the throwing pattern between the overarm and the underarm throw.

d) Relationships between angular displacement and angular velocity or between angular displacement of one joint related to another joint as illustrated in phase plane plots, angle-angle plots, and relative phase plots can act as order parameters for the throwing movement.

Hypothesis 9: Measurement of coordination

Visual comparison and cross-correlation provide the same information when used to measure pattern of coordinated movement, phase plane plots and angle-angle plots, as the distance thrown increases.

3.11.2 Equipment set up

An adjustable chair was placed at the focusing point of all cameras. To avoid any limitation of the movement pattern, no tables were used in this final stage of the investigation. Mats were positioned in front of the subject and were labelled to ten distances as targets. The first seven targets had an area of 0.53 m^2 and they were 0.6, 1.06, 1.52, 1.98, 2.44, 2.90, 3.36 m from each subject. Targets number eight, nine, and ten were 4.05, 5.20, and 6.91 meters and had areas of 1.06, 1.59, 2.37 m^2 respectively.

Three copper plates were attached to a plastic ball weighing 500 g. Two copper plates were also placed on the index and the middle finger of the subject's right hand. The copper acted as a switch. Subjects were told to hold the ball so that all copper plates were touching. The external circuits were turned on and off when subjects held or released the ball. These circuits were also connected to the synchronising unit. By this method, the point at which the subjects released the ball could be detected using the cursor light which appeared on the monitor. Figure 3.3 shows balls, two copper plates and the external circuit.

Subjects rested their throwing hand on a wooden box which was 20 cm wide, 10 cm long and 10 cm high. This box was fixed to the subjects' right thigh using Velcro straps. The position of the box was arranged so that the subjects' shoulder was in the neutral position while the subjects' hand rested on the box (Figure 3.15). A pneumatic button which was flat and had a round shape was secured on the box. This button was connected to a synchronising unit and produced a signal light on the screen when it was activated. Its function was to synchronise the video frames and to pinpoint the starting point of the throw as had been done in the second stage of the study. Figure 3.16 displays the starting position and the position of all markers used in Stage Three.

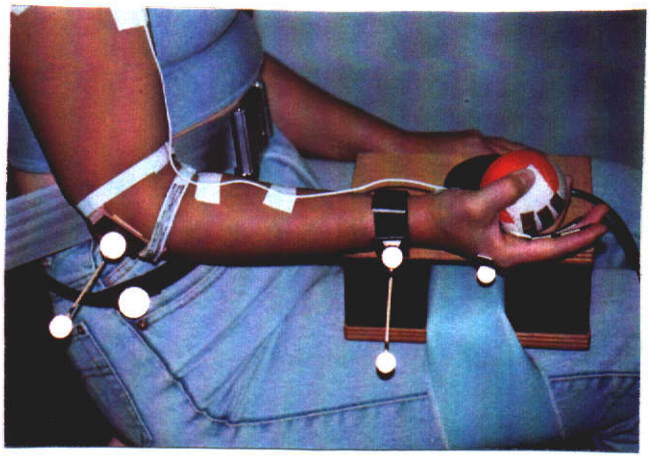


Figure 3.15 The photograph shows the position of a wooden box on subject's thigh and the method of holding a ball so that the copper switch is turned on and off.

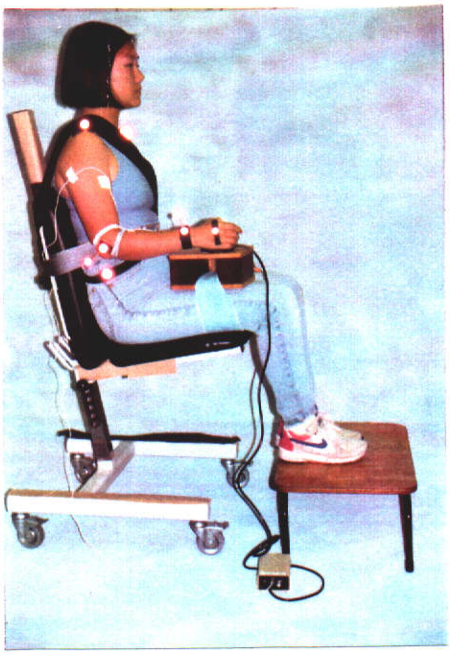


Figure 3.16 A subject with all markers in the starting position

Three cameras (Panasonic F15) were used and adjusted as explained in Section 3.7.2. The first camera was placed on the right hand side of the subjects at a distance of 6.15 m. The second camera was positioned in front of the subjects and slightly toward the right side, at a distance of 6.70 m. The third camera was set behind each subject at 7.20 m away (Figure 3.17). The height of the first, the second and the third cameras from the floor was 0.94, 1.14 and 1.04 m respectively. The overhead camera was not used because it did not solve any of the problems as discussed in Section 3.10.7.2.

3.11.3 Task

Subjects sat on an adjustable chair in front of the mats. There were two testing sequences in this stage of the study. The first sequence allowed subjects to use any style of throwing. In addition an elbow orthosis (Figure 3.18) which was set to move from 95-120 degrees was also used in this sequence to test the effect of limitation of the elbow joint on the pattern of throwing. The range of motion limited by an elbow orthosis was set in flexion movement because it seems to disturb throwing motion more than extension of the elbow joint. Furthermore, adjusting range of the elbow orthosis also depended on the specific characteristics of the hinge of the orthosis used in the study.

In the second testing sequence, the styles of throwing were defined for the subjects. They were told to use an underarm and an overarm pattern and to throw the ball to ten different distances in a randomly assigned order. The ball used for both tests weighed 500 g.

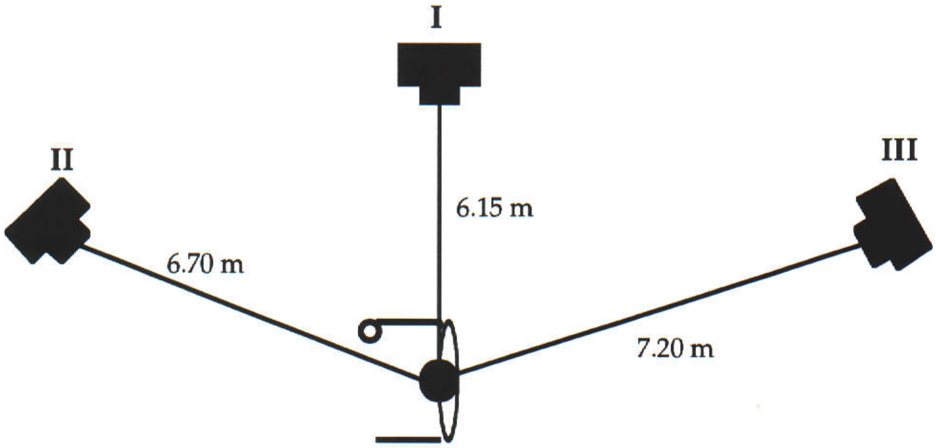


Figure 3.17 The set up of cameras used in data collection in the main study

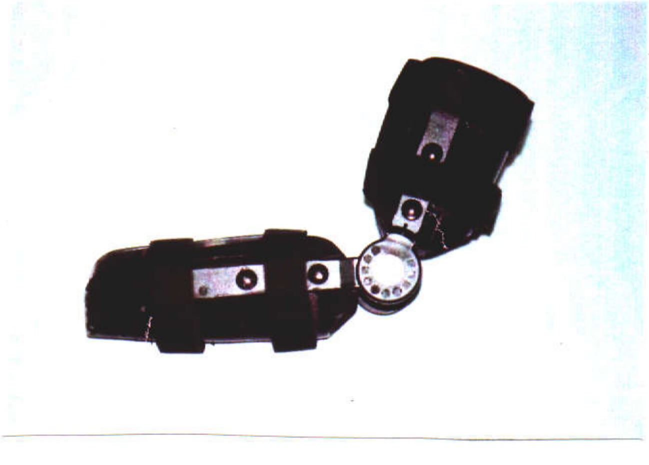


Figure 3.18 The elbow orthosis with the adjustable hinge.

3.11.4 Protocol

Unlike the first and the second stage of the study, only eight markers were placed on the subjects. These were the same as explained in Section 3.7.3 except that there were no markers on the tip of the thumb or the index finger. The height of the chair was adjusted so that subjects felt comfortable and all markers were seen by at least two cameras.

The procedure was divided into two sequences. The first was aimed at observing the pattern of throwing when the distance increased with and without the elbow orthosis. Subjects practised using their own styles and no information about the style of throwing was provided. Subjects were told to use the pattern of movement in which they could perform confidently and successfully for each distance. They could also change the pattern when the distance of the throw increased. A period of practice was allowed so that subjects became accustomed to the task. Then an elbow orthosis was strapped to the subjects' right limb and they were allowed to practice throwing again. For the first testing sequence, they were instructed to throw the ball from the closest to the farthest distance in sequence having one trial for each distance.

The second testing sequence was intended to identify the invariant characteristics of the different patterns of throwing. Subjects were told to throw a ball using the underarm and overarm pattern to each target in random order. The projectile had to hit within the prescribed target area at least three times. Subjects could throw up to five times for each distance.

To reduce any influence of the instruction upon the styles of throwing, the first testing sequence was always completed before the second testing sequence started.

3.11.5 Data management

The digitising process was accomplished as explained in Section 3.8.1. In the principal study, additional switches were installed to detect the beginning and the end of the activity as described in Section 3.11.2. The digitising process started 10 pictures before the first cursor light and stopped 20 pictures after the finishing point.

Sixteen markers (B, C, E, F, H, I, K, L, N, O, Q, R, T, U, W, X see Figure 3.1) on the calibration frame were digitised. Calibration error for this study ranged from 1.057-2.344, 1.452-3.036 and 1.144-2.038 mm in the x, y, and z dimensions respectively. The maximum RMS error for the calibration process was 2.803-3.79 mm.

The recording of the first testing sequence of the principal study was checked to identify the differences in the style of throwing as the distance increased. Only descriptive data will be reported. Complete digitisation was undertaken only for the second testing sequence of this main study. One trial of each throwing distance was digitised. The last trial in which the subject threw the ball was chosen. There were 320 trials in this stage of the study. Only 317 trials were analysed. One trial was omitted due to loss of markers at the wrist and the hand from the view of all cameras. The other two trials were omitted from the study because subjects could not throw to the required distance.

In order to report the results of the two testing sequences, it was found necessary to ensure that the frame of reference for each of the joint angles of interest could be compared among the subjects. The next chapter, therefore, will present the analytical methodology used to deal with the data.

The results and discussion related to Stage Three of the study will be presented in Chapter 5 and 6 respectively. Hypothesis One for Stage Three will also be dealt with in Chapter Four. This is essential to the presentation of the remainder of the results in Chapter 5.

3.12. Summary

The basic methodology used in Stage Three of the study including the principle hypotheses and research design have been described. This included the detail experimental procedures in Stage Three of the study. The results and the discussion of the first and second stages are also included. The emphasis is on different processes in each stage. The evolution of the experimental protocol was developed from the results of the first and the second stages of the study.

Chapter 4

Analytical procedures

> *In Dynamic Patterns, it turns out that rather abstract variables are required to describe the collective or coordinative behavior of complex living things.*
>
> *- J. A. Scott Kelso*

4.1 Calculation of the kinematic parameters

4.1.1 Frame of reference

The three-dimensional coordinate data collected from the Peak System were derived from the coordinate system of the calibration frame. The calibration frame was set up for each subject at the time of filming. The x, y, and z axes of the calibration frame have been defined by the manufacturer. Even though the frame was placed in the same place each time, its position was not exactly the same for every subject. So the calibration axes and planes varied from subject to subject and there was no consistent relationship between these and the axes and planes of the body. Thus calculation of joint angles which have more than one degree of freedom (for example shoulder flexion and extension and shoulder adduction and abduction relative to the reference frame) could not be compared between subjects.

To compare the data between subjects and to calculate the joint angle, translation and rotation of the reference axes was necessary. The origin or the zero coordination was translated to the marker at the joint of interest. The x and/or y axes were rotated from the calibration frame to the markers attached on the subject. For example, to calculate shoulder flexion and extension, the zero coordination was translated to the right acromion process marker, the x and y axes were rotated to the tubercle of iliac crest and the left acromion process marker respectively. By this means the angular displacements were calculated from the same frame of reference relative to the body for every subject.

Although the Peak software allows the calculation of the joint angles and the translation and rotation of axes of the coordinate system, the methodology employed by the software was unsuitable for this project. The system software only allows for rotation of a point to an axis (x, y, or z) but not to the plane of the movement. So rotation of the two external lines to the two axes could not be done correctly unless these lines were perpendicular to each other. For these reasons, angular movements were calculated from the filtered coordinate data using macro sheets written in Microsoft Excel.

4.1.2 Angular displacement

The angular displacement was the datum fundamental to this evaluation. Seven joint angles of the upper extremity were calculated. These were, shoulder flexion and extension, shoulder adduction and abduction, shoulder rotation, elbow flexion and extension, forearm rotation, wrist flexion and extension and wrist ulnar and radial deviation.

For the shoulder and wrist joints, which have more than one degree of freedom, the method of calculation of the joint angle was not straight forward. Euler's technique (Woltring, 1991) was used to determine angular displacements. This technique was defined anatomical reference planes in each body segment in the anatomical position (Cole et al., 1993). The coordinate systems of markers are fixed in each segment based on these reference planes (Cole et al., 1993). Thus angular joint motion of the shoulder and the wrist joints in each plane can be calculated in a specified sequence. A detailed explanation of joint angle calculation has been described in Chapter 4, Section 4.1.1 & 4.1.2.

The calculated angular displacements in the present study were used as input data to simulate the movement from a dynamic model of upper limb written by von Konsky (1994). A computer graphic model of an identical motion was compared with the movement of the subjects recorded on video tape. This result provided the basis for establishing the accuracy of the calculation method employed in the present study.

The accuracy of angular displacement empolyed in the study has been discussed and quantified in some aspects in Section 4.3.2.

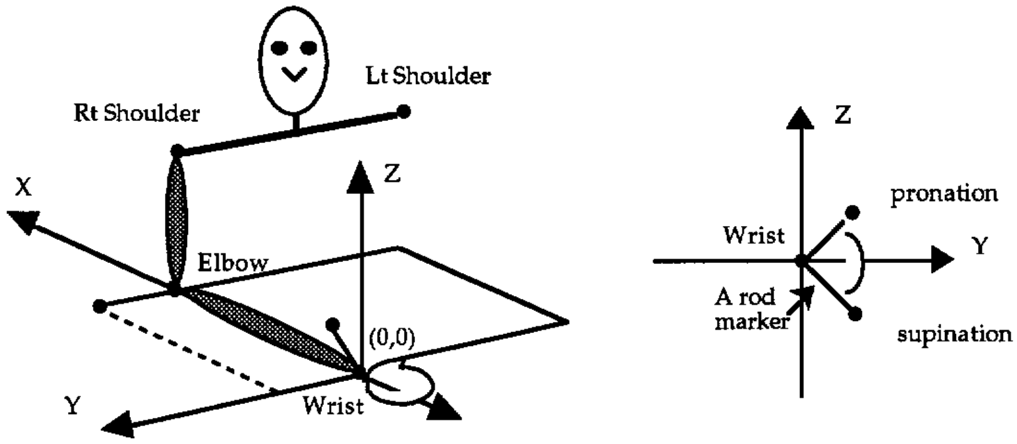


Figure 4.1 Diagrams for the calculation of shoulder elevation. **A)** The projected angle of arm segment on the xy plane was first determined as shoulder adduction and abduction. **B)** After the elbow marker was rotated onto the xz-plane, shoulder flexion and extension was then computed. The z axis was projected out of the paper plane.

4.1.2.1 Shoulder complex elevation

Shoulder elevation can occur in either the sagittal (flexion and extension) or the frontal plane (adduction and abduction). In order to differentiate the movements of the shoulder joints in each plane, the marker at the right acromion process was translated to the origin. The marker at the tubercle of the iliac crest was rotated to the x-axis and the marker at the left acromion process was rotated onto the xy-plane (Figure 4.1). So the xy-plane was the frontal plane and the xz-plane was the sagittal plane. Shoulder adduction and abduction was calculated first then shoulder flexion and extension and finally shoulder rotation. The projected angle of the arm segment onto the xy or the frontal plane was described as adduction and abduction of the shoulder joint. The marker at the lateral epicondyle of the elbow joint was then rotated onto the xz plane. Flexion and extension components of the shoulder joint were then determined. Flexion and adduction had a positive sign and extension and abduction had a negative sign.

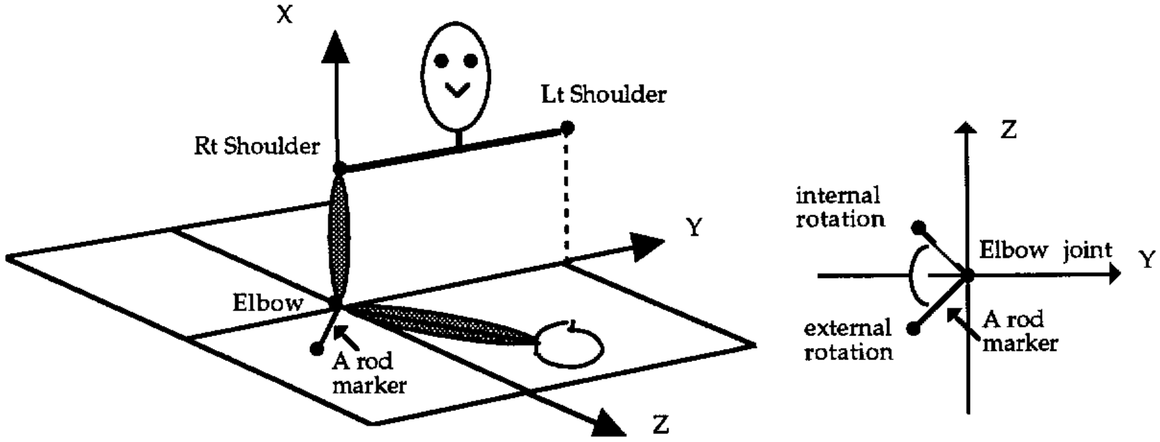


Figure 4.2 The diagram shows axes for the calculation of internal and external rotation of the shoulder joint.

4.1.2.2 Shoulder rotation

Internal and external rotation of the shoulder occur around the longitudinal axis of the arm. In the clinical situation, the forearm is used as a moving arm for this measurement such that the elbow joint is held at 90 degrees. The present study used a rod placed at the lateral epicondyle of the humerus as the moving arm. To fix a frame of reference, the marker at the lateral epicondyle was translated to the zero coordinate position. The right shoulder marker was rotated to the x-axis and the left shoulder marker was rotated onto the xy-plane (Figure 4.2). From these processes, the yz-plane was made perpendicular to the axis of the arm in every position. So rotation of the shoulder could be calculated from the projected angle of the rod attached at the elbow joint onto the yz-plane. Internal rotation had a positive sign and external rotation had a negative sign.

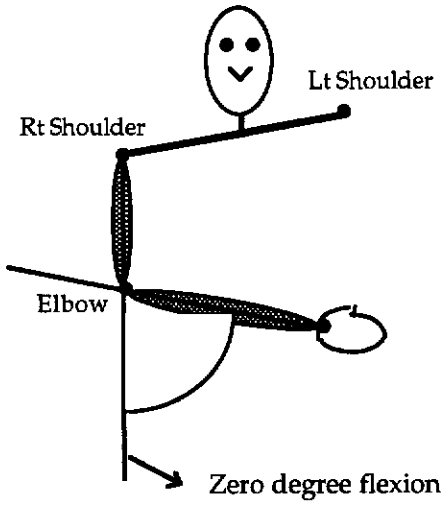


Figure 4.3 The diagram shows elbow joint angle and the zero degree position.

4.1.2.3 Elbow flexion/extension

Calculation of the elbow angle can be done in any frame of axes, because movement of the elbow joint occurs only in one plane. In this study, only translation of the origin to the elbow joint was performed. The zero degree of flexion was defined as the fully extended position of the elbow joint (Figure 4.3). Flexion had a positive sign and extension had a negative sign.

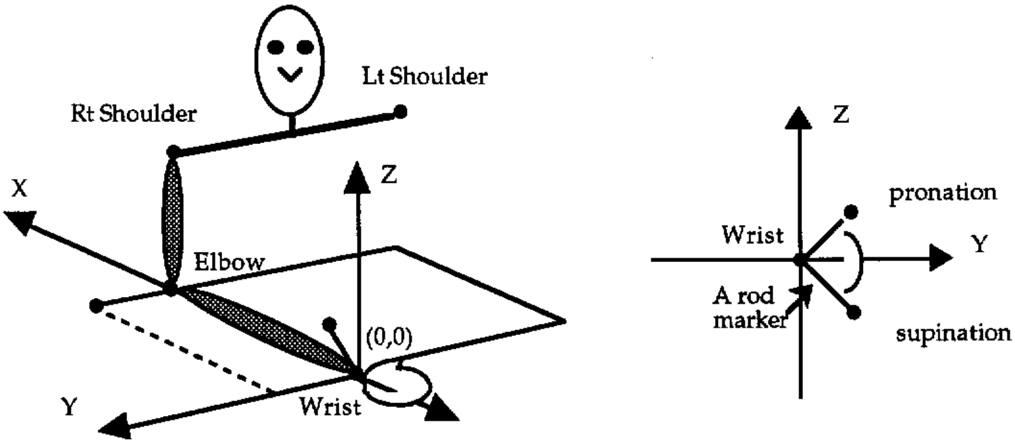


Figure 4.4 The diagram shows axes for the calculation of pronation and supination of the radioulnar joint.

4.1.2.4 Forearm rotation

Pronation and supination of the forearm occur around the longitudinal axis of the forearm. To measure these movements, a rod attached at the wrist joint was used as the moving arm. The marker at the wrist joint was set as the origin. The marker at the elbow joint was rotated to the x-axis and the marker at the end of the rod attached at the elbow joint was rotated onto the xy-plane. So forearm rotation could be calculated as the projected angle of a rod at the wrist joint onto the yz-plane (Figure 4.4). Pronation of the forearm had a positive sign and supination had a negative sign.

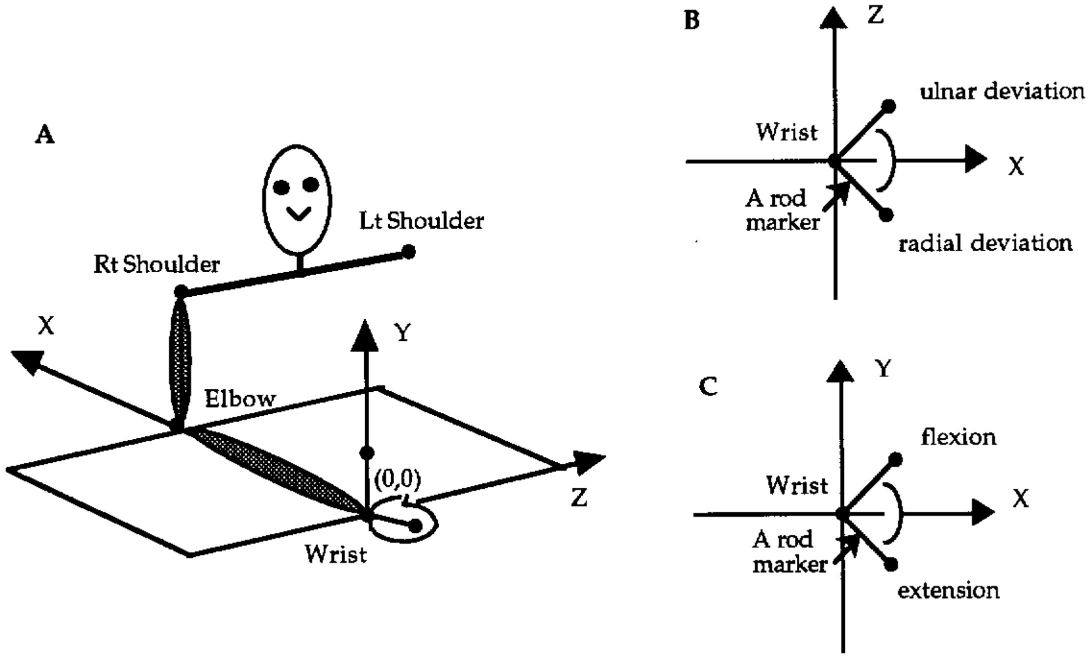


Figure 4.5 A) Diagram for the calculation of wrist motions. **B)** The projected angle of the hand segment on the xz plane was calculated as the wrist ulnar and radial deviation first. **C)** After the hand segment was rotated onto xy-plane, determination of wrist flexion and extension was then performed.

4.1.2.5 Wrist flexion/extension and adduction/abduction

A wrist joint has two degrees of freedom. Flexion and extension occur in the sagittal plane whereas ulnar and radial deviation occur in the frontal plane. To measure these movements, the marker at the wrist joint was translated to the origin. The marker at the elbow joint was rotated to the x-axis and the marker at the end of a rod attached at the wrist was rotated onto the xy-plane. So the frontal plane of the wrist joint was the xz-plane and the sagittal plane was the xy-plane for every position of the wrist and hand in space (Figure 4.5). The projected angle of the third metacarpal bone onto the xz-plane was calculated first as ulnar and radial deviation. Then the marker at the head of the third metacarpal bone was rotated onto the xy-plane. The projected angle of the third metacarpal bone onto the xy-plane was measured as a wrist flexion and extension. Wrist flexion and ulnar deviation had a positive sign and wrist extension and radial deviation had a negative sign.

4.1.3 Angular velocity

Angular velocity was calculated from the angular displacement data using the following equations (Winter, 1990).

$$\omega_i = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t}$$

Whereas w_i is the velocity at the time i, q_i is the displacement data at the time i, i is an instant in time, and t is the time increment.

4.1.4 Angular acceleration

Angular acceleration was calculated from the angular displacement data using the following equations (Winter, 1990).

$$\alpha_i = \frac{(\theta_{i+1} - 2\theta_i + \theta_{i-1})}{\Delta t^2}$$

Whereas a_i is the angular acceleration at the time i, q_i is the angular displacement data at the time i, i is an instant in time, and Δt is the time between consecutive samples q_{i+1} and q_i.

4.2 Calculation of the other parameters

4.2.1 Trajectory

Trajectory is the motion of a point on the plane of interest to the movement. The movement plane of each subject was determined by the position of the calibration frame at the time of filming. This frame determined the global reference. To compare the profile of each joint between subjects, the global coordinate position had to be redefined to the common coordinate system for all subjects. Markers at the right and the left shoulder joint and at the tubercle of the right iliac crest in the first picture were chosen to define the reference frame. The zero coordinate point was translated to the right shoulder joint. The x axis was rotated to the iliac tubercle and the y axis was rotated to the xy plane formed by these three markers. By this procedure, the xz plane represented the sagittal plane and the xy plane reflected the frontal plane of the subjects. Trajectories on the xz plane were selected.

4.2.2 Time normalisation

Time normalisation was performed using direct linear proportion method. All data files were normalised onto the interval [0;100].

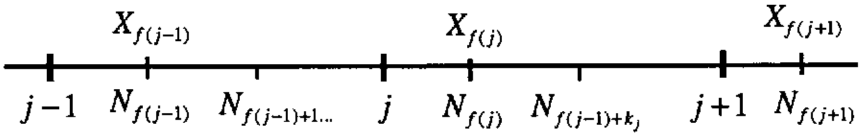
Let $g:\{i,\dots,n\} \rightarrow \{0,\dots,N\},(N=100)$

$$g(i) := \frac{N(i-1)}{n-1}, i = 1,\dots,n$$

For $j = 1,\dots N$:

let $f(j) := \min\{i \mid j \le g(i), i = 1,\dots,n\}$

and $N_{f(j)} := g(f(j)) = gof(j)$



For each $j = 1,\dots N$:

Let $k_j := \max\{l \mid N_{f(j-1)+l} < j+1, l \ge 0\}$

Clearly $k_j \ge 1$

Define weights w_j^l for $X_{f(j-1)+l}$ $l = 0,\dots,k_j$

such that 1) $w_j^l \ge 0$

2) $\sum_{l=0}^{k_j} w_j^l = 1$

and define the new data point

$$Y_j = \sum_{l=0}^{k_j} w_j^l X_{f(j-1)+l}$$

at the point j.

If $k_j = 1$ for all j, that is $N_{f(j-1)} < j \le N_{f(j)}$ and $N_{f(j-1)} = N_{f(j)-1}$

then use

$$Yj = \frac{N_{f(j)} - j}{N_{f(j)} - N_{f(j-1)}} X_{f(j-1)} + \frac{j - N_{f(j-1)}}{N_{f(j)} - N_{f(j-1)}} X_{f(j)}$$

4.2.3 Amplitude normalisation

The magnitude of angular displacement and angular velocity were normalised to the range of -1 and 1 using the following equation (Scholz, 1993b). The maximum and the minimum value were determined from the data file between the starting and the releasing points.

$$X_{norm} = \frac{2X_i}{(X_{\max} - X_{\min})} - \frac{(X_{\max} + X_{\min})}{(X_{\max} - X_{\min})}$$

Whereas X_{norm} is the normalised angular displacement or angular velocity, X_i is the actual angular displacement or angular velocity at the sample i, $X_{\max}$ is the maximum angular displacement or angular velocity and $X_{\min}$ is the minimum angular displacement or angular velocity over the interval from the starting to the releasing point.

4.2.4 Relative phase

Relative phase was calculated from the time and amplitude normalised data. The mathematical equation of the relative phase was defined as the difference between the movement phase of each individual joint for a pair of joints (Scholz, 1993b).

$$\varnothing_i = \tan^{-1}(AVi_{norm}/ADi_{norm})$$

$\varnothing_i$ is the movement phase of a particular joint motion, AV_{norm} is the normalised angular velocity and AD_{norm} is the normalised angular displacement data.

The relative phase is defined, for example for shoulder flexion and elbow flexion.

$$\varnothing_{Sf\text{-}E} = \varnothing_{Sf} - \varnothing_{Ef}$$

$\varnothing_{Sf\text{-}E}$ is the relative phase between shoulder flexion and elbow flexion, $\varnothing_{Sf}$ is the movement phase of shoulder flexion and extension and $\varnothing_{Ef}$ is the movement phase of elbow flexion and extension

4.2.5 Joint moments data

Joint moment data were calculated from the program specific to the study written by Dr Timothy M. Baker from Queensland University of Technology (1996(in press)). The calculation was based on the inverse dynamic method and an assumption, that is, the position of markers attached at the joints of the upper limb was assumed to be located at the centre of the joint axis. No transformation used to relocate joint centres with respect to marker locations. The angular displacement, angular velocity, angular acceleration and the anthropometric data were needed to enter into the program. The anthropometric data used for the calculation are presented in Appendix D.

The results were used to compare the overarm and the underarm throw only. All subjects threw an equal weight ball using both throwing styles, therefore, any errors with respect to the assumption of the joint axis should affect the results in both patterns in a similar way.

The mean data of angular displacement, angular velocity and angular acceleration were used to calculate the joint moments for each distance thrown in both throwing patterns. Therefore, there is no variance of the moments data for each distance thrown.

4.2.6 Mechanical power and work of muscles

Muscle mechanical power for each joint angle was calculated from the joint moments data and the mean angular velocity using the following equation (Winter, 1990).

$$P_m = M_i \omega_i$$

Where P_m is the muscle power (watts, W), M_i is the net muscle moment (Nm) and ω_i is the joint angular velocity (radian/sec).

From Winter (1990), the mechanical work of muscles was equal to the product of power and time, and it is measured in joules (1 J = 1 W sec). Thus calculation of muscle work was performed by integrating the power data.

The summation of the mechanical work of muscles for all joint angles was calculated for each distance thrown. The positive, the negative and the total work for each distance thrown were determined. Positive and negative work is defined as work done during a concentric and eccentric contraction

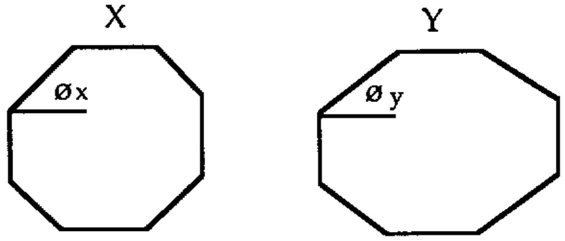


Figure 4.6 Two octagons with sides of unequal length for the application of the cross-correlation function.

respectively (Winter, 1990). The integral of power over time is the net work done by the muscle and represents the generated energy transferred from the muscles to the limb in concentric contraction and a flow of energy from limbs into the muscles (absorption) in eccentric contraction (Winter, 1990).

4.2.7 Cross-correlation

Cross correlation as described by (Sparrow et al., 1987) was used to determine two aspects of movement patterns in the study. The first was the difference between the joint angle curves of each trial in the reliability test (Section 4.3.1). The second was the difference between the angle - angle plots or the phase plane plots as the independent variables changed.

The cross correlation function is defined as:

$$R_{xy(j)} = \frac{1}{n}\sum_{i=1}^{n} Cos\left(\theta_{x,i} - \theta_{y,i+j}\right) \times \frac{\left|\overline{X}_i\right|}{\left|\overline{Y}_{i+j}\right|} \text{ if } \left|\overline{X}_i\right| \le \left|\overline{Y}_{i+j}\right|$$

or

$$R_{xy(j)} = \frac{1}{n}\sum_{i=1}^{n} Cos\left(\theta_{x,i} - \theta_{y,i+j}\right) \times \frac{\left|\overline{Y}_{i+j}\right|}{\left|\overline{X}_i\right|} \text{ if } \left|\overline{X}_i\right| > \left|\overline{Y}_{i+j}\right|$$

where R_{xy} has n-1 values for j = 0, 1, 2 . . . n-1. $\theta_{x,i}$ and $\theta_{y,i+j}$ are the angles from the horizontal axis of the ith and $i + j$th segments from the X and Y segments respectively (Figure 4.6). $\left|\overline{X}_i\right|$ and $\left|\overline{Y}_{i+j}\right|$ are the lengths of the ith and the $i + j$th segments from the figures X and Y being compared.

The equation will give the cross-correlation coefficient equal to unity when the two figures have the same angle between segments, equal segment lengths, and similar orientations.

4.3 Reliability and validity of the measurement

4.3.1 Reliability of the angular displacement within a subject

The angular displacement of the joints of the upper limb was one of the necessary parameters used in the study. The experimental protocol required that all subjects repeated the task at least three times for each distance, using the same pattern of the movement for each repetition.

The time necessary to digitise all three trials for all subjects presented a problem. In order to reduce the number of trials to be digitised it was found essential to establish the degree to which each performance could be considered the same as all other performances on the same occasion. This requirement represented Stage One of the study.

Four subjects were asked to perform three trials of the task for each of the nominated distances in the Stage One of the study (Chapter 3, Section 3.9). Digitising was completed for all trials and the angular displacements of the upper limb as described in Section 4.1.2 were calculated and then normalised to 100 data points.

For each subject, seven joint angles of the placing and throwing movement for the same distance and the same condition were separately compared. Three curves of angular displacement were statistically evaluated for similarity. A modified equation of cross-correlation which has been described by (Sparrow et al., 1987) was used. The cross-correlation formula has been explained in the Section 4.2.7. A chain encoded method (Sparrow et al., 1987) was applied to the angular displacement curves. That is, each trial for each of the joint angles was divided into segments so that the distance between every second data point formed a short segment. The corresponding segments of each joint angle for each trial were then compared. The calculation was performed only at the case of $i = 1$ and $j = 0$ since the purpose of the test was to determined the repeatability of the angular displacement profiles not the shift of the joint angle phase.

The R_{xy} of the seven joint angles in the same conditions of the individual subject were averaged (Table 4.1). The maximum and the minimum values of the cross-correlation coefficient are presented in Table 4.2. The R_{xy} for the shoulder and elbow joints varied from .80 to .99 and .69 to .92 for the radioulnar and wrist joints.

In summary, the results showed that subjects performed the task consistently under the same conditions. Thus it was established that in the next stage of the study, only one trial needed to be examined.

4.3.2 Comparison of calculated joint angles and clinical joint angles measured by a goniometer

All the parameters in the study were calculated from the coordinate data of the markers which were placed on the subjects' body segments. The positions of the markers determined the magnitude of these parameters. To evaluate the extent to which comparison of the results between the subjects could be made, the angular displacement was compared with angles measured by a goniometer or the standard position at which the zero position and the maximum and the minimum range of joint angles are defined in clinical practice.

The determination for this aspect was conducted during the main study before the subjects were asked to perform any tasks. All sixteen subjects seated in position on an adjustable chair with their trunks fixed to the backrest were included. All the markers were attached on the subjects' upper limb and trunk as explained in the Chapter 3, Section 3.7.3. Subjects were asked to hold their right upper extremity in a series of set positions for a few seconds while the position was recorded.

Table 4.1 Cross-correlation coefficient of seven joint angles under different conditions. P1 and P2 denotes the first and second pattern of movement respectively. H = Heavy projectile, L = Light projectile, S = Small size target, T = Large size target, A, B and C are the distances thrown which were equal to 1, 1.5 and 2 times the length of the arm respectively

PATTERN	Shfl/ex	Shad/ab	Shrot	Elb	Forrot	Wrfl/ex	Wrul/ra
P1HSA	0.95	0.98	0.95	0.89	0.91	0.86	0.89
P1HSB	0.92	0.97	0.92	0.86	0.81	0.83	0.76
P1HSC	0.91	0.93	0.88	0.85	0.76	0.79	0.69
P1HTA	0.94	0.98	0.96	0.86	0.91	0.83	0.86
P1HTB	0.96	0.98	0.94	0.91	0.85	0.84	0.79
P1HTC	0.90	0.91	0.87	0.83	0.72	0.77	0.78
P1LSA	0.94	0.99	0.96	0.89	0.89	0.82	0.84
P1LSB	0.95	0.98	0.93	0.88	0.89	0.85	0.83
P1LSC	0.86	0.95	0.85	0.80	0.82	0.81	0.72
P1LTA	0.92	0.98	0.94	0.82	0.92	0.86	0.88
P1LTB	0.93	0.98	0.93	0.86	0.89	0.89	0.85
P1LTC	0.95	0.96	0.93	0.90	0.84	0.90	0.80
P2HSA	0.95	0.98	0.89	0.88	0.83	0.81	0.78
P2HSB	0.87	0.95	0.85	0.83	0.78	0.81	0.76
P2HSC	0.86	0.85	0.81	0.83	0.71	0.79	0.76
P2HTA	0.93	0.97	0.90	0.88	0.83	0.86	0.87
P2HTB	0.87	0.94	0.82	0.82	0.75	0.78	0.74
P2HTC	0.85	0.88	0.84	0.83	0.75	0.78	0.73
P2LSA	0.92	0.99	0.94	0.88	0.90	0.88	0.86
P2LSB	0.91	0.96	0.86	0.83	0.80	0.86	0.82
P2LSC	0.88	0.89	0.82	0.84	0.77	0.80	0.73
P2LTA	0.90	0.96	0.91	0.86	0.88	0.88	0.87
P2LTB	0.92	0.94	0.83	0.85	0.79	0.84	0.78
P2LTC	0.90	0.92	0.85	0.85	0.80	0.84	0.75

Table 4.2 The maximum and minimum values of R_{xy} of all joint angles

Joint Angles	Max	Min
Sh fl/ex	0.96	0.85
Sh ad/ab	0.99	0.85
Sh rot	0.96	0.81
Elbow	0.91	0.80
Forrot	0.92	0.71
Wr fl/ex	0.90	0.77
Wr ul/ra	0.89	0.69

Six postures of arm and forearm were selected to compare the angles of the joints of the upper limb. To determine:

a) fully extended angle of the elbow joint, subjects were told to fully extend their elbow joint while relaxing their arms beside the body with palms facing forward ,

b) the zero angle of the shoulder flexion, adduction, and rotation, subjects relaxed their arm beside the trunk and held their forearm level with the horizontal (the elbow joint flexed at 90 degrees) without rotation of the shoulder and radioulnar joints,

c & d) the full range of motion of the internal rotation and the external rotation of the shoulder joint, subjects relaxed their arms beside the body, the elbow joints flexed about 90 degrees and fully rotated the shoulder joint internally and externally respectively,

e & f) the full range of the pronation and the supination of the forearm, subjects held their arms in the same position as in (c) and (d) and fully pronated and supinated respectively.

All the positions were set using the end range of individual subject motion or the zero degree positions except for flexion of the elbow joint at 90 degrees for which a water level goniometer was used to set subjects' forearm at the desired angle.

The results of the angular displacement in each position are shown in Tables 4.3 to 4.6. The joint angles of shoulder, elbow and radioulnar joints when subjects were set at the clinical zero position are shown in Table 4.3. The clinical zero position of the upper extremity is defined as the position where the arm and forearm rest beside the torso, the elbow and wrist joint extend. The mean angle of the zero position for shoulder flexion and extension and shoulder adduction and abduction are -8.26 ± 3.34 and -12.27 ± 2.32 respectively. The standard deviations of these two angles are relatively small compared with the angles of elbow extension and shoulder and forearm rotation. For the elbow joint, the mean value of the zero position is 20.25 ± 6.31. The rotations of the shoulder and radioulnar joints have mean values equal to -41.05 ± 8.15 and 18.22 ± 13.44 respectively. Table 4.4 shows flexion of the elbow joint set at the 90 degree position. The mean and standard deviation of elbow flexion are 90.68 ± 3.92 degrees.

The recorded angle of the elbow joint at the 90 degrees of flexion can be compared with the set position, that is 90 degrees. Comparison of the results which had means and standard deviations equal to 90.68 ± 3.92 with the variation of angular measurement in clinical practice (which was 3.7 degrees for the elbow motion using a goniometer (Boone et al., 1978)) implied that the marker attachment between subjects at the shoulder, elbow and wrist joint as used in the study was reliable.

The angular variation between subjects for the zero position may have been due to the process of setting the zero position, a position which was visually determined and therefore subject to error.

Furthermore, the rotation angle of shoulder and radioulnar joints showed large standard deviations at the zero and at the fully rotated set positions (Table 4.3, 4.5, and 4.6). This variation may have resulted from the use of a marker with an extension rod. The rod was difficult to fix to the body segment so that the angle between the rod and the longitudinal axis of the arm and forearm was the same for all subjects. In addition, the movement of skin over bony prominences should have the greater effect on a rod marker than an ordinary marker. Thus the results of this study should not be used to compare the absolute angle of shoulder and forearm rotation or wrist movement since these angles were derived from coordinate data based on rod markers.

In conclusion, the Hypothesis One for Stage Three of the study could be supported only by some joint angles. The value of the shoulder and forearm rotation or angular displacement of the wrist joint could not be compared between subjects because the calculated values shown a high variation. On the other hand, flexion and extension of the shoulder and elbow joints and adduction and abduction of the shoulder joint might support this Hypothesis. However, the fact that the procedure used in the study in which the position was visually set up may be subject to error, could be a reason to reexamined this hypotheses. Because of this result, only the results of the mean data were utilised in the present study.

Table 4.3 Angular displacement (degrees) of shoulder flexion and extension, shoulder adduction and abduction, shoulder rotation, elbow flexion and extension and forearm rotation when subjects were set at the zero position.

Subject number	SHfl/ex	SHad/ab	SHrot	Elbow	Forrot
1	-14.00	-11.35	-45.71	26.43	33.90
2	-13.49	-12.75	-30.35	16.79	11.75
3	-4.89	-13.17	-29.37	20.20	16.06
4	-9.62	-9.65	-51.65	30.00	49.23
5	-4.64	-12.61	-47.23	17.07	4.60
6	-8.15	-13.42	-39.39	14.88	10.77
7	-9.18	-13.32	-36.95	18.19	24.12
8	-14.91	-14.05	-42.78	11.24	2.75
9	-9.72	-15.18	-34.70	12.26	14.86
10	-6.65	-16.94	-54.59	28.13	0.84
11	-5.05	-11.83	-41.39	14.63	17.10
12	-6.33	-11.38	-46.57	23.65	33.30
13	-5.47	-9.17	-48.99	20.60	29.62
14	-5.58	-7.85	-36.87	26.48	17.90
15	-6.97	-13.46	-26.60	29.30	22.29
16	-7.48	-10.21	-43.66	14.13	2.35
MEAN	-8.26	-12.27	-41.05	20.25	18.22
SD	3.34	2.32	8.15	6.31	13.44

Table 4.4 Angular displacement of elbow joint when subjects were set at the 90 degree of elbow flexion position.

Subject number	Elbow
1	98.90
2	93.64
3	96.11
4	96.02
5	87.61
6	90.71
7	92.19
8	88.42
9	90.36
10	87.78
11	86.13
12	86.61
13	92.00
14	90.72
15	87.79
16	85.84
MEAN	90.68
SD	3.92

Table 4.5 Angular displacement of shoulder rotation when subjects were set at the fully external and internal rotated position.

Subject number	Sh ext.rot	Sh int.rot
1	-77.93	22.54
2	-111.49	49.30
3	-59.87	49.33
4	-96.69	18.84
5	-104.64	32.55
6	-101.13	42.50
7	-96.25	35.17
8	-104.45	34.00
9	-111.89	39.75
10	-92.27	31.23
11	-97.47	56.42
12	-110.11	26.92
13	-109.42	55.84
14	-99.58	39.04
15	-102.73	43.04
16	-100.57	47.54
MEAN	-98.53	39.00
SD	13.34	11.16

Table 4.6 Angular displacement of forearm rotation when subjects were set at the fully pronated and supinated position.

Subject number	Pronation	Supination
1	84.59	-34.23
2	76.03	-73.50
3	82.44	-67.05
4	99.04	-12.76
5	70.35	-58.37
6	91.41	-48.89
7	87.26	-41.70
8	74.33	-65.87
9	77.25	-68.65
10	82.13	-58.49
11	82.45	-54.33
12	84.28	-40.48
13	91.68	-40.17
14	75.51	-33.96
15	74.87	-36.79
16	75.63	-54.10
MEAN	81.83	-49.33
SD	7.74	16.20

4.3.3 Reliability and validity of the angular displacement

Evaluating the reliability of the marker attachment was obviously of benefit. That is, it was particular interest in the case of marker reattachment (which might occur if the experiment was conducted over more than one day) or if the markers were pulled off and had to be reattached within the one testing period. For the present study, each stage of the experiment was performed within the same day. Markers were attached to the subjects' bony landmarks and all motions were recorded before the markers were detached. Only if the marker fell off during the filming process was reattachment necessary.

To overcome the problem of reattachment, the anatomical landmark was clearly marked on the subject's skin with a pen. This procedure ensured that, where required, reattachment was correct. For the sixteen subjects in the main study, two subjects lost a marker during recording, one at the wrist joint and the other at the iliac tubercle of the pelvis.

Thus the experimental protocols used in the present study did not require an established reliable method of marker reattachment.

Testing the validity of the joint angles of the upper extremity recorded by the Peak was not essential in the present study because this research was aimed at observing the change in the joint angle or the pattern of the movements. In addition, the accuracy of the angle measurement using this equipment has been investigated ((Scholz & Millford, 1993), see Chapter 2 section 2.5.1.1).

The absolute value of the angular motion was not of interest. The range of the joint angle depended not only on the position of the markers but also on how the zero angle was defined for each joint. For the total study, most of the zero degree positions were determined in the same way as is used in the clinical measurement of joint range in physiotherapy practice. For example, the anatomical position was used to define the zero angle of shoulder flexion and extension, shoulder adduction and abduction, elbow flexion and extension and wrist ulnar and radial deviation.

While such an approach has face validity in that it is widely used in clinical practice, some difficulties are apparent when translated to the laboratory setting. For example, the zero angle of the rotation of the shoulder and the radioulnar joints and the flexion and extension of the wrist joint were determined by using the position of the rod marker placed on the elbow and wrist joints as already described in the Section 4.1.2. The zero position defined by the rod marker varied from subject to subject as reflected by the variation of the zero position of the shoulder and forearm rotation (Table 4.5). This variation was due to the difficulty in controlling the angle between the rod marker and the longitudinal axis of the body segment especially at the lateral epicondyle of the elbow joint.

Even though, it is not essential to test the validity of joint angle measurement in the present study, comparison of the calculated joint angles between subjects at the setting positions suggested that the validity of calculated angles was low. Thus the relative change of joint angles or the mean data was used in the present study.

4.4 Summary

The determination of the angular displacements using Euler's method was described for each joint angle. Calculation methods of all variables have also been presented.

The repeatability of the angular displacement which was the fundamental variable in the study was determined. The repeatability of throwing within a subject was high. The correlation of the seven joint angles varied from .69 to .99. Even though, comparison of calculated angles with angles measured by a goniometer suggested that Hypothesis One for the Stage Three of the study could be supported, further examination was required. Furthermore, the joint angle derived from the use of a marker with an extension rod showed high variation. Thus the analysis of results was mainly focused on the relative change and was performed using mean data only.

Chapter 5

Results

A picture may instantly present what a book could set forth only in a hundred pages

- Ivan Sergeyevich Turgenev

5.1 Introduction

The results are presented in four sections. The first section describes the kinematic data of the throwing movement, that is, the phase of throwing, relative timing, angular displacement, and angular velocity of the seven joint angles of the throwing limb. Then the data related to the identification of control parameters are described. The third section is associated with order parameters. The trajectories of movement, the phase plane plots, the angle - angle plots and the relative phase are explained in detail. The last section presents the mechanical work of muscles in throwing. This section is intended to identify the energy expenditure for each style of throwing since pattern shifting is also related to the energy utilisation as has been discussed in Chapter 2, Section 2.2.1.4 a.

The coordinate data were used to calculate angular displacement, angular velocity and other parameters as described in Chapters 3 and 4. All data files were time normalised to ensure that the proportion of pictures analysed prior to the onset of the event of interest and at the conclusion of the event was consistent for all files analysed. Then the data were normalised to 100 data points and the average and the standard deviation of each data point were determined. After the normalisation, the picture at the start of the event was number 10 and the number denoting the releasing picture was 81. Most of the results are presented using the mean values for 16 subjects. For the data related to the work done by muscles, the results for each distance thrown were computed from the mean value of angular displacement, angular velocity and angular acceleration. Therefore, no standard deviation can be presented.

The amplitude normalisation of angular displacement and angular velocity were calculated from the starting to the releasing picture of the mean data. The equation used for the calculation has been described in the Chapter 4, Section 4.2.3. The phase plane plots and the angle - angle plots were delineated from the starting picture to the tenth picture after the releasing point.

5.2 Statistical Procedures

The visualised comparison was generally used to differentiate the profiles of trajectories. For example, the pictures of angle - angle plots and the phase plane plots of 10 distances thrown were illustrated separately for each distance thrown on a single page. The likeness of the curves was determined for the whole throwing event and also among the throwing phases. In addition, a comparison of the phase plane plots and the angle-angle plots was also undertaken using the cross-correlation coefficient values. Correlation of all the phase plane plots and the angle - angle plots between two segmental distances thrown for each of the ten distances were determined. There are forty five distance pairs for each joint angle or each joint pair.

Statistical tests were applied to determine the differences among the relative timing and the angular displacement at the releasing point as the distance thrown increased. A repeated measures ANOVA (Pillais trace) was used to test whether there were any significant differences as the distance thrown increased. Then the paired t-test was used to identify significant difference between distances thrown. The selected level of significance (p) was .05.

5.3 Identification of the control parameter

5.3.1 Change in the style of throwing as the distance thrown increased

In the main study, subjects were asked to throw a ball to different distances using their own styles. They were informed that they could change the pattern of throwing as the distance thrown increased. Subjects performed the task under normal conditions and under a condition in which limitation of elbow motion was produced using an elbow orthosis.

All 16 subjects selected either an overarm or an underarm throw or both patterns. No subjects used other patterns of throwing. In the normal condition, nine subjects chose the underarm and seven subjects used the overarm pattern as the initial style of throwing. With the elbow orthosis on, ten subjects selected the underarm and six subjects performed the task using the overarm throw. Figure 5.1 shows the number of subjects for each style of throwing at different distances in both conditions.

Most subjects used the same pattern of throwing in both conditions, with or without the elbow orthosis. Only one subject selected a different style of throwing, that is, the overarm pattern with the orthosis and an underarm pattern without the orthosis. However, with the orthosis on, this subject altered the style from the underarm to the overarm over the last distance thrown.

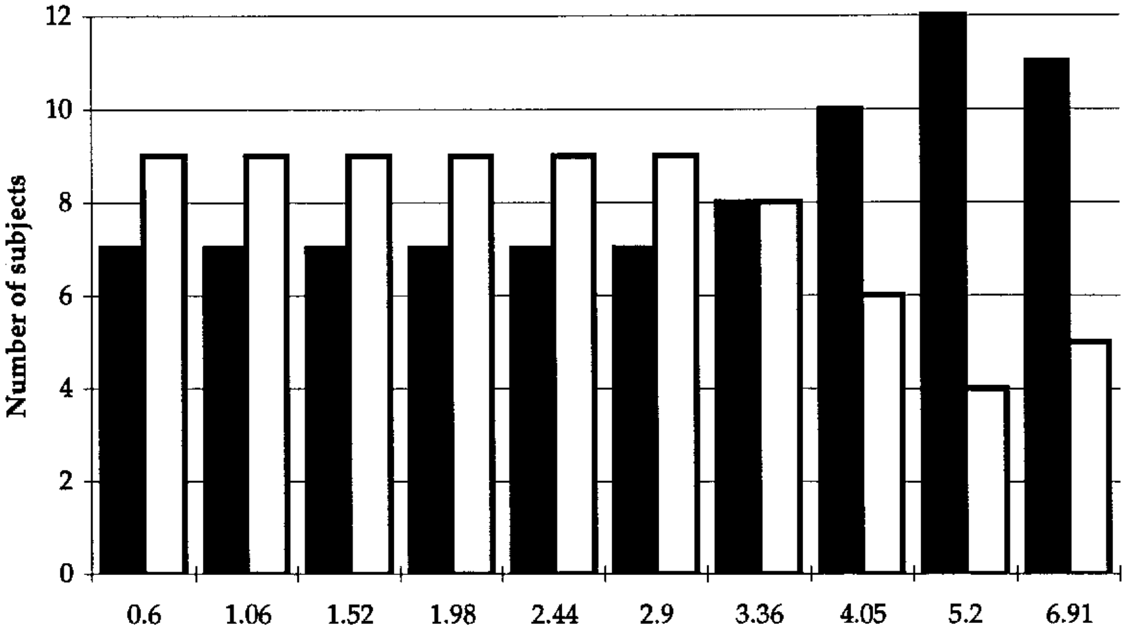
At the shortest distance, a greater number of subjects selected an underarm throw. As the distance thrown increased in both conditions, some subjects switched to using the overarm throw. Thus the number of subjects completing the task using the overarm throw was greater than those who performed using the underarm throw. At the distance of 3.36 m, there were eight subjects (50%) using both styles of throwing. Alteration of the throwing pattern mainly occurred from the underarm to the overarm throw. In the normal condition, only one subject changed the style of throwing twice from the underarm to overarm and then reversed back to the underarm throw over the last distance. In the elbow limitation condition, one subject (same one as in the normal condition) changed the pattern of throwing three times. She started with the underarm throw moved to overarm at the fifth distance then reverted to the underarm and finally reversed to the overarm at the seventh distance.

The results of the study imply that distance thrown may be one of the control parameters of the throwing movement. These findings also supported the acceptance of Hypotheses Two and Three of the study, which stated that:

Hypotheses 2:

a) Subjects, given a choice, will demonstrate more than one style in executing the defined throwing task.

A) Without elbow orthosis



B) With elbow orthosis

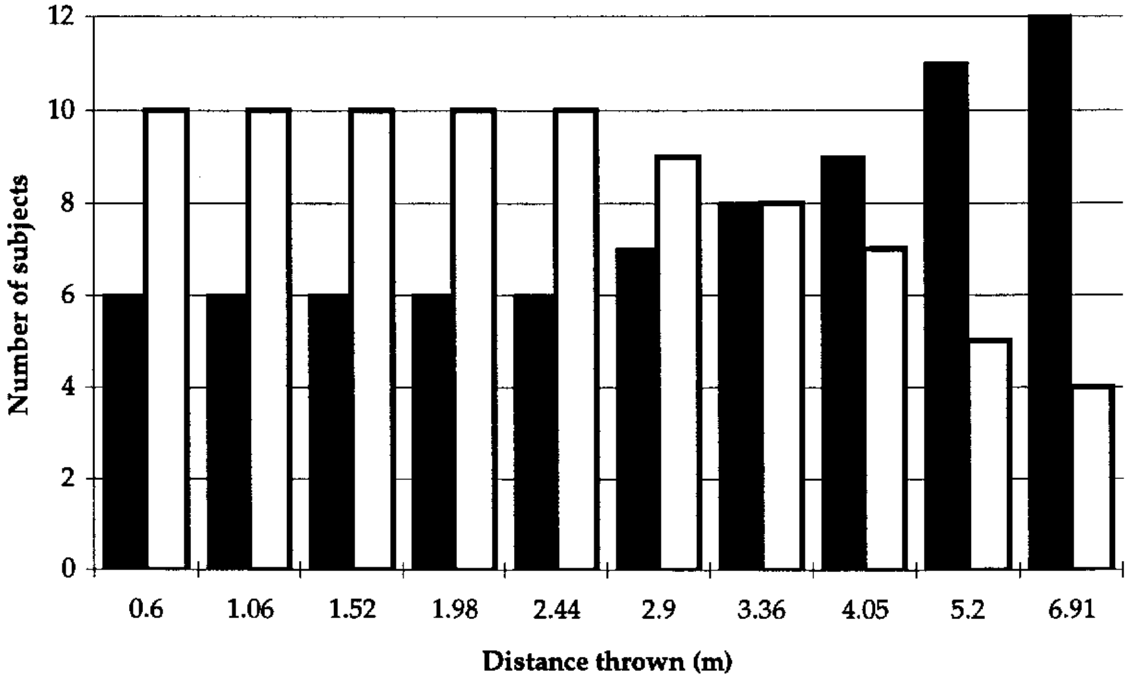


Figure 5.1 Number of subjects using the overarm and the underarm throw as the distance thrown increased. A) when subjects threw without the elbow orthosis, B) with the elbow orthosis. ■ = Overarm, □ = Underarm

b) At least two throwing patterns, the overarm and the underarm throw, will be demonstrated when subjects freely selected throwing patterns.

Hypotheses 3:

a) A phase transition will be demonstrated by changes in proposed order parameters as the distance thrown increased.

b) Changes in the throwing pattern in individual subjects may occur in the direction of the overarm throw or in direction of the underarm throw.

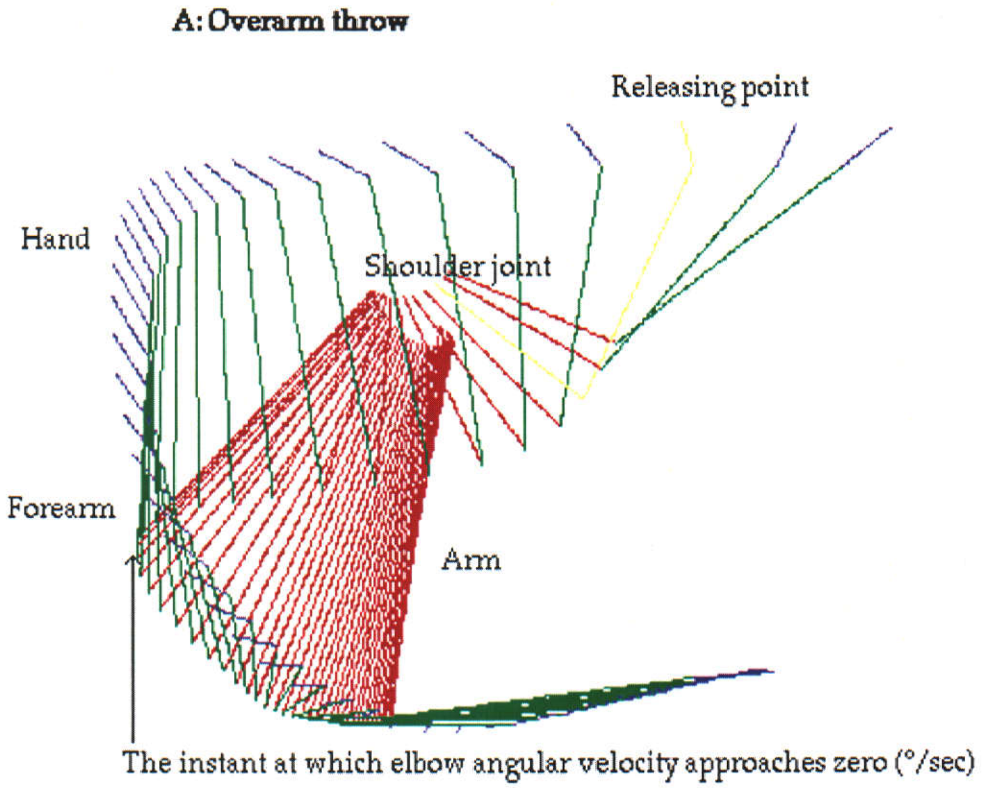
However, these results were not supported for the Hypotheses Five (c) which suggested that:

Limitation of the elbow joint angle will force a change in throwing styles as the distance thrown increases.

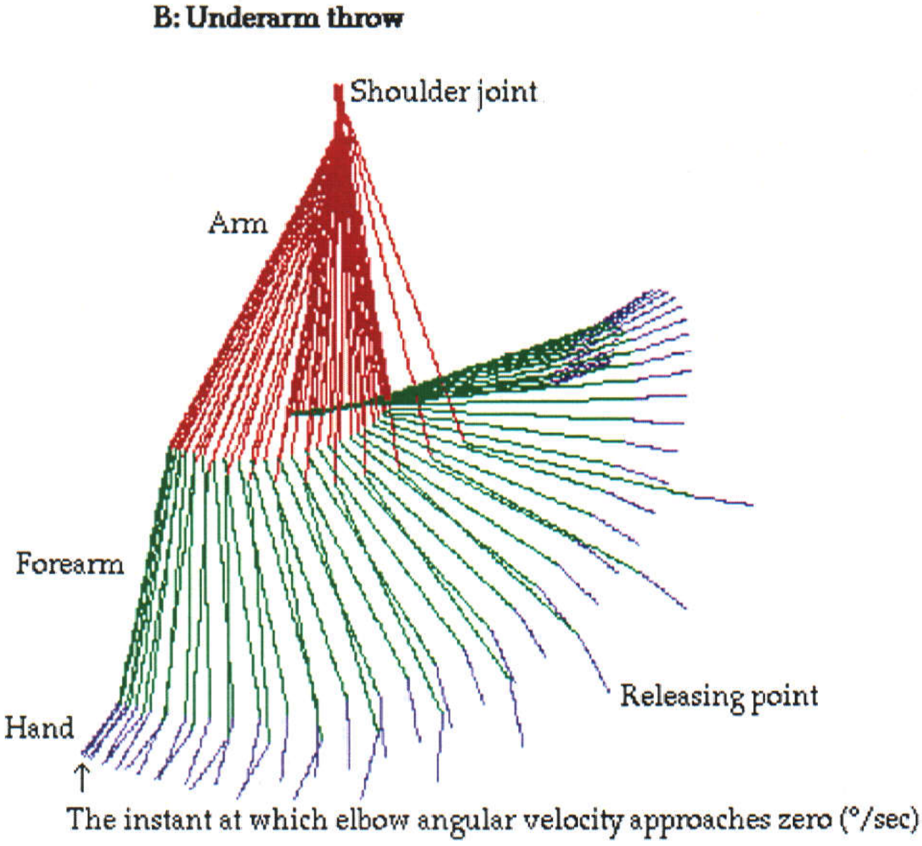
5.3.2 The phases of throwing

The throwing movement in the study was divided into two parts defined as the preparation and the releasing phases.

The time point at which the maximum and the minimum elbow flexion occurred in the overarm and the underarm throw respectively was used to separate the phases of movement. This time point approximately coincides with the point where the elbow angular velocity approaches zero degrees per second. It was the point where the throwing hand was at the greatest distance from the target. Movement of the upper limb segments reversed at this point. Subjects also externally rotated the shoulder joint to the maximum angle within this phase in the overarm throw. Using stick figures (Figure 5.2) the overarm and the underarm throws for the maximum distance thrown (6.91 m) are shown and the point used to separate the phases of throwing is indicated.



A: Overarm throw



B: Underarm throw

Figure 5.2 Stick figures of the overarm and the underarm throw for the greatest distance thrown (6.91 m)

5.3.3 Direction-dependent coordination

The plots between flexion and extension of the elbow and wrist joints for each throwing pattern were compared with rotation of the radioulnar joint and flexion and extension of the shoulder joint.

For the overarm throw, the antiphase relationships between flexion and extension of the wrist and elbow joints are demonstrated while the radioulnar joint pronates (Figure 5.3 A) or while the shoulder joint flexes (Figure 5.3 C). On the other hand, the underarm throw shows an in-phase relationship between the elbow and wrist joints when the radioulnar joint supinates (Figure 5.3 B) or when the shoulder joint extends (Figure 5.3 D).

Comparison of flexion and extension of the elbow and wrist joints with other joints, that is shoulder adduction, shoulder rotation and wrist deviation has not been performed since these joint angles demonstrated the same action in both throwing patterns.

Figure 5.3 shows only the results at the distance thrown of 2.0 m. The other distances thrown also illustrate the same results and are presented in Appendix C.

These results indicate the effects of the orientation of the forearm and the shoulder joint on the motions of the elbow and wrist joints. It seems that the throwing motion is naturally performed using the easiest pattern. This point will be reviewed in Chapter 6, Discussion.

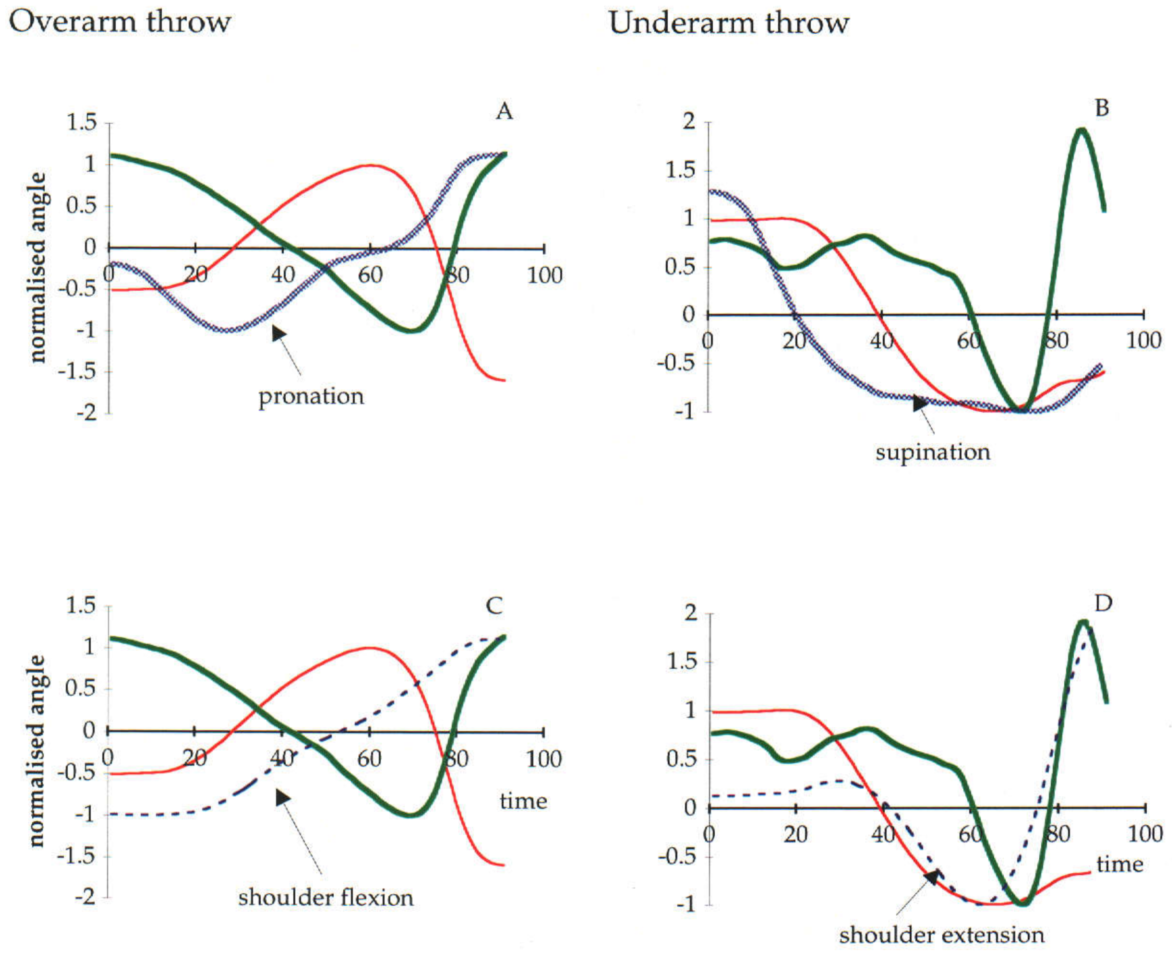


Figure 5.3 Normalised angular displacement of elbow and wrist flexion for the overarm throw (left) and the underarm throw (right) plotted with forearm pronation (A), supination (B), shoulder flexion (C) and shoulder extension (D) over the distance of 1.98 m. — = Elbow flexion, — = Wrist flexion

5.4 Kinematic data of throwing

5.4.1 Movement time and relative timing

Duration of the total movement time (TMT), the preparation phase (Prep) and the releasing phase (Rel) were calculated. Then the ratios of each movement duration were determined and compared between the overarm and the underarm patterns, that is, the Prep/TMT, Rel/TMT, and Rel/Prep. The mean and standard deviation of the three types of relative timing are illustrated in the Figure 5.4 (A to C). A repeated measure ANOVA (Pillais trace) confirmed the ratios to be constant for the underarm pattern ($F_{(9,6)}$ = 0.9, p = .583; $F_{(9,6)}$ = 0.9, p = .583 and $F_{(9,6)}$ = 1.1, p = .469 for Prep/TMT, Rel/TMT and Rel/Prep respectively) and showed significant differences for the overarm pattern ($F_{(9,5)}$ = 18.6, p = .002; $F_{(9,5)}$ = 18.6, p = .002 and $F_{(9,5)}$ = 33.3, p = .001 for Prep/TMT, Rel/TMT and Rel/Prep respectively). For the overarm pattern, the Prep/TMT ratio shows an increasing trend but Rel/TMT and Rel/Prep ratios demonstrate a decreasing trend. Analysis of variance of the relative timing for an overarm and an underarm throw is shown in Table 5.1.

The degrees of freedom for the overarm throw (9, 5) differ from the underarm throw (9,6) because in throwing to the longest distance, the results of two subjects in the overarm pattern and one subject in the underarm pattern were lost.

These findings did not provide support for Hypothesis Four, namely:

a) There will be no significant differences in the relative timing of the overarm throw and the underarm throw as the distance thrown of a projectile increases.

b) There will be no significant difference in the relative timing between the overarm and the underarm throw at the same distance thrown.

Therefore this hypothesis had to be rejected.

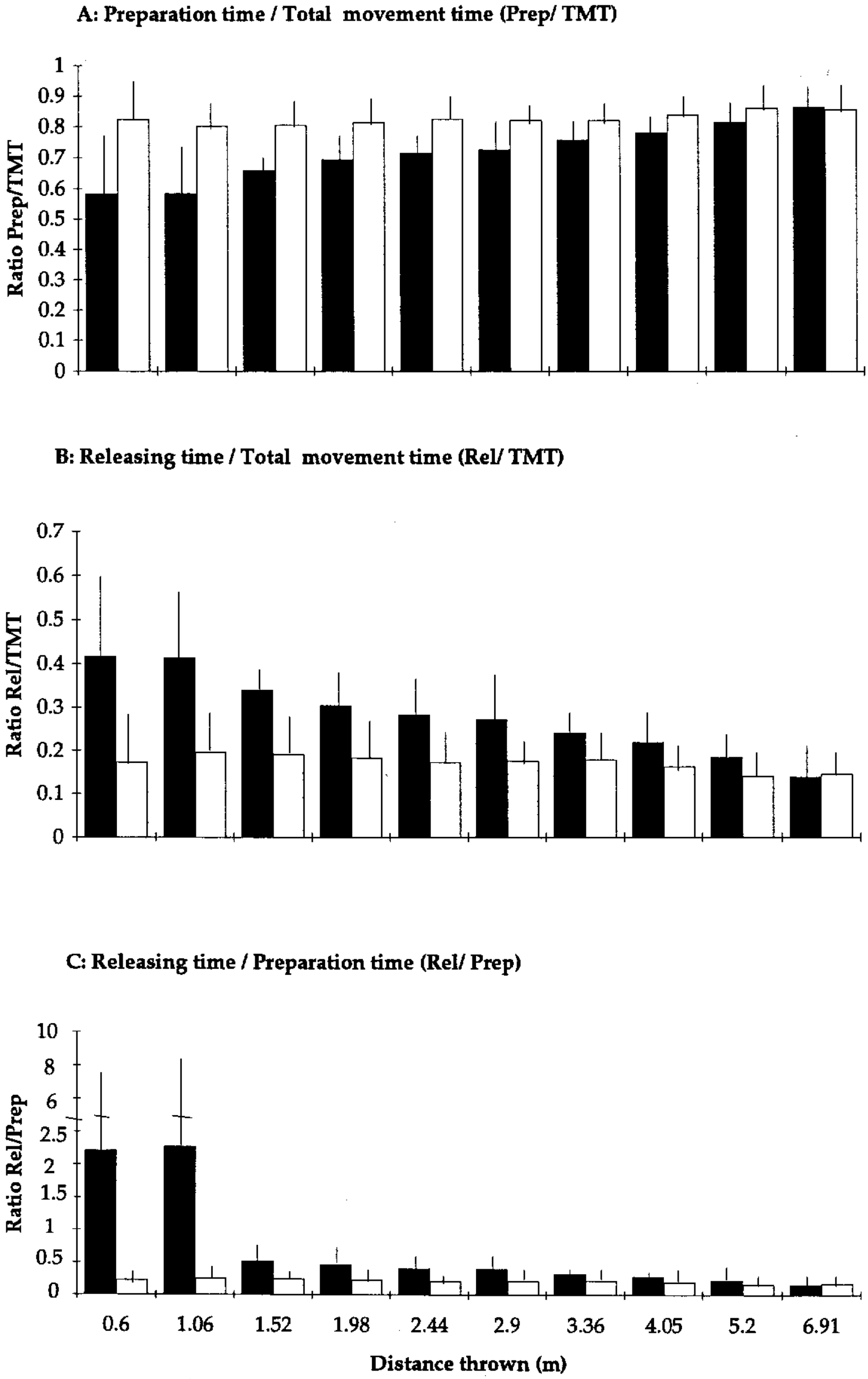


Figure 5.4 Mean and standard deviation of the relative timing for the overarm and the underarm throw as the distance thrown increased.
■ = Overarm, ☐ = Undeararm

Table 5.1: Summary of the repeated measures ANOVA (Pillais trace) of each throwing pattern as the distance thrown increased.

A) Overarm throw

Dependent variable	df	F	p
Prep/TMT	9	18.6	.002*
Error	5		
Rel/TMT	9	18.6	.002*
Error	5		
Rel/Prep	9	33.3	.001*
Error	5		

B) Underarm throw

Dependent variable	df	F	p
Prep/TMT	9	0.9	.583
Error	6		
Rel/TMT	9	0.9	.583
Error	6		
Rel/Prep	9	1.1	.469
Error	6		

5.4.2 Angular displacement of the overarm and the underarm patterns

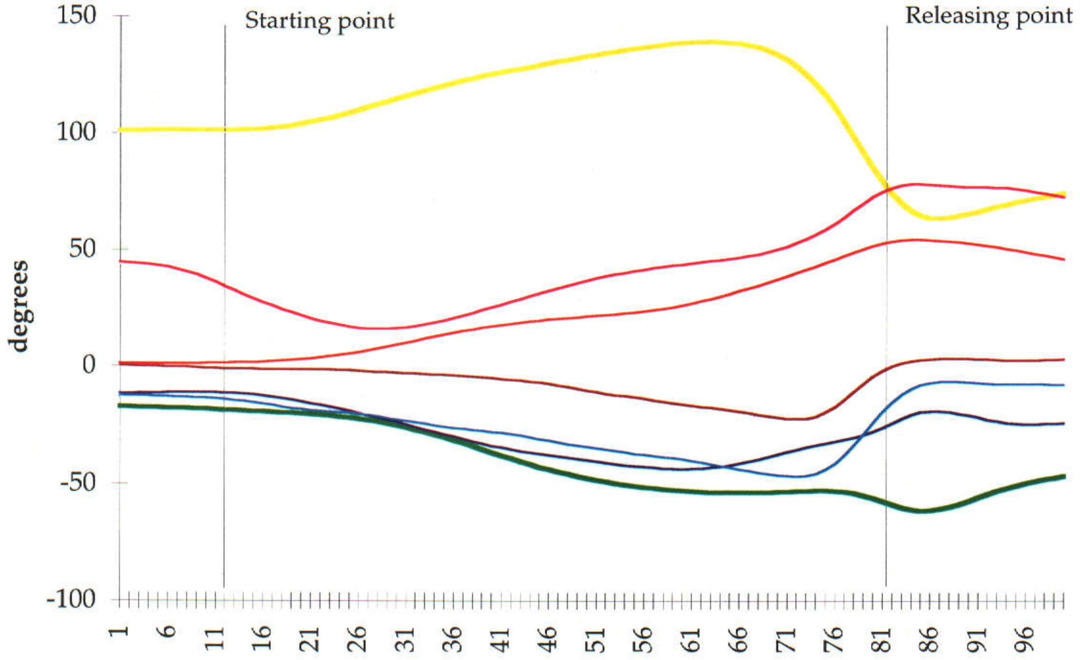
Seven joint angles of the upper limb were calculated, that is, shoulder flexion and extension, shoulder adduction and abduction, shoulder internal and external rotation, elbow flexion and extension, forearm pronation and supination, wrist flexion and extension and wrist ulnar and radial deviation. The mean angular displacement of the 16 subjects for the seven joint angles at the distance thrown of 2.9 m for overarm and underarm throws is shown in Figure 5.5.

For the overarm throw (Figure 5.5 A), subjects flexed, abducted and externally rotated the shoulder joint. At the same time they also flexed the elbow joint. The forearm supinated or was in the semipronated position while the wrist joint extended and deviated radially. These motions occurred in the preparation phase. As subjects reached the point of maximum flexion of the elbow joint or maximum external rotation of the shoulder joint, the action started to move back in the opposite direction. That is, subjects extended, adducted and internally rotated the shoulder joint while extending the elbow joint and pronating the forearm. The wrist joint flexed and deviated to the ulnar side at the point of release.

For the underarm throw (Figure 5.5 B), subjects started the throwing movement with supination of the forearm and external rotation of the shoulder joint. The shoulder joint then slightly flexed, then extended, while extension of the elbow joint increased. Movement of the shoulder joint in the frontal plane, shoulder adduction and abduction, was maintained in the same relationship as that of the starting position throughout the preparation phase.

As the moving hand reached the point of greatest distance from the target, the opposite motion of some joint angles occurred. For example, the shoulder motion reversed after reaching the maximum extension performing for that distance. The angular displacement of other joints remained relatively constant or else moved through only a small range. The elbow and the radioulnar joint remained in the extended and supinated position respectively.

A) Overarm throw



B) Underarm throw

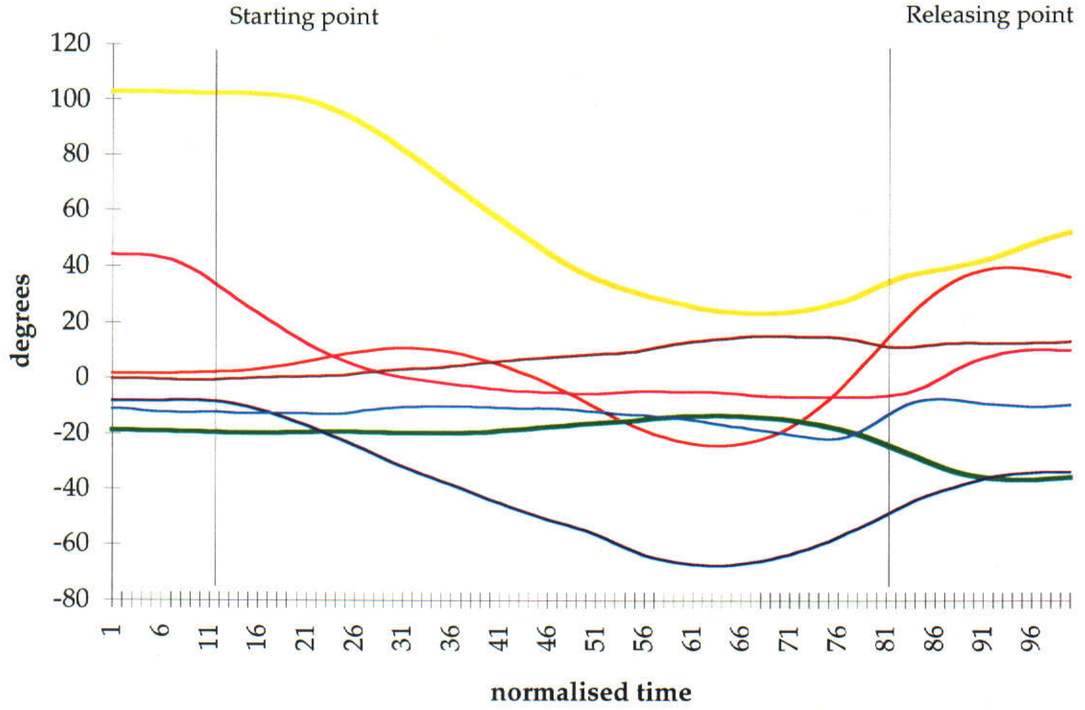


Figure 5.5 Mean angular displacement at the distance thrown of 2.9 m. A) an overarm throw, B) an underarm throw. —— Shoulder flexion/extension, —— Shoulder adduction/abduction, —— Shoulder internal/external rotation, —— Elbow flexion/extension, —— Forearm rotation, —— Wrist flexion/extension, —— Wrist ulnar/radial deviation. Flexion, adduction, internal rotation, pronation and ulnar deviation have a positive sign whereas extension, abduction, external rotation, supination and radial deviation have a negative sign.

Flexion and extension of the wrist joint in the underarm throw were similar to that observed for the overarm throw, that is, there was an increase in extension which changed to flexion at the releasing phase. In contrast to the amount of flexion and extension, ulnar and radial deviation of the wrist joint in the underarm throw shows an opposite motion when compared with the overarm pattern. The extension of the wrist joint was synchronised with ulnar deviation before changing to radial deviation at the point of release.

These results confirmed Hypothesis Five (a) which stated that:

Each throwing pattern can be defined by the changing of angular displacement over time of all joint angles of the throwing limb.

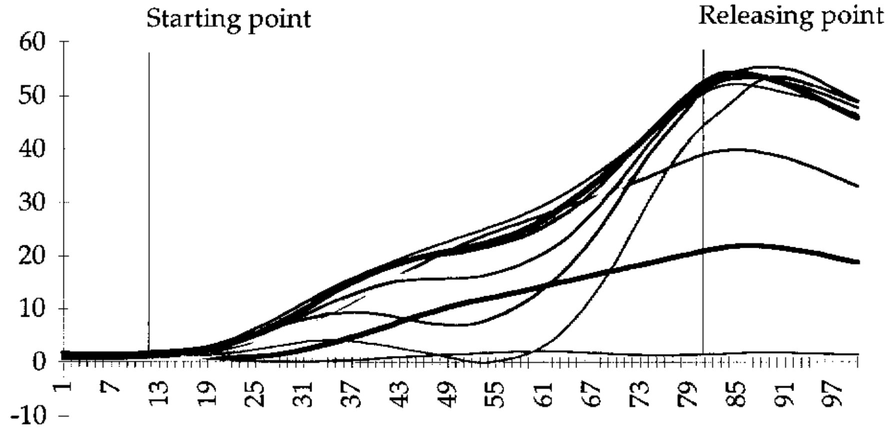
Hypothesis Five (a) can therefore be accepted.

5.4.3 Angular displacement as the distance thrown increased

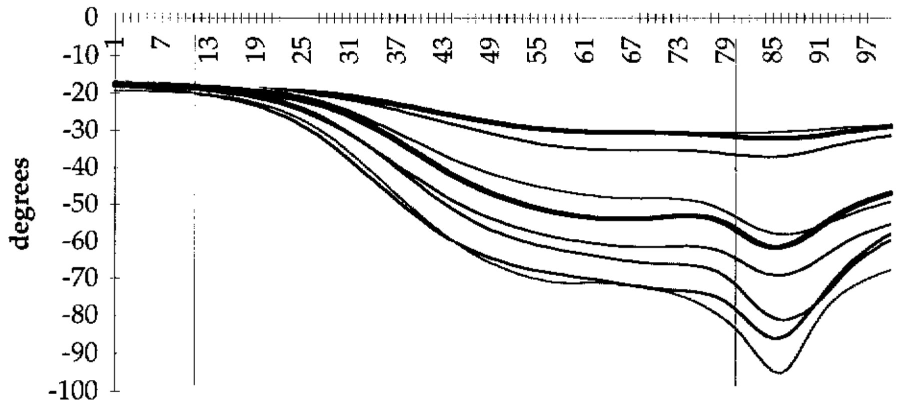
For the overarm throw (Figure 5.6), most of the joint angles show a stepwise increase in range of motion or the pattern of the joint motion changes as the distance thrown increased. Only the elbow joint angle moves in a small range of flexion (Figure 5.6 D). The step increase in range of motion was clearly demonstrated as subjects threw to the first three distances (Figure 5.6 A, E and G). The amount of flexion and extension of the shoulder and wrist joints and ulnar and radial deviation of the wrist joint can be readily observed. The step increase was also obviously differentiated over the last four distances thrown in other movements, for example, in rotation of the shoulder (Figure 5.6 C) and radioulnar joints (Figure 5.6 E). For shoulder abduction, the increment in range of motion can be seen clearly for most of the distances thrown (Figure 5.6 B).

Unlike other joint angles in the overarm throw, shoulder flexion and extension demonstrates both the step increase in range of motion and change of the pattern of movement as the distance increased (Figure 5.6 A). The pattern of shoulder flexion started to change as subjects threw to the last four distances. A gradual increase in the maximum flexion of the shoulder joint occurred for the first five distances thrown. The maximum value of shoulder flexion was relatively maintained even though the distance

A) Shoulder flexion and extension



B) Shoulder adduction and abduction



C) Shoulder internal and external rotation

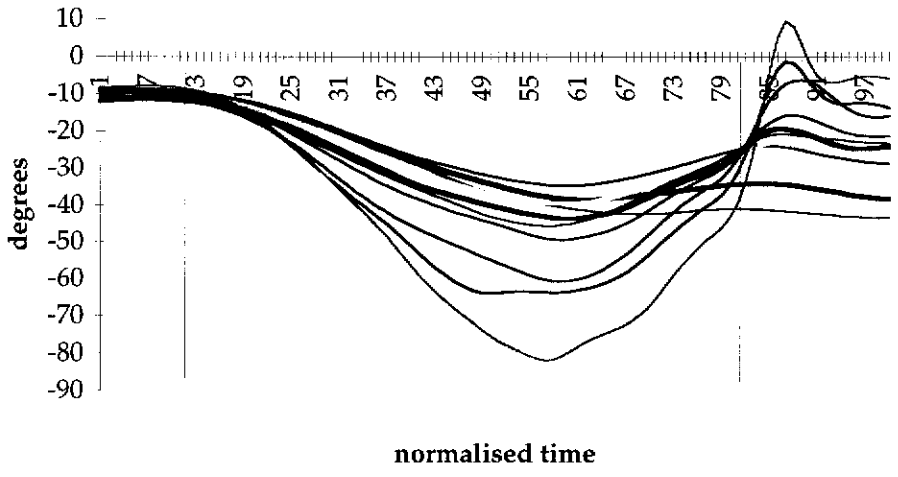
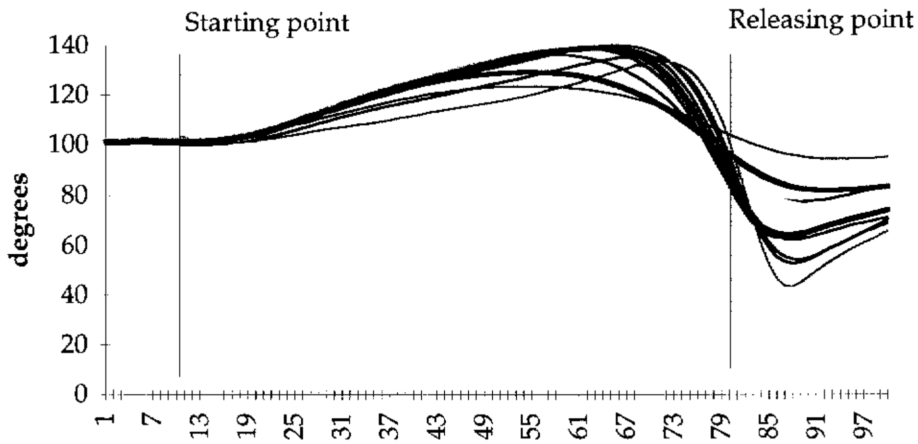


Figure 5.6 Mean angular displacement of the overarm throw as the distance thrown increased. (Legend see page 162)

D) Elbow flexion and extension



E) Forearm pronation and supination

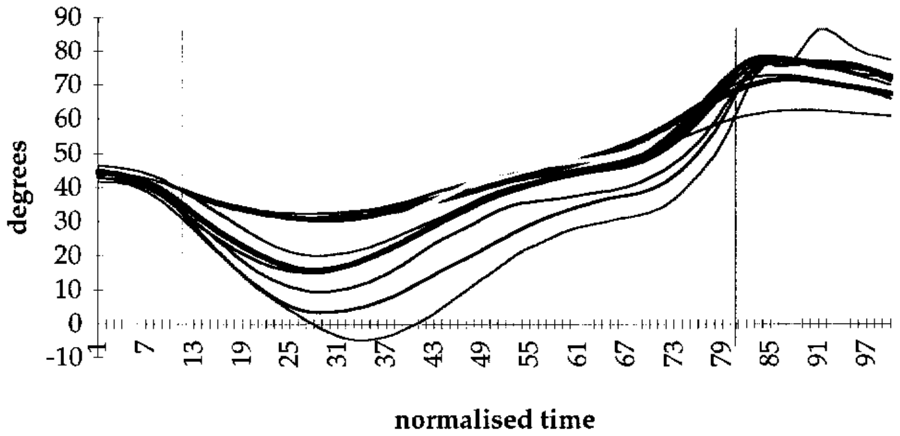
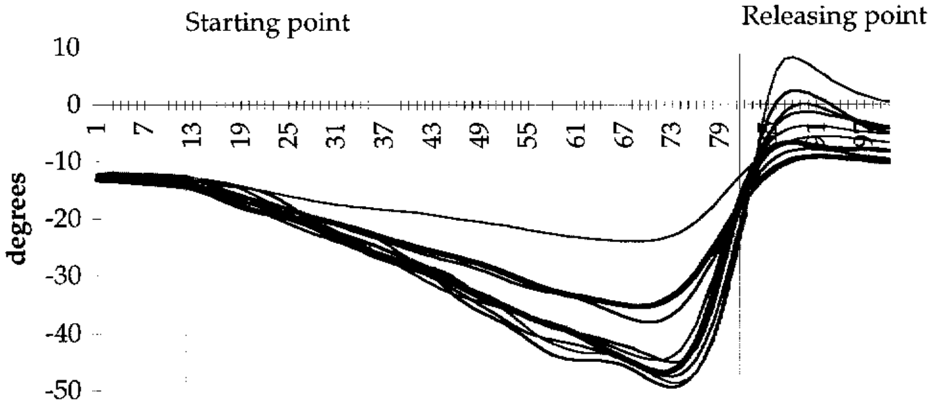


Figure 5.6 (continued) Mean angular displacement of the overarm throw as thedistance thrown increased. (Legend see page 162)

F) Wrist flexion and extension



G) Wrist ulnar and radial deviation

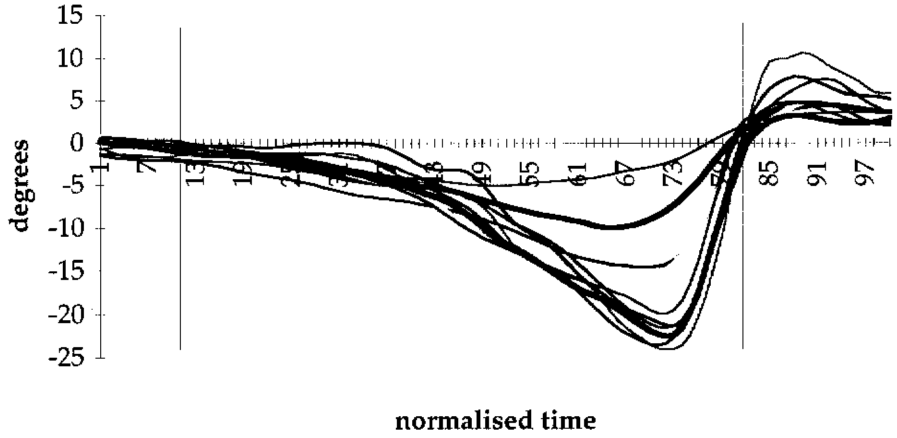


Figure 5.6 (continued) Mean angular displacement of the overarm throw as the distance thrown increased.

— 0.6 m, — 1.06 m,
— 1.52 m, 1.98 m,
— 2.44 m, — 2.9 m,
— 3.36 m, — 4.05 m,
— 5.2 m, — 6.91 m

Flexion, adduction, internal rotation, pronation and ulnar deviation have a positive sign whereas, extension, abduction, external rotation, supination and radial deviation have a negative sign.

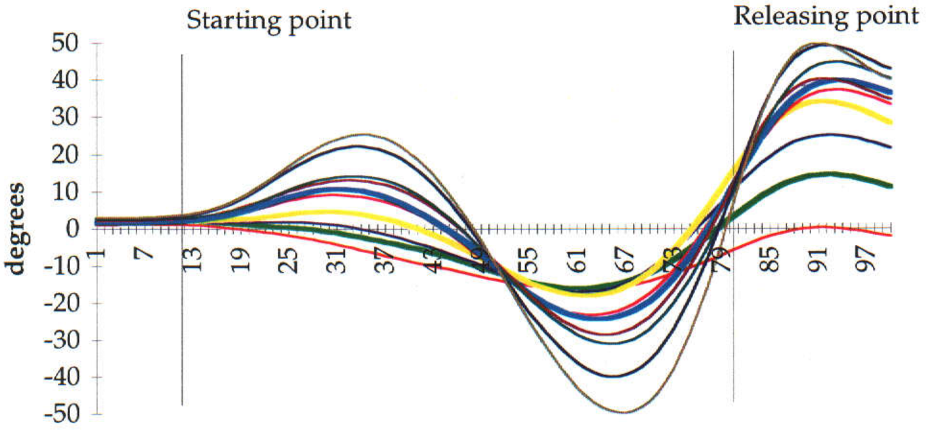
thrown increased. For the last four distances, the pattern of the shoulder flexion started to change by prolonging the small range of the flexion motion. This could be seen from the slight reduction of flexion curves in the preparation phase.

For the underarm throw (Figure 5.7), as the distance increased from 0.6 to 6.91 metres, the profiles of all joint angles remain similar. Most of the joints of the upper limb demonstrated the same range of angular displacement except for the shoulder joint. Only shoulder flexion and extension showed the step increment as the distance changed (Figure 5.7 A).

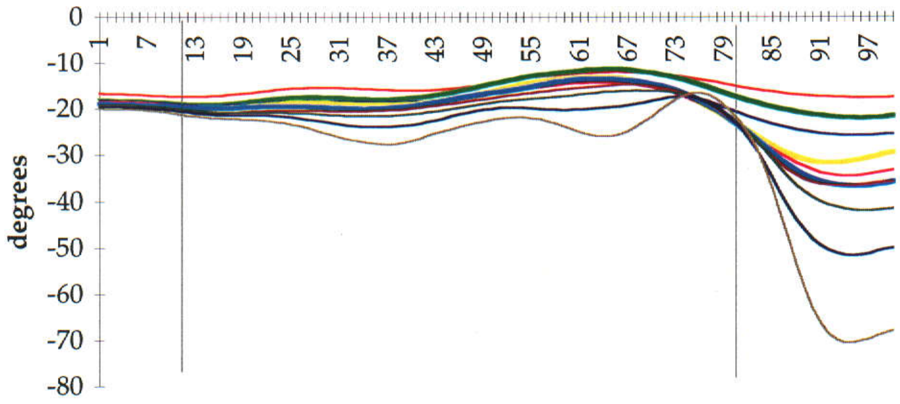
These results suggest that movement of the shoulder joint is responsible for the increase in the distance thrown. Increasing the shoulder motion as the distance thrown increases up to 6.91 m can be observed in both the overarm and the underarm throws. Other joint angles seem to move in a confined range or pattern and are not particularly affected by the length of the distance thrown. This is more apparent in the underarm than the overarm throws.

These findings partially supported Hypothesis Five (b), which stated that the range of joint angles will be greater when throwing to the longer distances. Only the results of some joint angles confirmed this hypothesis in the overarm throw. For the underarm throw, only the actions of the shoulder joint supported the acceptance of the hypothesis.

A) Shoulder flexion and extension



B) Shoulder adduction and abduction



C) Shoulder internal and external rotation

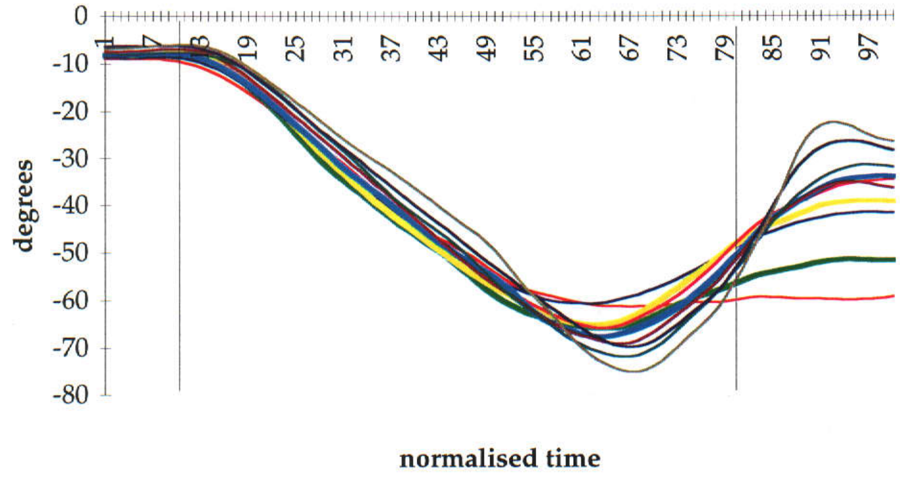
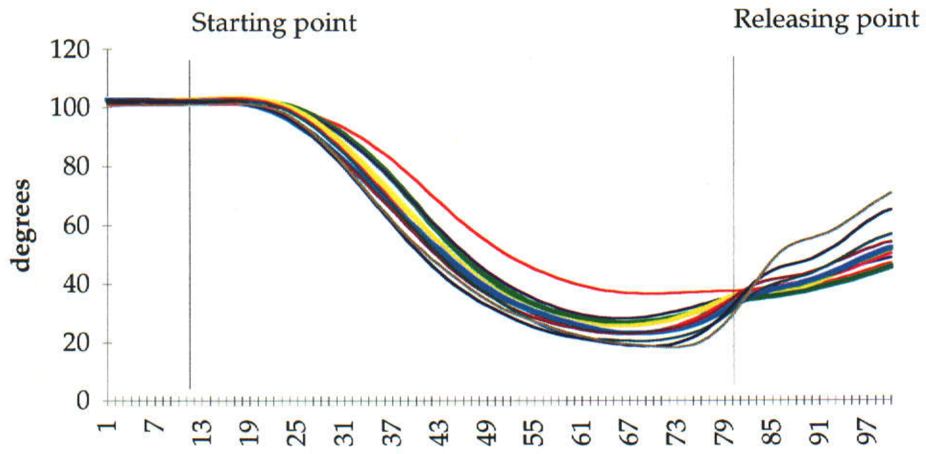


Figure 5.7 Mean angular displacement of the underarm throw as the distance thrown increased. (Legend see page 166)


D) Elbow flexion and extension

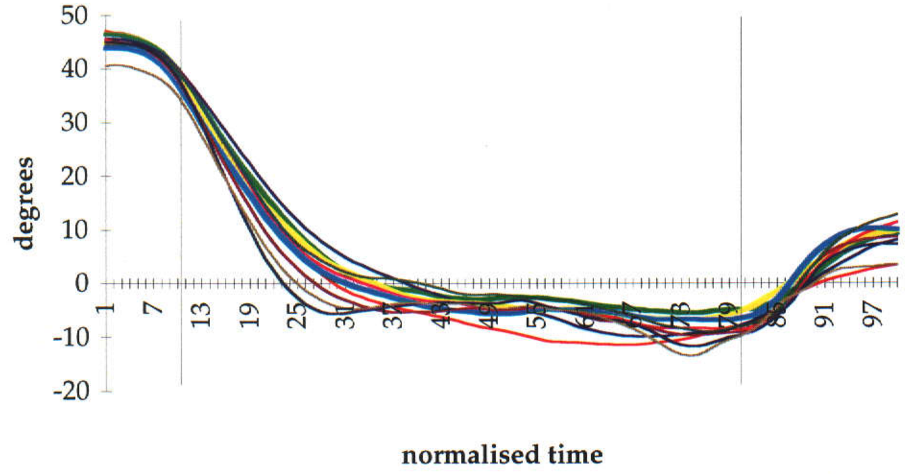
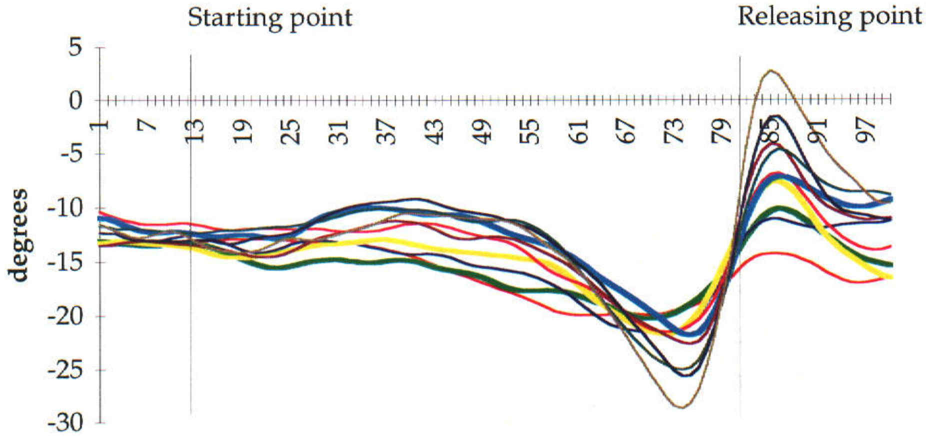

E) Forearm pronation and supination

Figure 5.7 (continued) Mean angular displacement of the underarm throw as the distance thrown increased. (Legend see page 166)

F) Wrist flexion and extension



G) Wrist ulnar and radial deviation

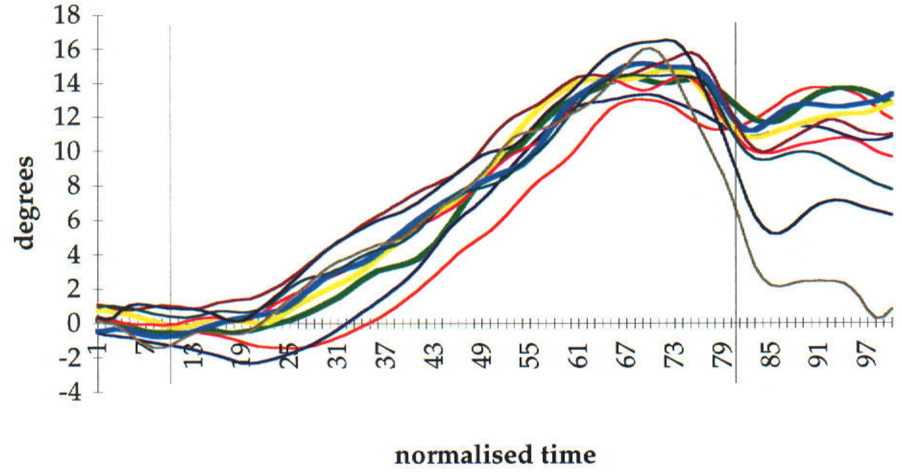


Figure 5.7 (continued) Mean angular displacement of the underarm throw as the distance thrown increased.

— 0.6 m, — 1.06 m,
— 1.52 m, — 1.98 m,
— 2.44 m, — 2.9 m,
— 3.36 m, — 4.05 m,
— 5.2 m, — 6.91 m

Flexion, adduction, internal rotation, pronation and ulnar deviation have a positive sign whereas, extension, abduction, external rotation, supination and radial deviation have a negative sign.

5.4.4 Total range of motion as the distance thrown increased

Total range of motion was calculated for each joint angle, to help visualise the contribution of each joint angle as the distance thrown increased. The overall range of motion was averaged from the angular displacement data of the 16 subjects. Total range of motion was the sum of the consecutive difference of joint angles from the starting point to the releasing point for each distance thrown. The characteristics of the increase in range of motion as the distance thrown increased for the overarm throw differed from those of the underarm throw (Figure 5.8 & 5.9).

For the overarm pattern (Figure 5.8), the action of joints can be divided into three groups. The first group is the motion of flexion and extension of the shoulder, elbow and wrist joints and deviation of the wrist joint which together appear to be responsible for the change in the three shortest distances thrown. As the distance thrown increased further, these flexion, extension and deviation motions are maintained or show only small increments. The second group which can be identified are the movements which take place in the transverse plane (shoulder and forearm rotation). The rotational angles are markedly amplified, especially for the four longest distances. The total range of motion of shoulder adduction and abduction, which constitutes the third group of movements, shows a more regular step increase over all the distances thrown.

In contrast to the overarm pattern (Figure 5.9), the underarm throw showed adjustment mainly of shoulder flexion and extension as the distance thrown increased. Shoulder adduction and wrist movements showed a marked increase only over the longest distance thrown while they were maintained in a relatively constant range of motion for the shorter distances. Other joint angles, that is, elbow, shoulder rotation and forearm rotation, demonstrated a very small increment in range as the distances thrown increased. This is particularly so for forearm rotation.

In conclusion, the overarm throw appears to require a greater joint recruitment of range of motion and degrees of freedom (from flexion and extension to rotation) than the underarm throw. For the underarm throw, only shoulder flexion shows a noticeable increase when the distance thrown increases.

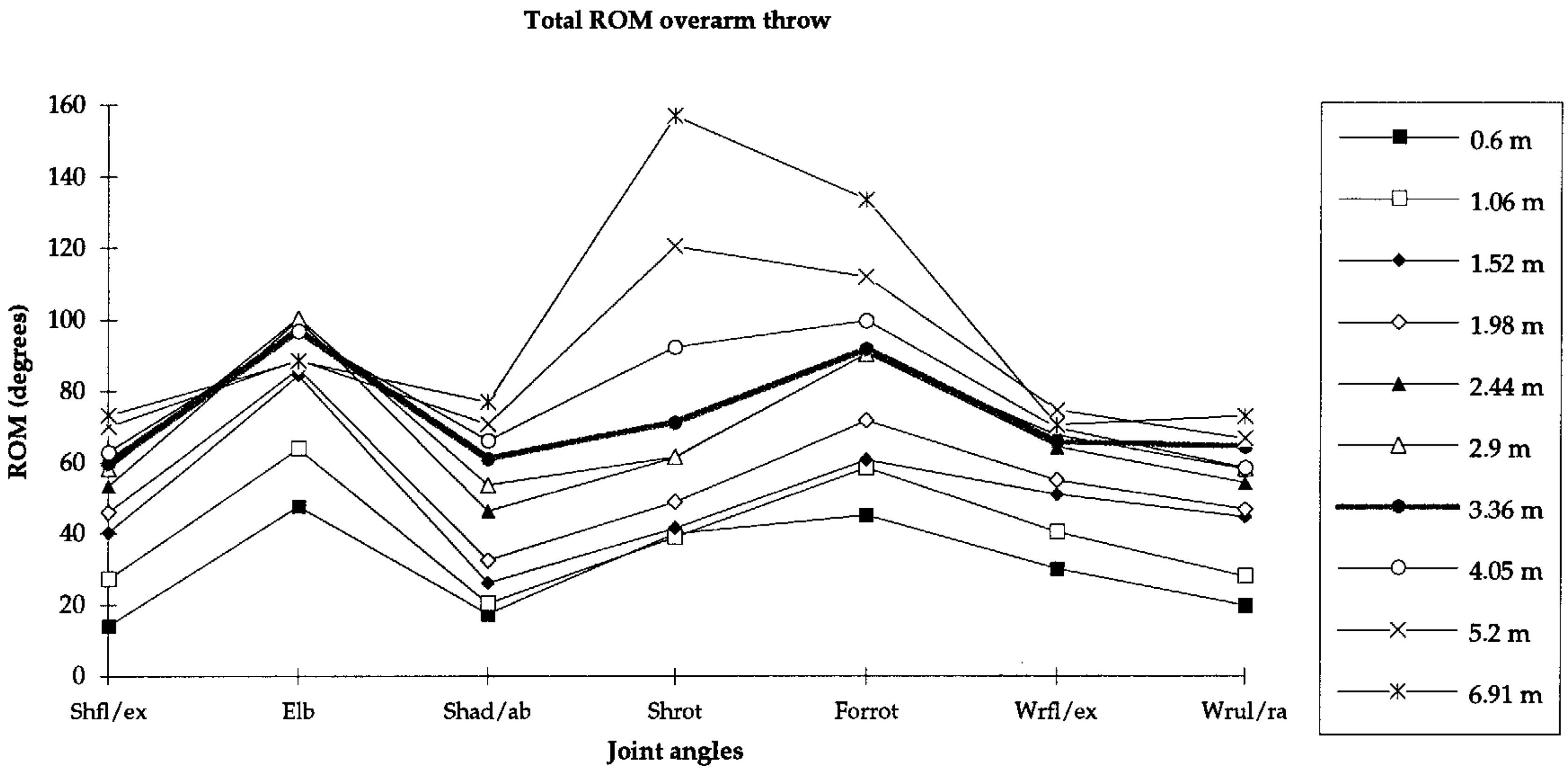


Figure 5.8 Mean total range of motion of the upper limb joint angles for the overarm throw during throwing from the starting to the releasing picture

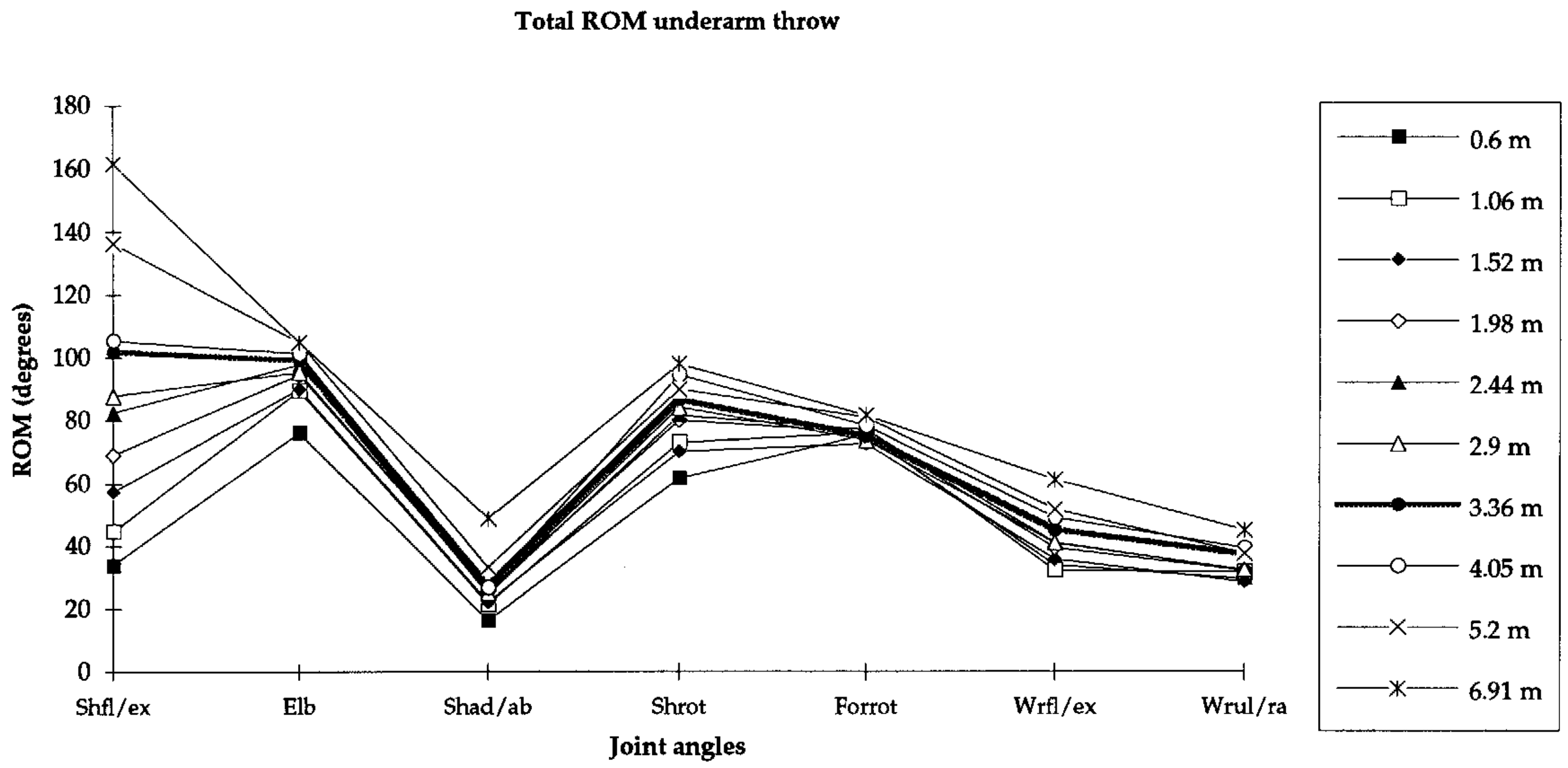


Figure 5.9 Mean total range of motion of the upper limb joint angles for the underarm throw during throwing from the starting to the releasing picture

5.4.5 Angular displacement as a means of differentiating the throwing pattern

To characterise the throwing movement in the overarm and the underarm patterns, a certain number of joint angles have to be described. Flexion and extension of the shoulder and elbow joints, forearm rotation and wrist ulnar and radial deviation demonstrate the different actions in each pattern. Thus angular displacement of the shoulder, elbow, forearm and deviation of the wrist joint will be examined in detail. Furthermore, from the total range of motion of the overarm and the underarm throw shown in Figure 5.8 & 5.9, the relationships among shoulder flexion, shoulder rotation, elbow flexion and forearm rotation will be described and compared.

5.4.6 Angular displacement at the releasing point

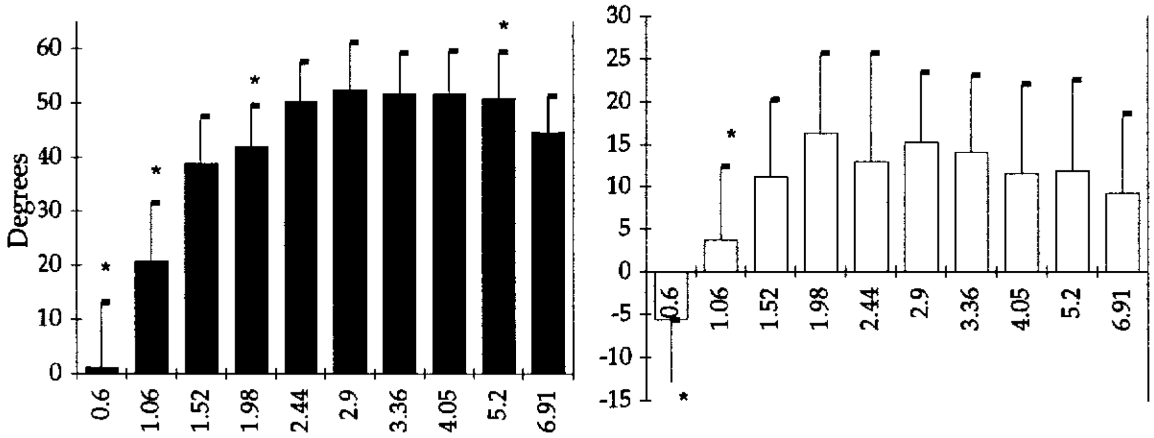
The joint angles of the throwing limb at the releasing point were calculated for each style of throwing. Mean and standard deviations of the seven angular displacements at the releasing point as the distance thrown increased are shown in Figure 5.10.

The repeated measures ANOVA (Pillais trace) was used to test the differences in joint angles at the releasing point as the distance thrown increased. Significant differences for shoulder flexion and extension, shoulder adduction and abduction, shoulder rotation, elbow flexion and extension and forearm rotation in the overarm throw were shown ($F_{(9,5)}$ = 49.198, p = .000; $F_{(9,5)}$ = 7.783, p = .018; $F_{(9,5)}$ = 5.661, p = .035; $F_{(9,5)}$ = 8.162, p = .016 and $F_{(9,5)}$ = 5.373, p = .039 respectively). For the underarm throw, only shoulder flexion and extension, shoulder adduction and abduction and shoulder rotation demonstrated significant differences ($F_{(9,6)}$ = 42.710, p =.000, $F_{(9,6)}$ = 20.653, p = .001 and $F_{(9,6)}$ = 5.485, p = .025 respectively). The summary results of the repeated measures ANOVA for all seven joint angles are shown in the Table 5.2

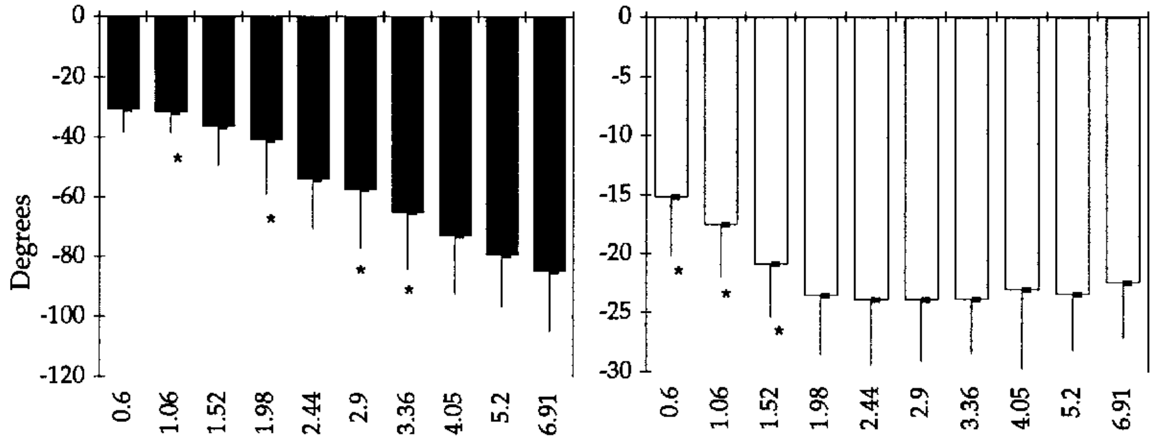
These findings did not provide support for Hypothesis Six, which stated that:

a) There will be no significant difference in the releasing joint angles of the overarm and the underarm throw as the distance thrown increases.

A: Shoulder flexion and extension



B: Shoulder abduction and adduction



C: Shoulder rotation

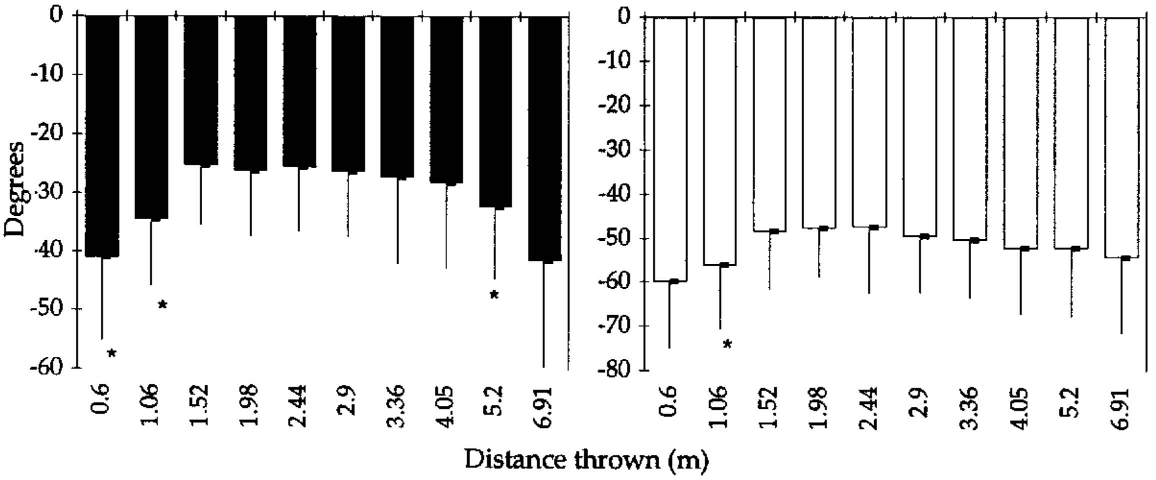
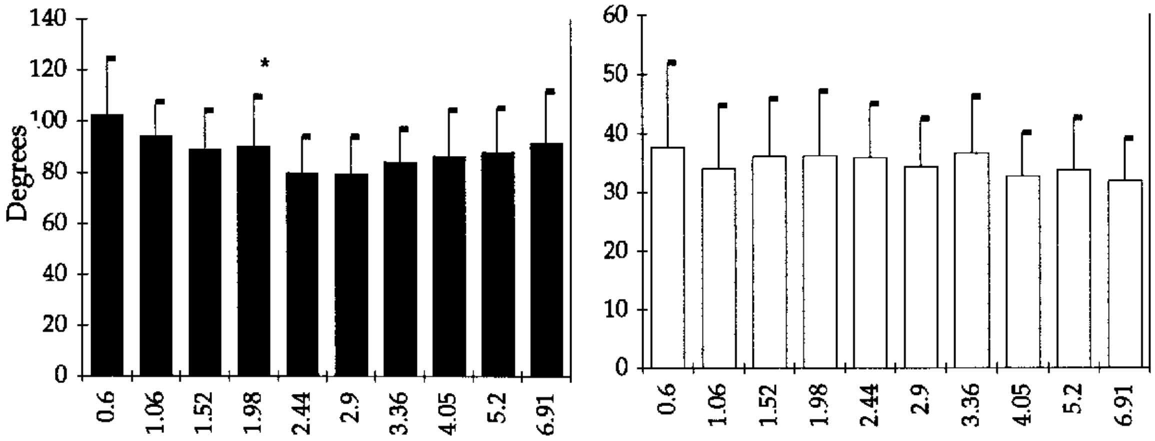


Figure 5.10 Means and standard deviations for angular displacement at the releasing point for the overarm and the underarm throw at increasing distances thrown. ■ = Overarm, □ = Underarm
* Significant difference from the next longest distance

D: Elbow flexion and extension



E: Pronation and supination

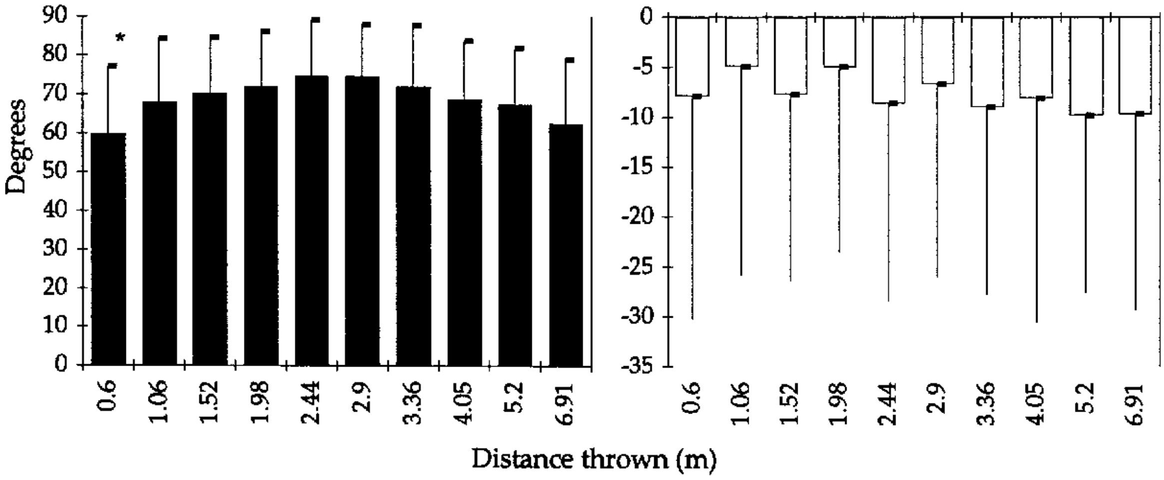
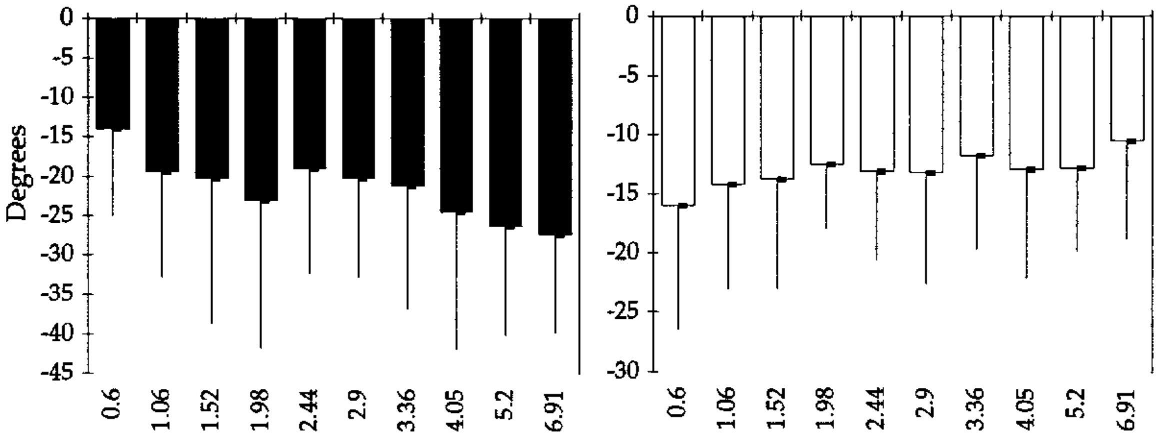


Figure 5. 10 (continued) Means and standard deviations angular displacement at the releasing point for the overarm and the underarm throw at the increasing distance thrown. ■ = Overarm, ☐ = Underarm

* Significant difference from the next longest distance

F: Wrist flexion and extension



G: Wrist ulnar and radial deviation

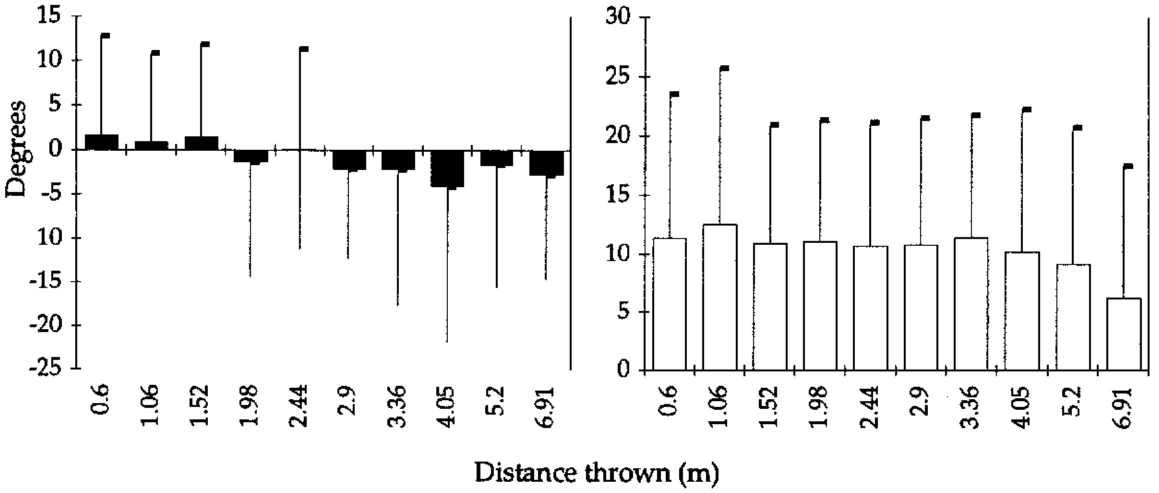


Figure 5. 10 (continued) Means and standard deviations angular displacement at the releasing point for the overarm and the underarm throw at the increasing distance thrown. ■ = Overarm, ☐ = Underarm

* Significant difference from the next longest distance

Table 5.2: Summary results of the repeated measures ANOVA (Pillais trace) in which the dependent variable is the releasing angle for each throwing distance in both patterns.

A) Overarm throw

Dependent variable	df	F	p
Shoulder flexion/extension	9	49.198	.000*
Error	5		
Shoulder adduction/abduction	9	7.783	.018*
Error	5		
Shoulder rotation	9	5.661	.035*
Error	5		
Elbow flexion/extension	9	8.162	.016*
Error	5		
Forearm rotation	9	5.373	.039*
Error	5		
Wrist flexion/extension	9	1.272	.415
Error	5		
Wrist ulnar/radial deviation	9	0.788	.644
Error	5		

B) Underarm throw

Dependent variable	df	F	p
Shoulder flexion/extension	9	42.710	.000*
Error	6		
Shoulder adduction/abduction	9	20.653	.001*
Error	6		
Shoulder rotation	9	5.485	.025*
Error	6		
Elbow flexion/extension	9	1.776	.249
Error	6		
Forearm rotation	9	1.067	..487
Error	6		
Wrist flexion/extension	9	0.387	.903
Error	6		
Wrist ulnar/radial deviation	9	1.289	.392
Error	6		

b) There will be no significant difference in the releasing joint angles between the overarm and the underarm throw for the same distance thrown.

However, for the Hypotheses Six (a), some joint angle, such as the wrist joint was confirmed this hypotheses.

Table 5.3 Mean and standard deviation, t and p values for the angular displacements at the releasing point of the overarm and the underarm throw for successive distances thrown.

A: Overarm throw

			First distance		Second distance			
Variables	df	A pair of distances	Mean	sd	Mean	sd	t	p
Shoulder flexion and extension	15	0.6 and 1.06	1.35	11.88	20.83	10.78	-7.73	0.00 *
	15	1.06 and 1.52	20.83	10.78	38.95	8.72	-11.00	0.00 *
	15	1.52 and 1.98	38.95	8.72	42.10	7.57	-1.46	0.16
	15	1.98 and 2.44	42.10	7.57	50.39	7.24	-3.87	0.00 *
	15	2.44 and 2.9	50.39	7.24	52.56	8.65	-1.80	0.09
	15	2.9 and 3.36	52.56	8.65	51.74	7.60	1.02	0.33
	15	3.36 and 4.05	51.74	7.60	51.72	7.94	0.02	0.98
	15	4.05 and 5.2	51.72	7.94	50.95	8.45	0.34	0.74
	13	5.2 and 6.91	50.95	8.45	44.65	6.75	5.07	0.00 *
Shoulder adduction and abduction	15	0.6 and 1.06	-30.56	7.66	-31.66	6.77	0.69	0.50
	15	1.06 and 1.52	-31.66	6.77	-36.42	13.04	2.25	0.04 *
	15	1.52 and 1.98	-36.42	13.04	-40.97	17.88	1.69	0.11
	15	1.98 and 2.44	-40.97	17.88	-53.76	16.96	3.45	0.00 *
	15	2.44 and 2.9	-53.76	16.96	-57.17	20.05	1.28	0.22
	15	2.9 and 3.36	-57.17	20.05	-64.86	19.31	3.07	0.01 *
	15	3.36 and 4.05	-64.86	19.31	-72.67	19.70	3.69	0.00 *
	15	4.05 and 5.2	-72.67	19.70	-79.15	17.55	1.71	0.11
	13	5.2 and 6.91	-79.15	17.55	-84.53	20.26	1.84	0.09

A: Overarm throw (continued)

Variables	df	A pair of distances	First distance Mean	First distance sd	Second distance Mean	Second distance sd	t	p
Shoulder rotation	15	0.6 and 1.06	-40.96	14.82	-34.42	11.42	-2.48	0.03 *
	15	1.06 and 1.52	-34.42	11.42	-25.31	10.02	-3.74	0.00 *
	15	1.52 and 1.98	-25.31	10.02	-26.20	11.10	0.52	0.61
	15	1.98 and 2.44	-26.20	11.10	-25.53	10.89	-0.35	0.73
	15	2.44 and 2.9	-25.53	10.89	-26.40	11.07	0.83	0.42
	15	2.9 and 3.36	-26.40	11.07	-27.19	14.83	0.62	0.54
	15	3.36 and 4.05	-27.19	14.83	-28.16	14.59	0.55	0.59
	15	4.05 and 5.2	-28.16	14.59	-32.23	12.35	1.48	0.16
	13	5.2 and 6.91	-32.23	12.35	-41.35	18.02	2.17	0.05 *
Elbow flexion and extension	15	0.6 and 1.06	102.99	21.50	94.54	13.39	1.77	0.10
	15	1.06 and 1.52	94.54	13.39	89.32	15.03	1.71	0.11
	15	1.52 and 1.98	89.32	15.03	90.65	19.41	-0.35	0.73
	15	1.98 and 2.44	90.65	19.41	80.23	14.02	2.47	0.03 *
	15	2.44 and 2.9	80.23	14.02	79.83	14.51	0.23	0.82
	15	2.9 and 3.36	79.83	14.51	84.56	12.83	-1.75	0.10
	15	3.36 and 4.05	84.56	12.83	86.73	17.83	-0.94	0.36
	15	4.05 and 5.2	86.73	17.83	88.30	17.12	-3.35	0.74
	13	5.2 and 6.91	88.30	17.12	91.94	19.97	-0.82	0.43
Forearm pronation and supination	15	0.6 and 1.06	59.97	17.37	68.17	16.37	-3.60	0.00 *
	15	1.06 and 1.52	68.17	16.37	70.36	14.30	-1.37	0.19
	15	1.52 and 1.98	70.36	14.30	72.08	14.25	-0.72	0.49
	15	1.98 and 2.44	72.08	14.25	74.79	14.44	-1.11	0.28
	15	2.44 and 2.9	74.79	14.44	74.85	13.32	-0.06	0.96
	15	2.9 and 3.36	74.85	13.32	72.17	15.77	1.42	0.18
	15	3.36 and 4.05	72.17	15.77	68.94	14.95	1.49	0.16
	15	4.05 and 5.2	68.94	14.95	67.54	14.45	0.54	0.60
	13	5.2 and 6.91	67.54	14.45	62.67	16.43	1.33	0.20

B: Underarm throw (continued)

Variables	df	A pair of distances	First distance Mean	First distance sd	Second distance Mean	Second distance sd	t	p
Shoulder flexion and extension	15	0.6 and 1.06	-5.55	7.31	3.81	8.63	-5.51	0.00 *
	15	1.06 and 1.52	3.81	8.63	11.27	9.06	-3.70	0.00 *
	15	1.52 and 1.98	11.27	9.06	16.45	9.26	-1.87	0.08
	15	1.98 and 2.44	16.45	9.26	13.02	12.81	1.06	0.31
	15	2.44 and 2.9	13.02	12.81	15.40	8.15	-0.89	0.39
	15	2.9 and 3.36	15.40	8.15	14.16	9.03	0.90	0.38
	15	3.36 and 4.05	14.16	9.03	11.60	10.52	1.57	0.14
	15	4.05 and 5.2	11.60	10.52	11.91	10.72	-0.14	0.89
	14	5.2 and 6.91	11.91	10.72	9.28	9.40	1.74	0.10
Shoulder adduction and abduction	15	0.6 and 1.06	-15.15	4.99	-17.49	4.48	2.89	0.01 *
	15	1.06 and 1.52	-17.49	4.48	-20.87	4.73	3.72	0.00 *
	15	1.52 and 1.98	-20.87	4.73	-23.53	5.00	2.93	0.01 *
	15	1.98 and 2.44	-23.53	5.00	-23.87	5.53	0.27	0.79
	15	2.44 and 2.9	-23.87	5.53	-23.89	5.16	0.03	0.98
	15	2.9 and 3.36	-23.89	5.16	-23.82	4.66	-0.11	0.91
	15	3.36 and 4.05	-23.82	4.66	-23.04	6.68	-0.91	0.38
	15	4.05 and 5.2	-23.04	6.68	-23.41	4.79	0.35	0.73
	14	5.2 and 6.91	-23.41	4.79	-22.42	4.73	-0.86	0.40
Shoulder rotation	15	0.6 and 1.06	-59.80	15.04	-56.00	14.59	-1.94	0.07
	15	1.06 and 1.52	-56.00	14.59	-48.27	13.25	-3.11	0.01 *
	15	1.52 and 1.98	-48.27	13.25	-47.64	11.08	-0.30	0.77
	15	1.98 and 2.44	-47.64	11.08	-47.29	15.08	-0.16	0.88
	15	2.44 and 2.9	-47.29	15.08	-49.34	12.94	1.01	0.33
	15	2.9 and 3.36	-49.34	12.94	-50.25	13.24	0.53	0.61
	15	3.36 and 4.05	-50.25	13.24	-52.14	15.12	0.90	0.38
	15	4.05 and 5.2	-52.14	15.12	-52.11	15.54	-0.01	0.99
	14	5.2 and 6.91	-52.11	15.54	-54.08	17.27	0.24	0.81

As the next step, only the significant angles from the Pillais trace were examined in detail. Paired t-tests were used to determined the difference between successive distances, that is, between the shortest (0.6 m) and 1.06 m, between 1.06 m and 1.52 m and so on. The last comparison was between 5.2 m and the longest distance thrown (6.91 m). The significant results of the paired t-tests are marked with an asterisk in Figure 5.10. Table 5.3 shows all the t and p values from the paired t-tests in both throwing patterns.

For the overarm throw, subjects mainly changed the range of motion of the shoulder joints at the releasing point as the distance thrown increased. That is four distances thrown are statistically different for shoulder flexion and extension ($t_{(15)} = -7.73$, $p = .00$; $t_{(15)} = -11.0$, $p = .00$; $t_{(15)} = -3.87$, $p = .00$ and $t_{(13)} = 5.07$, $p = .00$), four distances thrown are significantly different for shoulder adduction and abduction ($t_{(15)} = 2.25$, $p = .04$; $t_{(15)} = 3.45$, $p = .00$; $t_{(15)} = 3.07$, $p = .01$ and $t_{(15)} = 3.69$, $p = .00$) and three distances thrown were significantly different for shoulder rotation ($t_{(15)} = -2.48$, $p = .03$; $t_{(15)} = -3.74$, $p = .00$ and $t_{(13)} = 2.17$, $p = .05$). Only one distance thrown showed a significant difference for the releasing angles for elbow flexion and extension ($t_{(15)} = 2.47$, $p = .03$) and for forearm pronation and supination ($t_{(15)} = -3.60$, $p = .00$).

In general, there is a trend toward an increase in the releasing angles for shoulder motions as the distance thrown increased in the overarm throw. This tendency is not clearly shown in other joint angles, that is, the elbow, radioulnar and wrist joints.

For the underarm throw, the releasing angle of shoulder flexion and extension and shoulder adduction and abduction significantly increased particularly over the two shortest distances ($t_{(15)} = -5.51$, $p = .00$ and $t_{(15)} = -3.70$, $p = .00$ for shoulder flexion and $t_{(15)} = 2.89$, $p = .01$; $t_{(15)} = 3.72$, $p = .00$ and $t_{(15)} = 2.93$, $p = .01$ for shoulder adduction respectively). For shoulder rotation, a significant difference was shown between the second and the third distances thrown ($t_{(15)} = -3.11$, $p = .01$). Other joint angles, that is, forearm rotation, elbow and wrist motions, demonstrated the same releasing position over all the distances thrown.

5.4.7 Angular velocity of the overarm and the underarm patterns

The mean angular velocity of all 16 subjects for each joint angle was compared as the distance thrown increased. The joint velocity data for the overarm and underarm throws (Figure 5.11 to 5.12, respectively) demonstrate a common result. That is, the preparation phase showed a more homogenous velocity than the velocity recorded in the releasing phase as the distance thrown increased. This can be observed, for example, in the elbow and wrist motions for the overarm throw and shoulder adduction, shoulder rotation, elbow flexion, forearm rotation and wrist movements for the underarm throw (Figure 5.11 to 5.12). Most of the joint angle velocities in the releasing phase showed a degree of positive relationship to the distances thrown, except the forearm pronation and supination for the underarm throw. The rather consistent angular velocity of pronation and supination for the underarm throw suggests that the radioulnar joint does not contribute to the increasing velocity at the releasing point as the distance thrown increased when subjects used the underarm pattern.

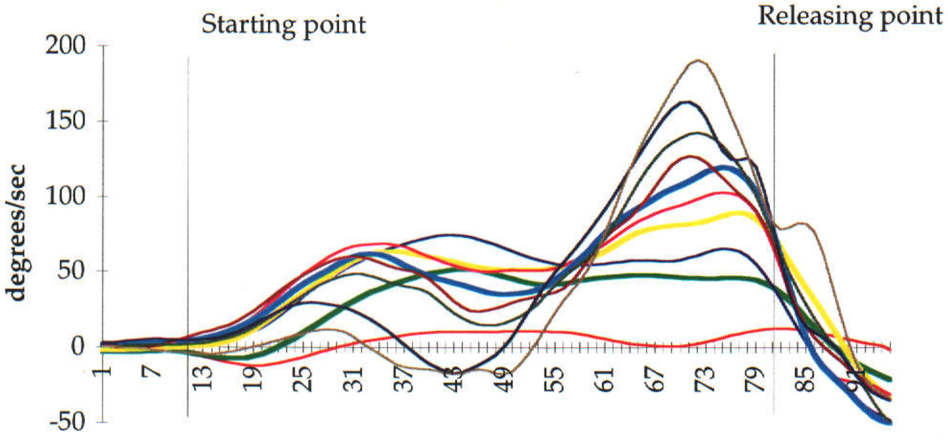
For the overarm throw, angular velocities for shoulder motions show a step increment in both the preparation and releasing phase as the distance thrown increased. Whereas, only shoulder flexion and extension showed a step increase in the preparation phase as the distance thrown increased for the underarm throw. The results suggest a more distinct role for the shoulder joint than for other joints as the distance thrown increased, a finding which is similar to the results for the angular displacements.

These results partially supported the Hypothesis Seven (a), which stated that:

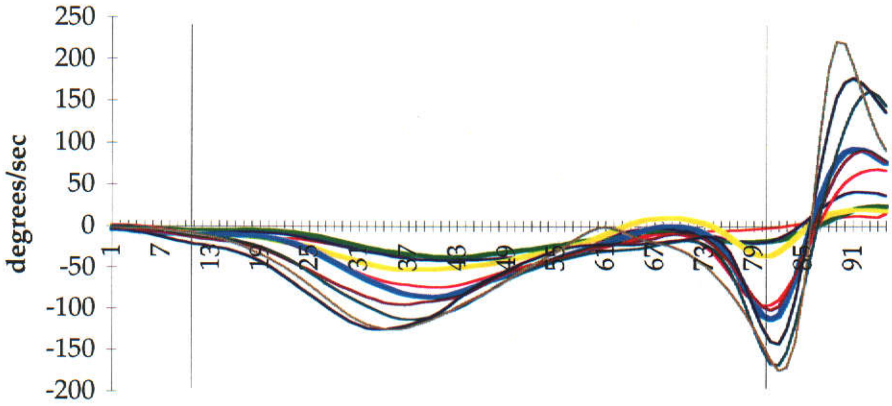
Angular velocity of all joint angles at the releasing point will be greater when throwing to the longer distances. Only the results of pronation and supination for the underarm throw do not agree with this hypothesis.

The sequential velocity for the overarm and the underarm throws are illustrated in Figure 5.13. The peak angular velocity of shoulder, elbow and wrist flexion and extension occurred at different times in the overarm throw. The shoulder joint reached the maximum value earlier than the other joints. However, the maximum angular velocity of the shoulder, elbow and wrist joints for the underarm throw was attained at approximately the same point in the throw. The results imply that the overarm movement may occur in a sequential manner while the underarm motion shows a pendulum like action.

A) Shoulder flexion and extension



B) Shoulder adduction and abduction



C) Shoulder internal and external rotation

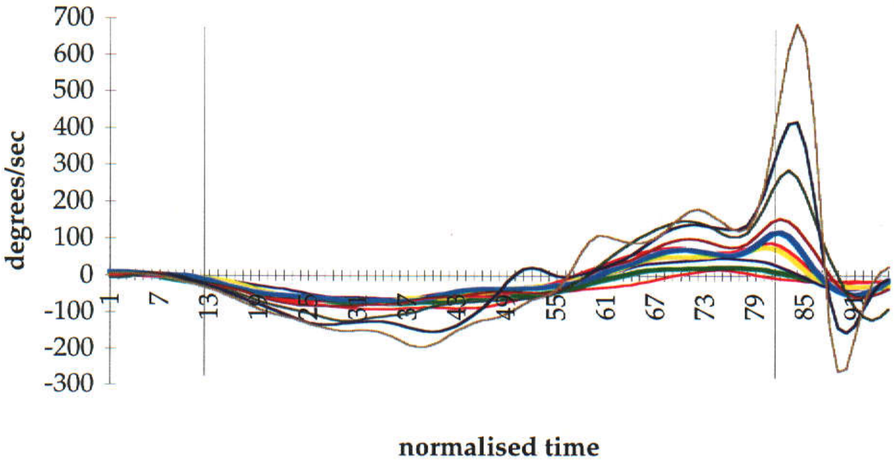
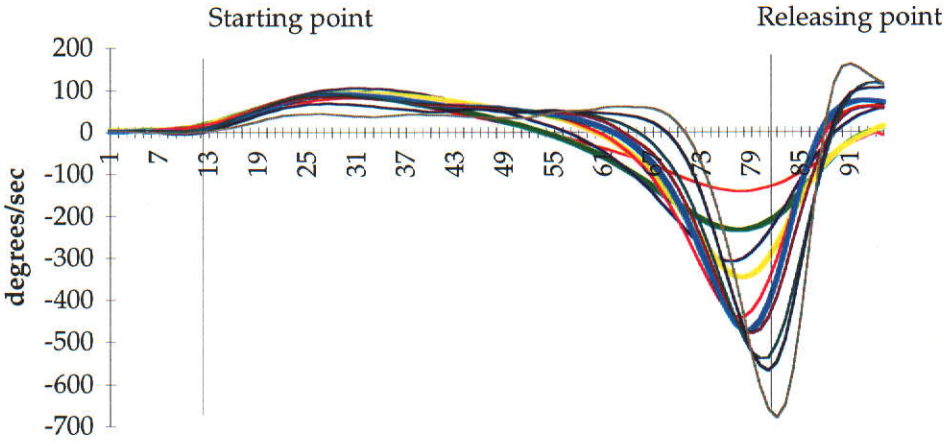


Figure 5.11 Mean angular velocity of the overarm throw as the distance thrown increased. (Legend see page 184)

D) Elbow flexion and extension



E) Forearm pronation and supination

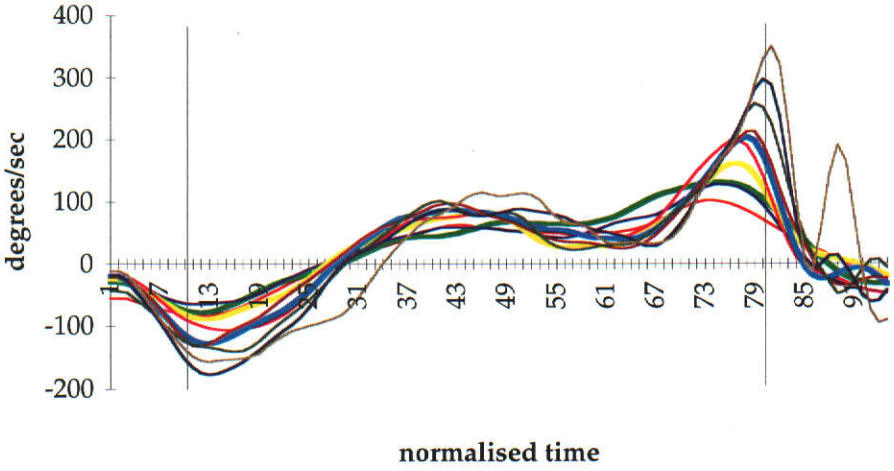
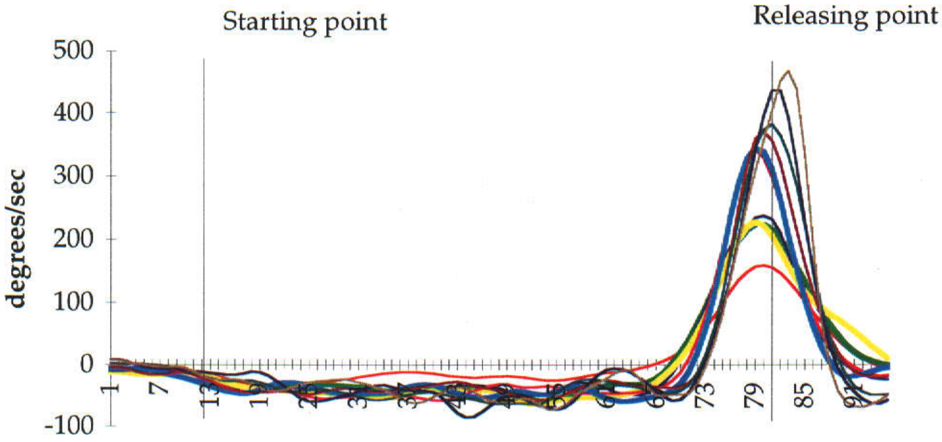


Figure 5.11 (continued) Mean angular velocity of the overarm throw as the distance thrown increased. (Legend see page 184)

F) Wrist flexion and extension



G) Wrist ulnar and radial deviation

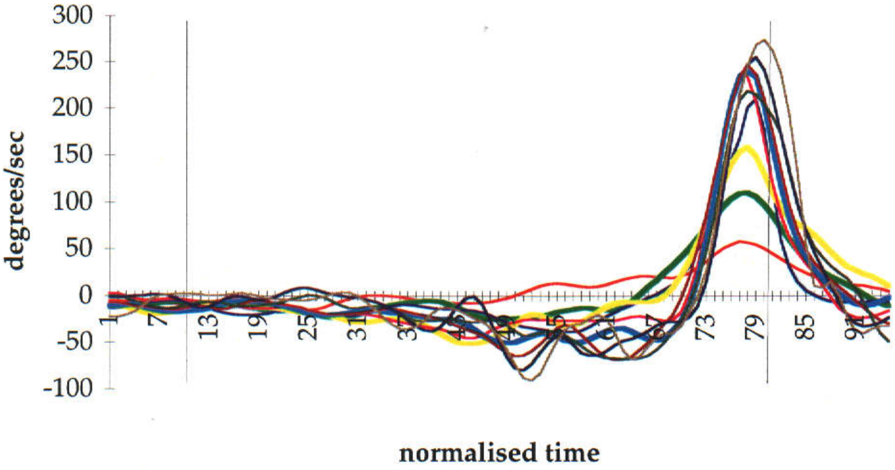
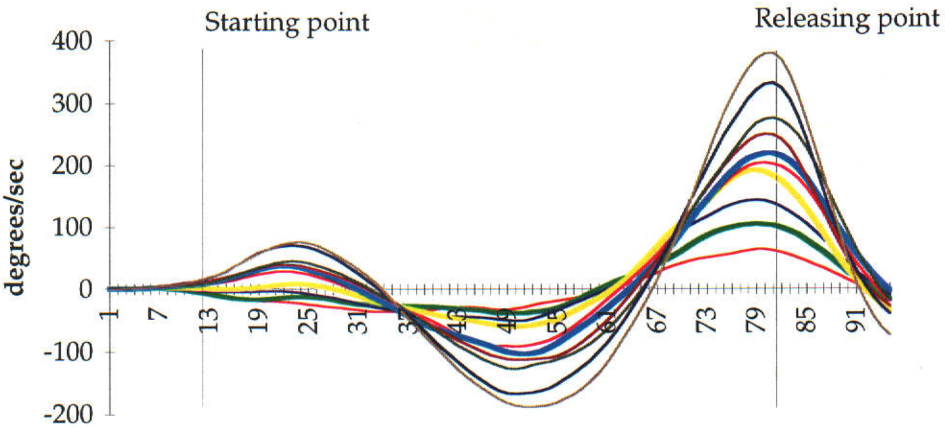


Figure 5.11 (continued) Mean angular velocity of the overarm throw as the distance thrown increased.

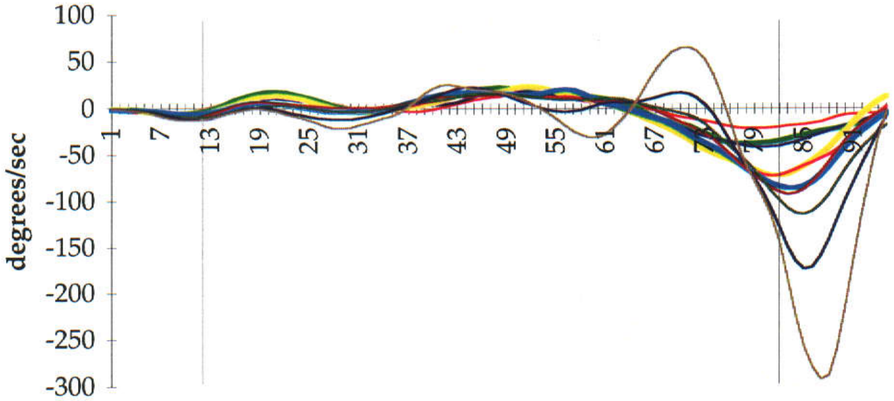
— 0.6 m, — 1.06 m,
— 1.52 m, — 1.98 m,
— 2.44 m, — 2.9 m,
— 3.36 m, — 4.05 m,
— 5.2 m, — 6.91 m

Flexion, adduction, internal rotation, pronation and ulnar deviation have a positive sign whereas, extension, abduction, external rotation, supination and radial deviation have a negative sign.

A) Shoulder flexion and extension



B) Shoulder adduction and abduction



C) Shoulder internal and external rotation

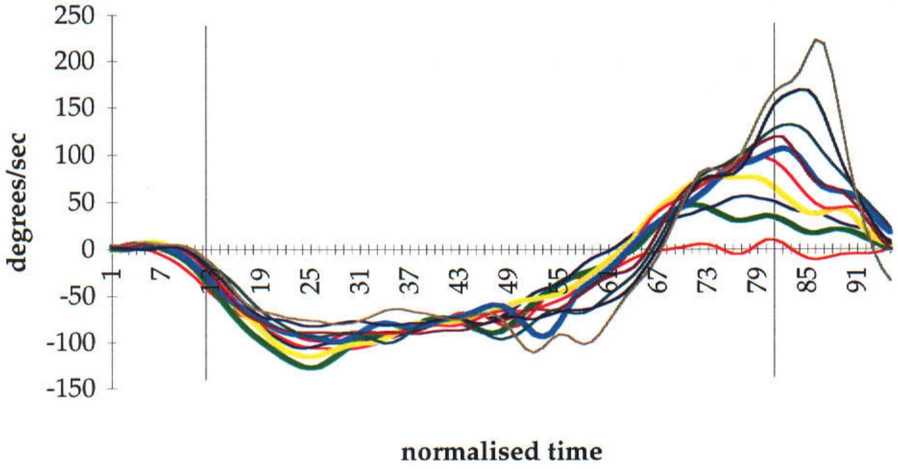
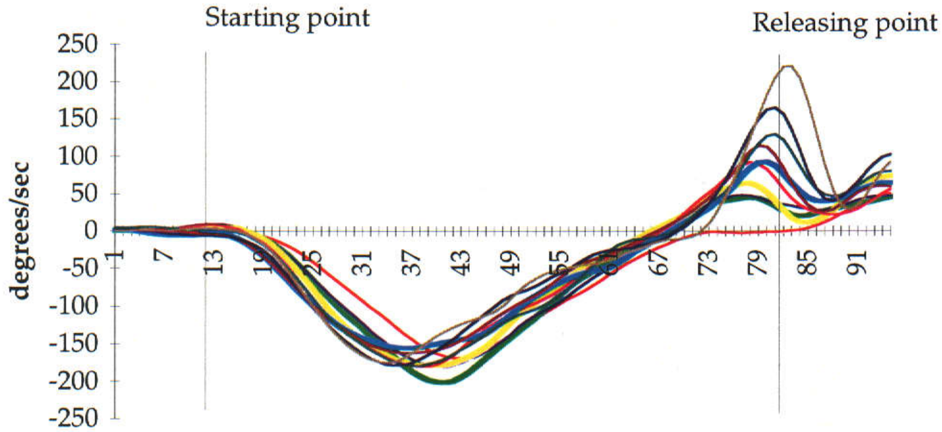


Figure 5.12 Mean angular velocity of the underarm throw as the distance thrown increased. (Legend see page 187)

D) Elbow flexion and extension



E) Forearm pronation and supination

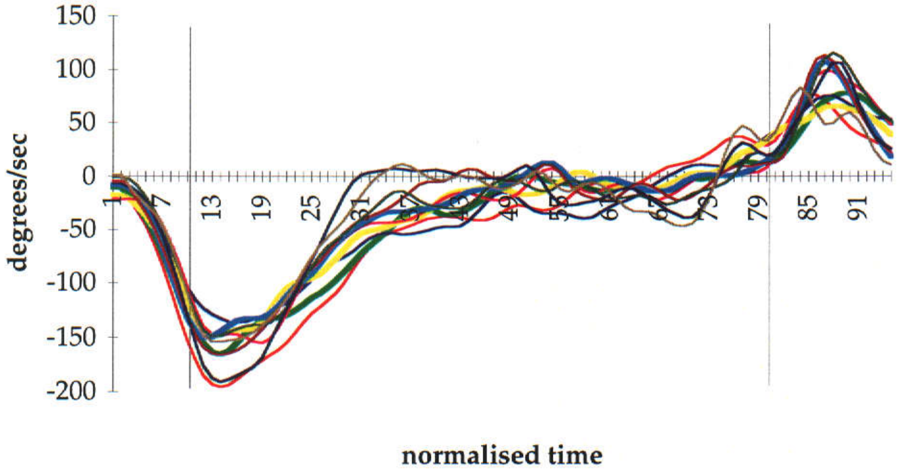
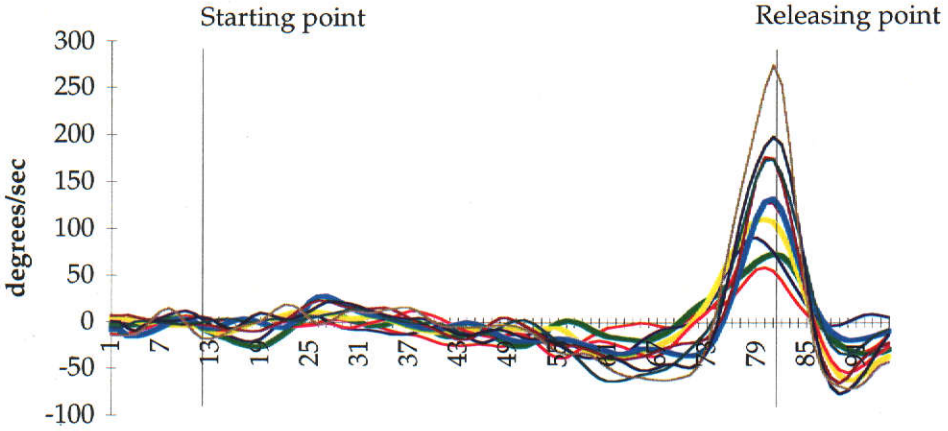


Figure 5.12 (continued) Mean angular velocity of the underarm throw as the distance thrown increased. (Legend see page 187)

F) Wrist flexion and extension



G) Wrist ulnar and radial deviation

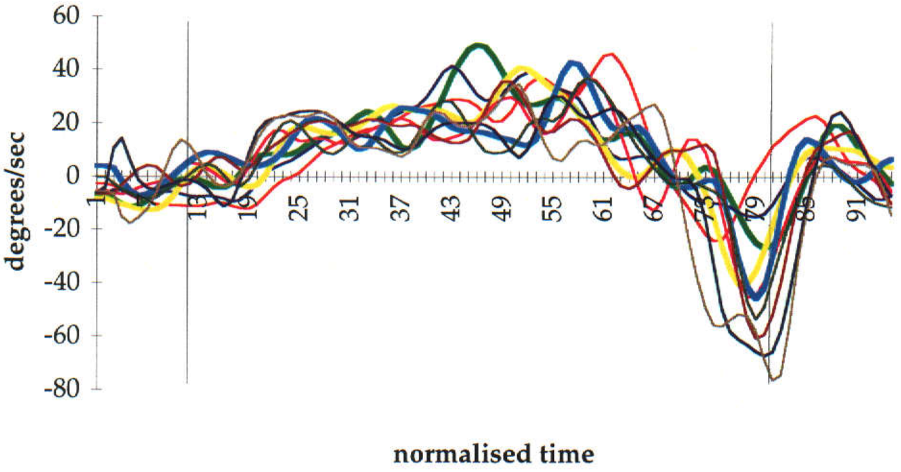
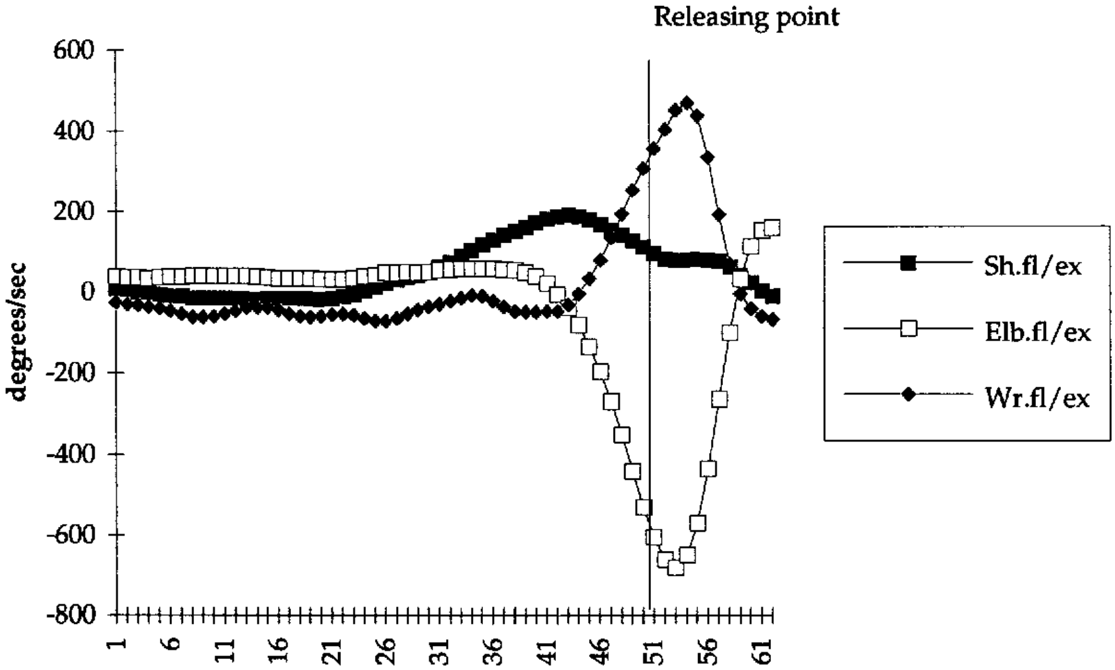


Figure 5.12 (continued) Mean angular velocity of the underarm throw as the distance thrown increased.

— 0.6 m, — 1.06 m,
— 1.52 m, — 1.98 m,
— 2.44 m, — 2.9 m,
— 3.36 m, — 4.05 m,
— 5.2 m, — 6.91 m

Flexion, adduction, internal rotation, pronation and ulnar deviation have a positive sign whereas, extension, abduction, external rotation, supination and radial deviation have a negative sign.

A) Overarm throw



B) Underarm throw

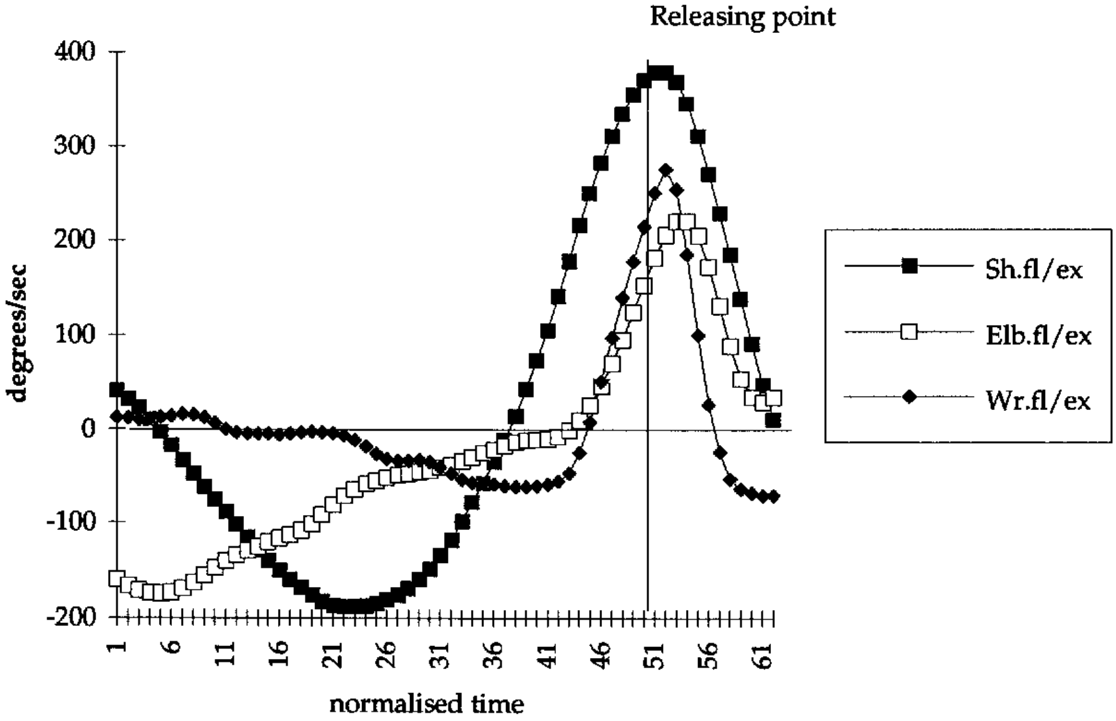


Figure 5. 13 The temporal position of the peak angular velocity of shoulder, elbow and wrist flexion and extension for the overarm and the underarm throws. The tracings represent the mean angular velocity over the distance thrown of 6.91 m. and include data from picture number 30th onward.

Only the results of the overarm throw supported Hypothesis Seven (b), which stated that:

Sequential peak angular velocity will be demonstrated especially at the longest distance thrown.

5.5 Order parameter

5.5.1 Trajectories of throwing

The trajectories of all 16 subjects for the overarm and the underarm throw are shown in the Figure 5.14 to 5.19. Only the tracings of the throwing motion for the distance 0.6, 1.98 and 6.91 m are illustrated. Movements of the shoulder, elbow, wrist and hand in the sagittal plane are displayed from the first picture (10 pictures before the starting point) to the end of the data files (20 pictures after the releasing point). The marker attached at the tubercle of the iliac crest (labelled as trunk) is shown as the reference point. The trajectories were plotted as if subjects were lying on their backs. Thus, it is easier to see the pattern of throwing when the figures were rotated to the right 90 degrees. Variability of the trajectories of movement was high when subjects threw to the shortest distance (0.6 m) for both patterns (Figure 5.14 and 5.17). Patterns of trajectories become more uniform when the distance thrown increased (Figure 5.15 and 5.16 for the overarm and Figure 5.18 and 5.19 for the underarm respectively).

These findings supported Hypotheses Eight (b &c) and were therefore accepted.

Hypotheses Eight (b & c) stated that:

b) Trajectories of movement can differentiate throwing patterns as the distance thrown increases for the overarm and the underarm throw.

c) Trajectories of movement can differentiate the throwing pattern between the overarm and the underarm throw.

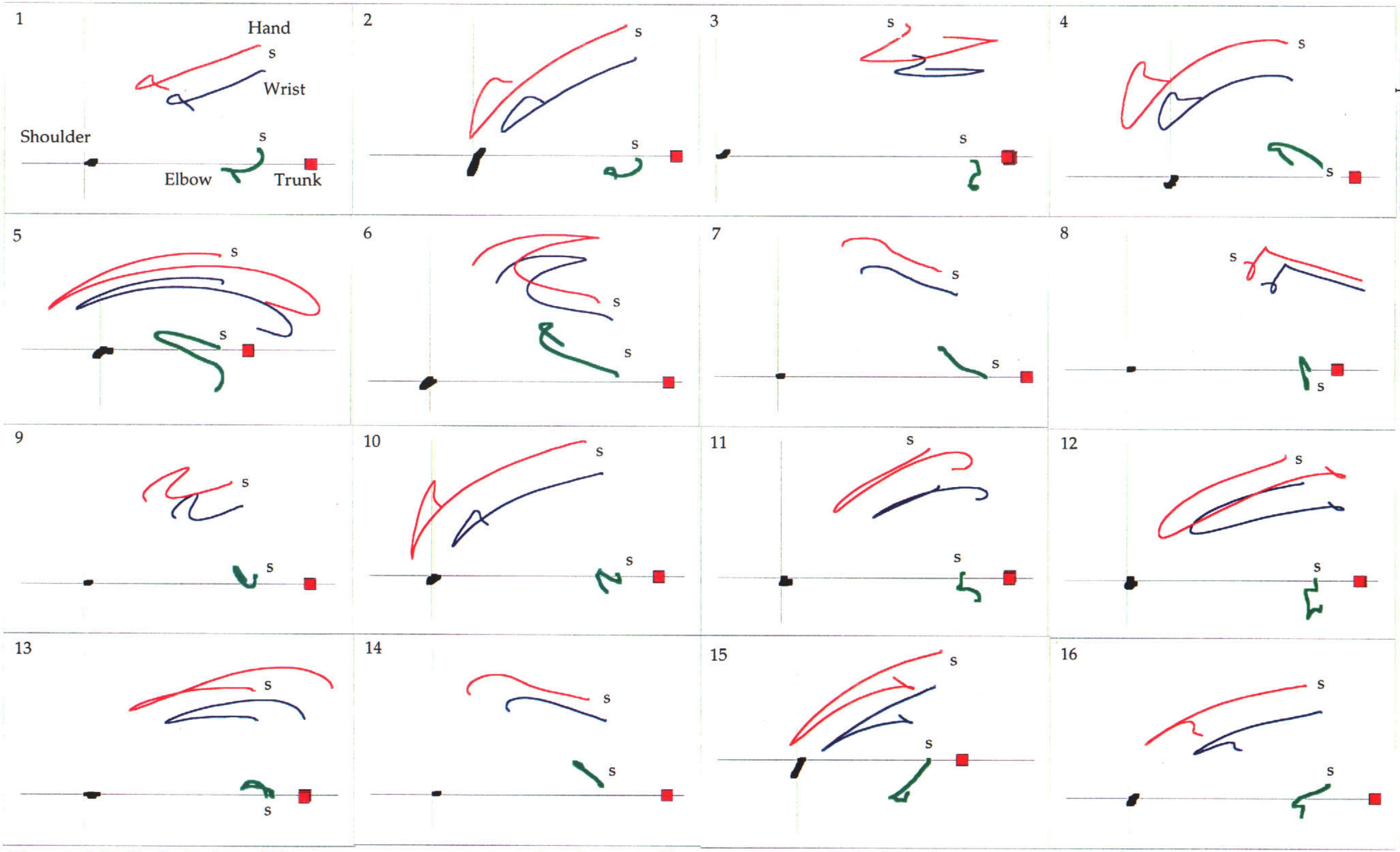


Figure 5.14 Trajectories of the overarm pattern over the shortest distance thrown (0.6 m) in the sagittal plane of 16 subjects. (s = starting point)

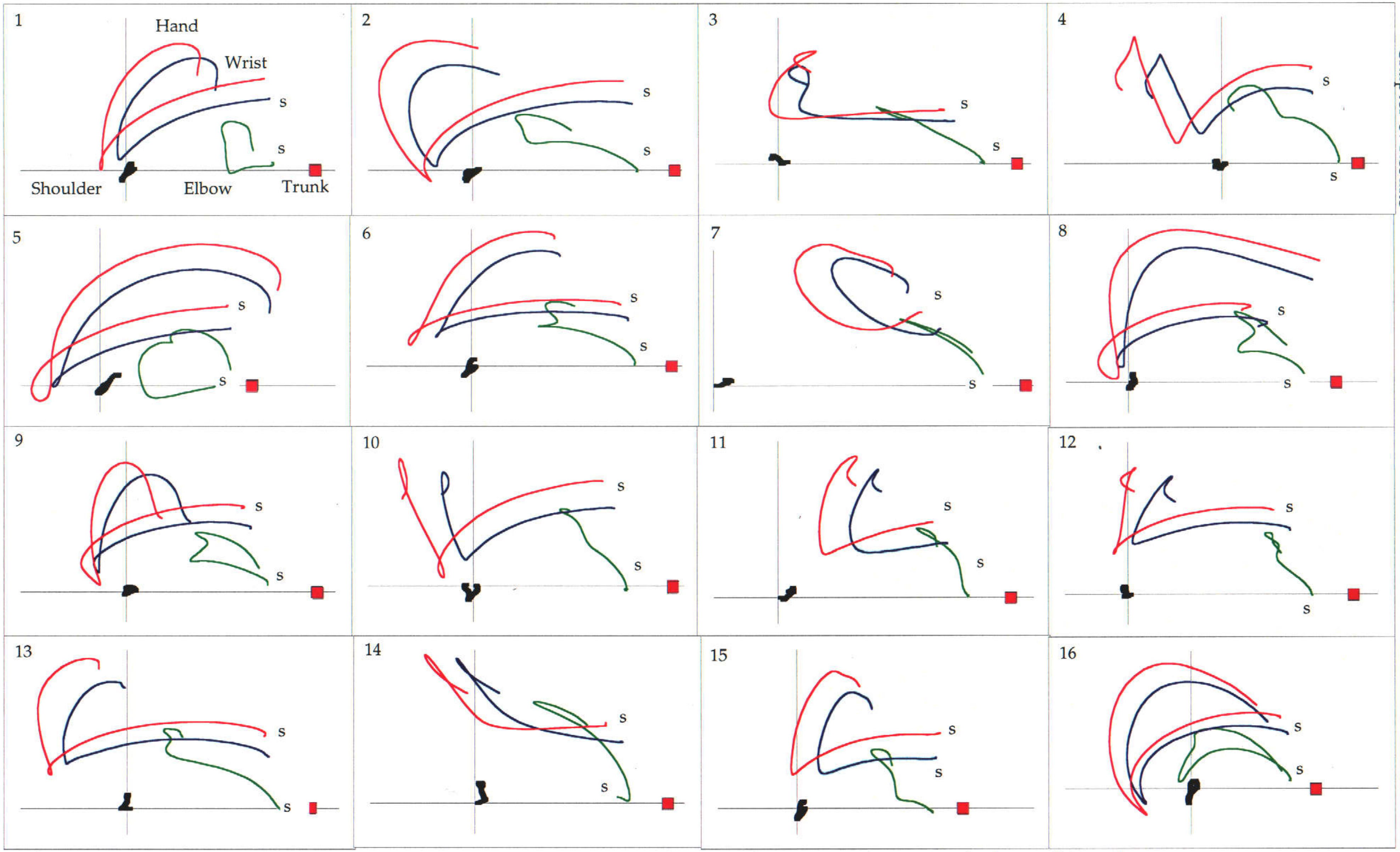


Figure 5.15 Trajectories of the overarm pattern over the distance thrown of 1.98 m in the sagittal plane of 16 subjects. (s = starting point)

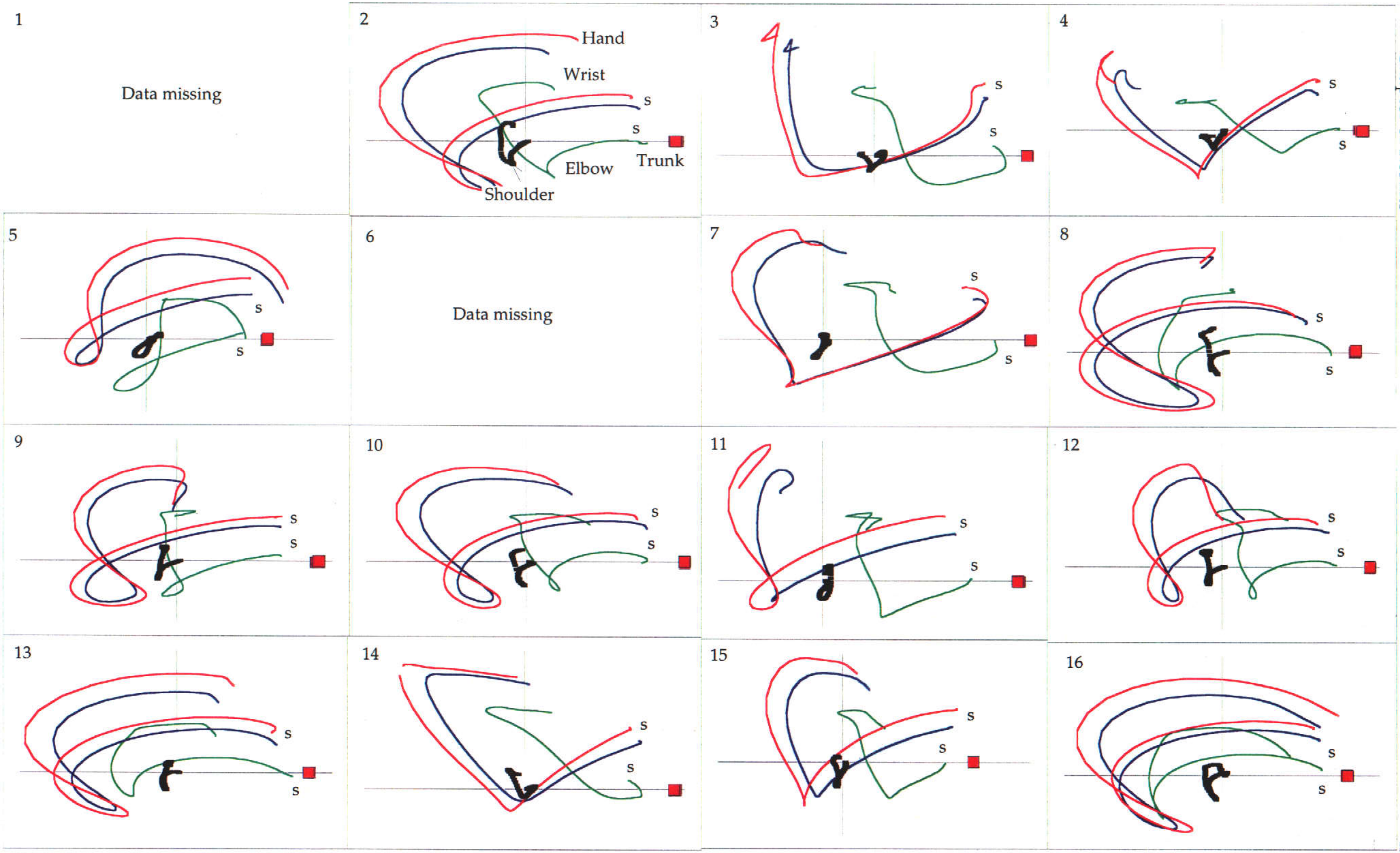


Figure 5.16 Trajectories of the overarm pattern over the longest distance thrown (6.91 m) in the sagittal plane of 14 subjects. (s = starting point)

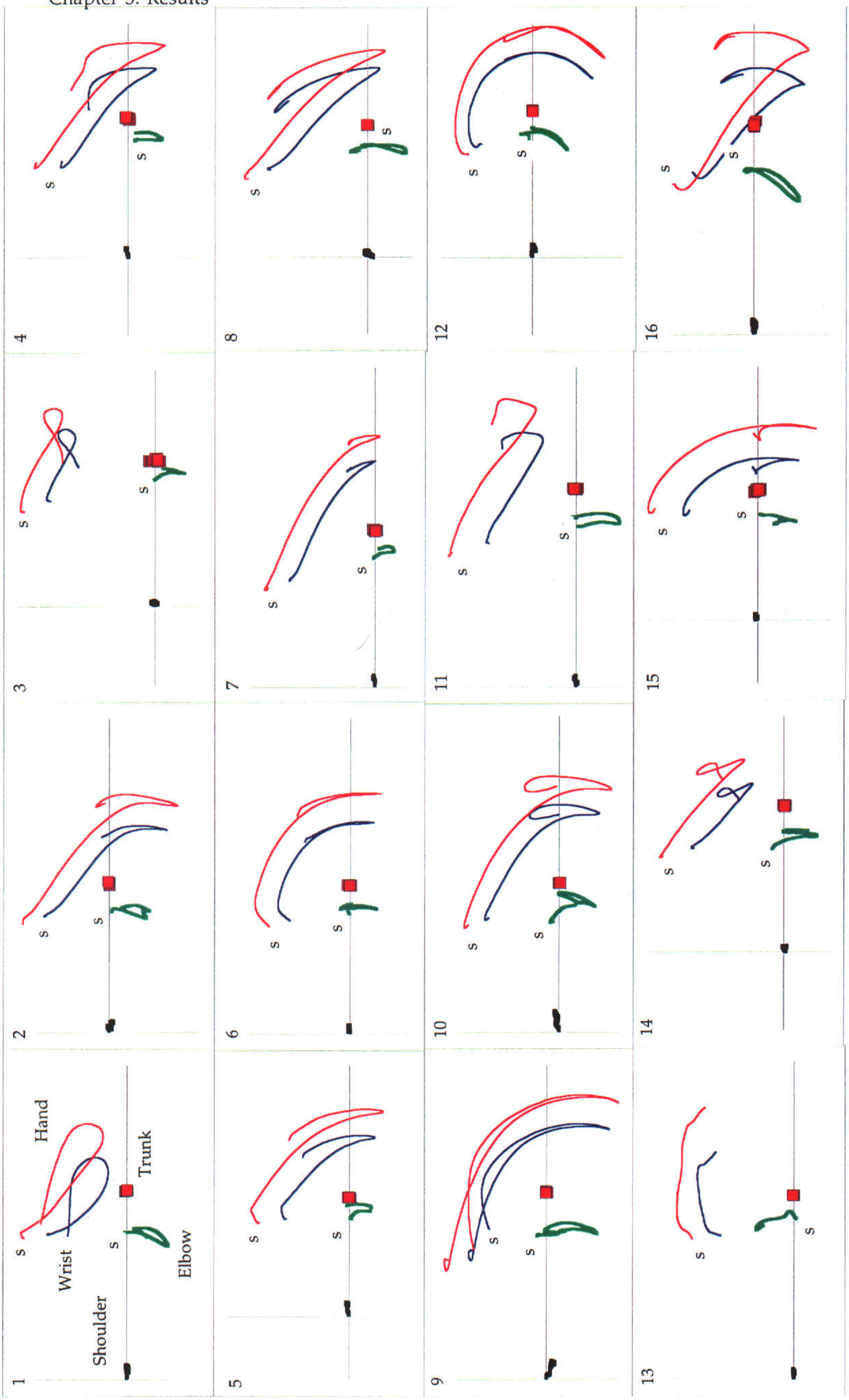


Figure 5.17 Trajectories of the underarm pattern over the shortest distance thrown (0.6 m) in the sagittal plane of 16 subjects. (s = starting point)

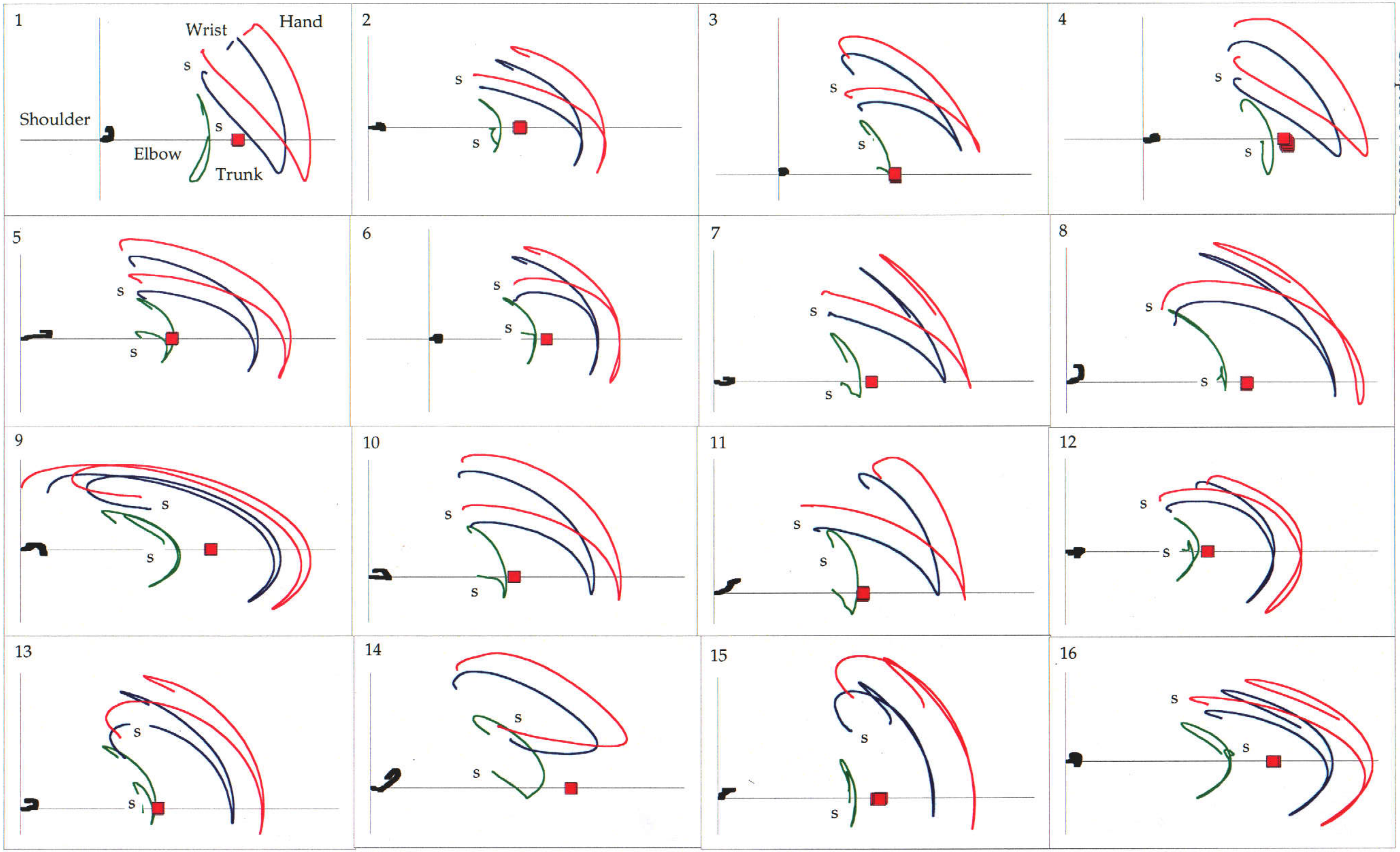


Figure 5.18 Trajectories of the underarm pattern over the distance thrown of 1.98 m in the sagittal plane of 16 subjects. (s = starting point)

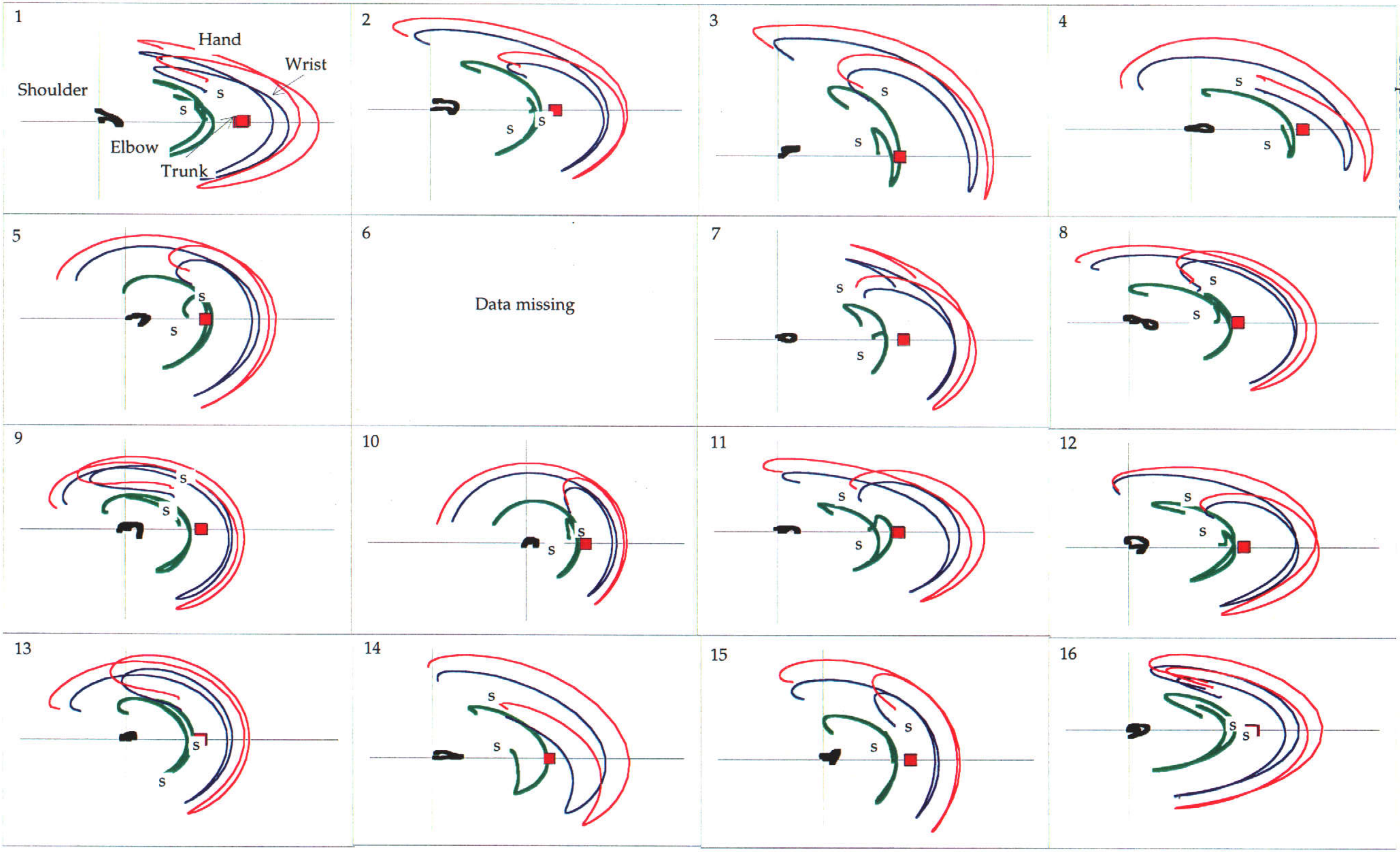


Figure 5.19 Trajectories of the underarm pattern over the longest distance thrown (6.91 m) in the sagittal plane of 15 subjects. (s = starting point)

5.5.2 The phase plane plot (angular displacement and angular velocity)

The mean angular displacement and angular velocity of 16 subjects were time and amplitude normalised as has been described in Chapter 4, Section 4.2. The normalised angular displacement and angular velocity were used to plot a phase plane diagram to aid comparison of the phase plane plots as the distance thrown increased. These phase plane plots characterise the control mechanisms of the throwing movement. Only the phase plane plots of shoulder flexion and extension for both throwing patterns are displayed in this section. The phase plane plots of other joints are presented in Appendix D.

5.5.2.1 Overarm throw

The phase plane plots for shoulder motion (Figure 5.20 and Figure 2 & 3 in Appendix D) proceed clockwise in a flexion, external rotation and abduction motion. The trajectories consist of a kink and a convex segments. The kink in the curve represents the point at which subjects changed the direction of movement. The profile of this joint is similar to that for rotation of the radioulnar joint (Figure 4 in Appendix D).

The phase plane plot for elbow flexion and extension (Figure 5 in Appendix D) moves parallel to the x-axis in the clockwise direction, crosses the zero velocity line and forms a round segment. The round corner of the trajectories before passing the zero line represents the time when subjects reversed the motion. The phase plane plots for the wrist joint (Figure 6 and 7 in Appendix D) are comparable to the phase plane plot for the elbow joint.

Even though the phase plane plots for the shoulder and the elbow joints demonstrate the position where movement changed direction, the characteristics of these curves are not the same. The first is represented by a kink and the second by a round segment crossing the zero velocity line. This difference implies that there are probably different control mechanisms for the shoulder and elbow joints.

Only the phase plane plots of shoulder flexion, shoulder adduction, shoulder rotation and wrist deviation showed different profiles when compared across the distances thrown. Phase plane plots of these angles for the shortest distance were different from the other distances. The phase plane plot of shoulder adduction at the shortest distance is slightly different from other distances thrown, that is, it does not show a kink in the releasing phase of throwing. Furthermore, phase plane plots of shoulder flexion at the two longest distances were also different from the other distances thrown. Phase plane plots of other joints, that is, elbow flexion, forearm rotation and wrist flexion appeared visually to be the same when compared across the distances thrown. The results suggest that subjects may employ different styles of shoulder motions when throwing to the shortest distance and the other longer distances.

5.5.2.2 Underarm throw

Unlike the overarm pattern, the displacement and the velocity plots in the underarm throw demonstrate different patterns between shoulder elevation and shoulder rotation. The trajectories for shoulder flexion and extension (Figure 5.21), shoulder adduction and abduction and wrist flexion and extension (Figure 8 to 10 in Appendix D) are rounded curves. This shape of the curve indicates the reversal of movement which resembles a pendular movement. The phase plane plot for shoulder rotation (Figure 11 in Appendix D) moves rather horizontally, cuts the zero velocity line then forms a round segment. The path during the flat horizontal segment for greater distances thrown shows a changing range of motion while the angular velocity is maintained. The phase plane plots for forearm rotation (Figure 12 in Appendix D) are similar to that of shoulder rotation but there is no horizontal segment in the trajectories of forearm rotation.

The phase plane plots for the elbow joint (Figure 13 in Appendix D) are similar to that for shoulder rotation except that there is a kink in the segment after the curve passes the zero velocity line.

Even though the phase plane plots for the shoulder joint in both styles of throwing demonstrate a reversal of the motion, the control of movement in these two patterns does not appear to be the same. A kink in the trajectory of the overarm throw represents a sudden change of direction of forces whereas the round segment in the underarm pattern suggests that the forces gradually vary as the movement progresses. This means that in the overarm throw, the shoulder joint alters its velocity by the sudden shift of force to the opposite direction whereas in the underarm throw the velocity is smoothly developed as the shoulder joint is displaced.

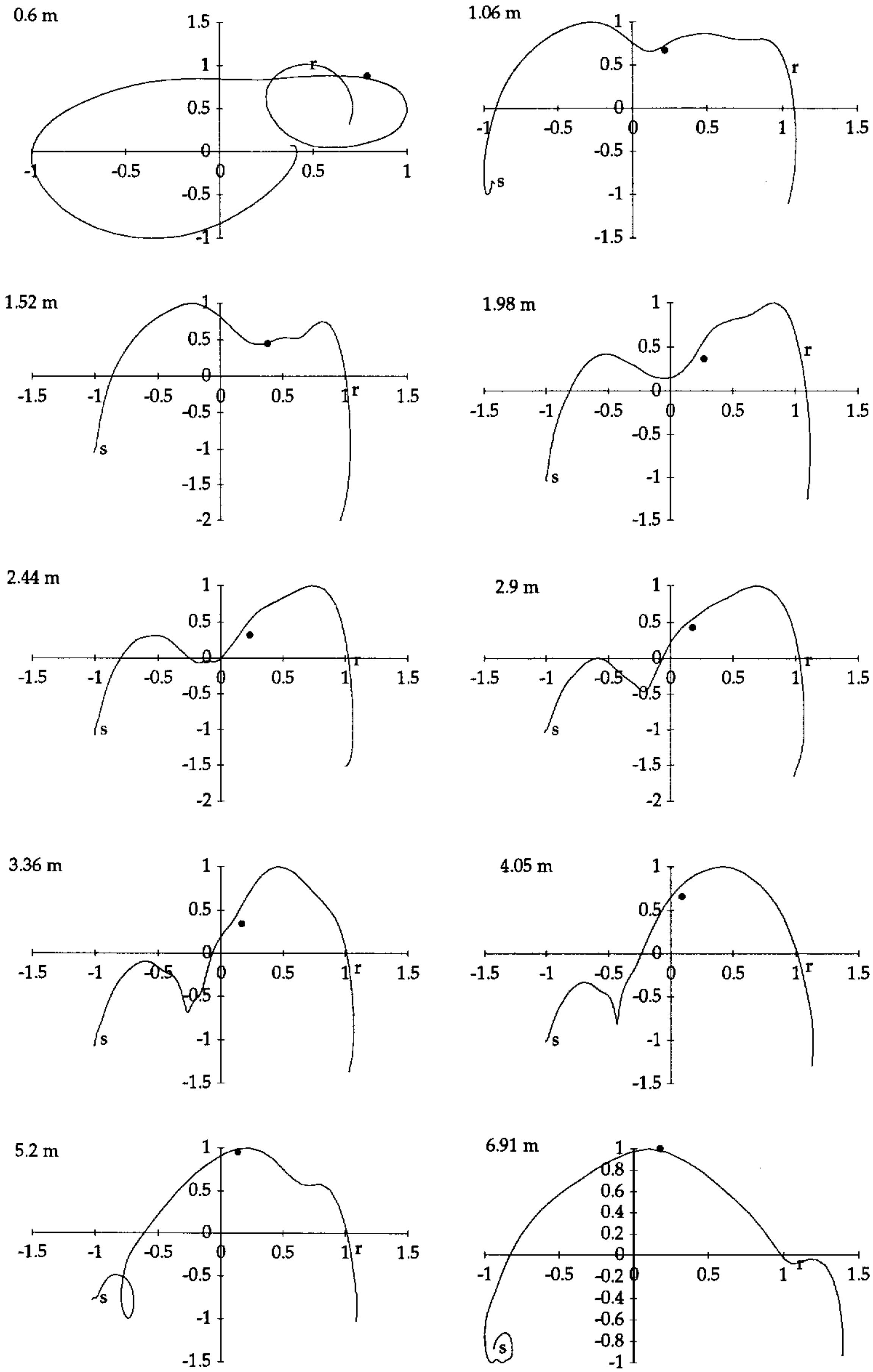


Figure 5.20 Phase plane plot of shoulder flexion and extension of the overarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

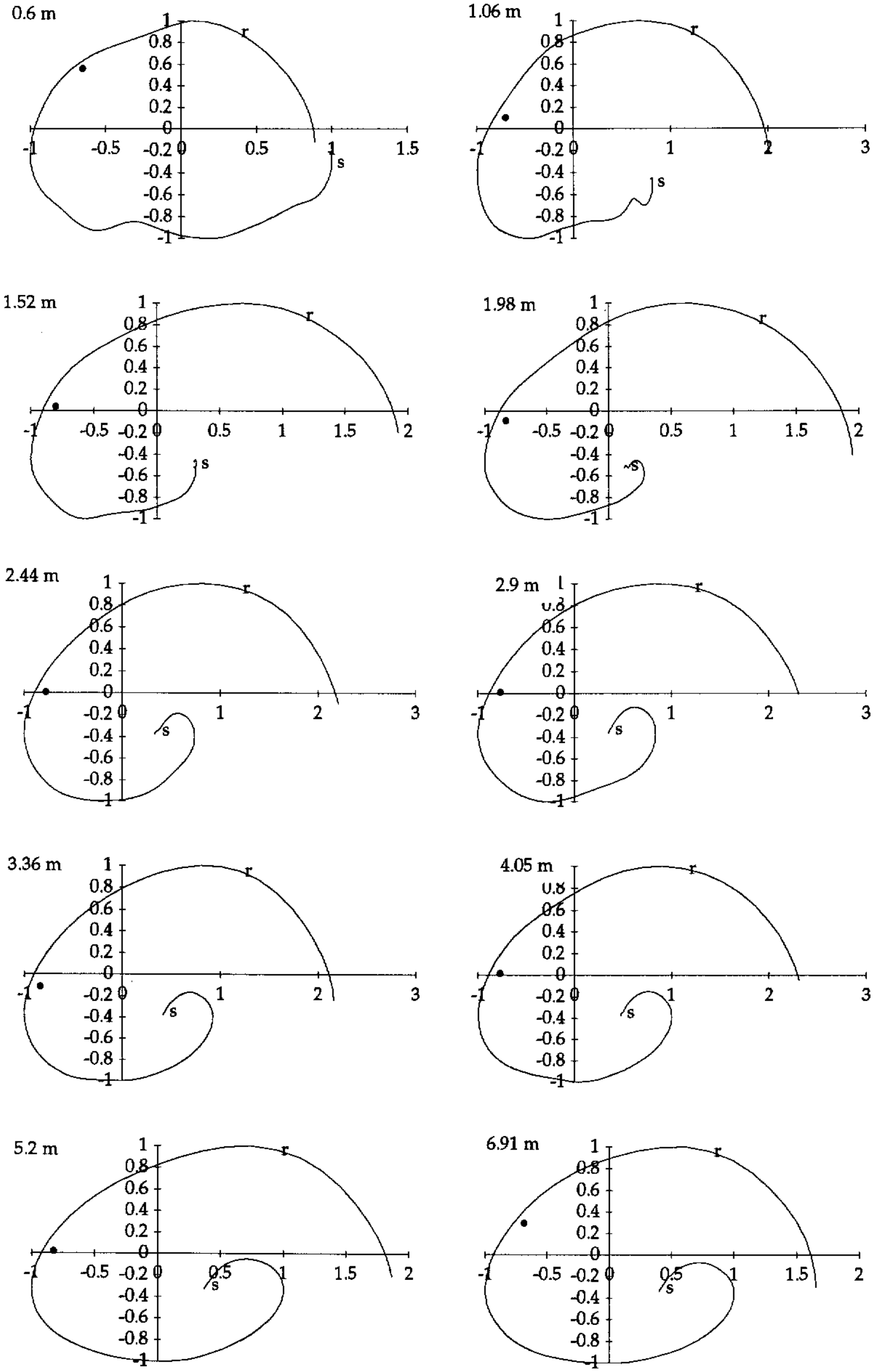


Figure 5.21 Phase plane plot of shoulder flexion and extension of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

Phase plane plots of the wrist ulnar and radial deviation (Figure 14 in Appendix D) show a similar shape as the distance thrown increased. The curve moves clockwise parallel to the x-axis then forms a rounded segment which becomes bigger as the distance thrown increases. The horizontal segment in the plots is not a smooth straight line but shows a high degree of variation. This may be due to the small amplitude in angular displacement (Figure 5.5G) and angular velocity (Figure 5.10G) which may be a result of noise being more apparent here than in other joint angles.

For the underarm throw, the phase plane profile of shoulder flexion and shoulder adduction for the shortest distance thrown is not the same shape as for the other distances. However, the difference was not obviously demonstrated when compared with the overarm throw.

The phase plane plots for both throwing patterns mainly show the change of the relationship between angular displacement and angular velocity of the shoulder joint as the distance thrown increases.

5.5.2.3 Cross-correlation

The cross-correlation (Rxy) between the pairs of distances thrown were determined for all phase plane plots in both throwing patterns. The calculation method has been described in Chapter 4 Section 4.2.7. Rxy of all phase plane plots for the overarm throw and the underarm throw were presented in Figure 5.22 and 5.23 respectively.

For the overarm throw, Rxy of the shortest distance (0.6 m) for shoulder flexion, shoulder rotation and wrist deviation (Figure 5.22 A, C and G) show the low correlation when compared with other distances thrown. In addition, Rxy of the phase plane plot of shoulder flexion for the two longest distances also show a lower correlation when compared across other distances thrown. Rxy of the phase plane plots of shoulder adduction, forearm rotation and wrist flexion (Figure 5.22 B, E and F) demonstrate a consistent relationship as the distance thrown increased. These results agree with the interpretation of the phase plane curve using visual comparison only. However, visual comparison of the phase plane plot for elbow flexion is different from the results of the cross-correlation. Rxy of elbow flexion (Figure 5.22 D) shows a graded lower correlation as the distance thrown

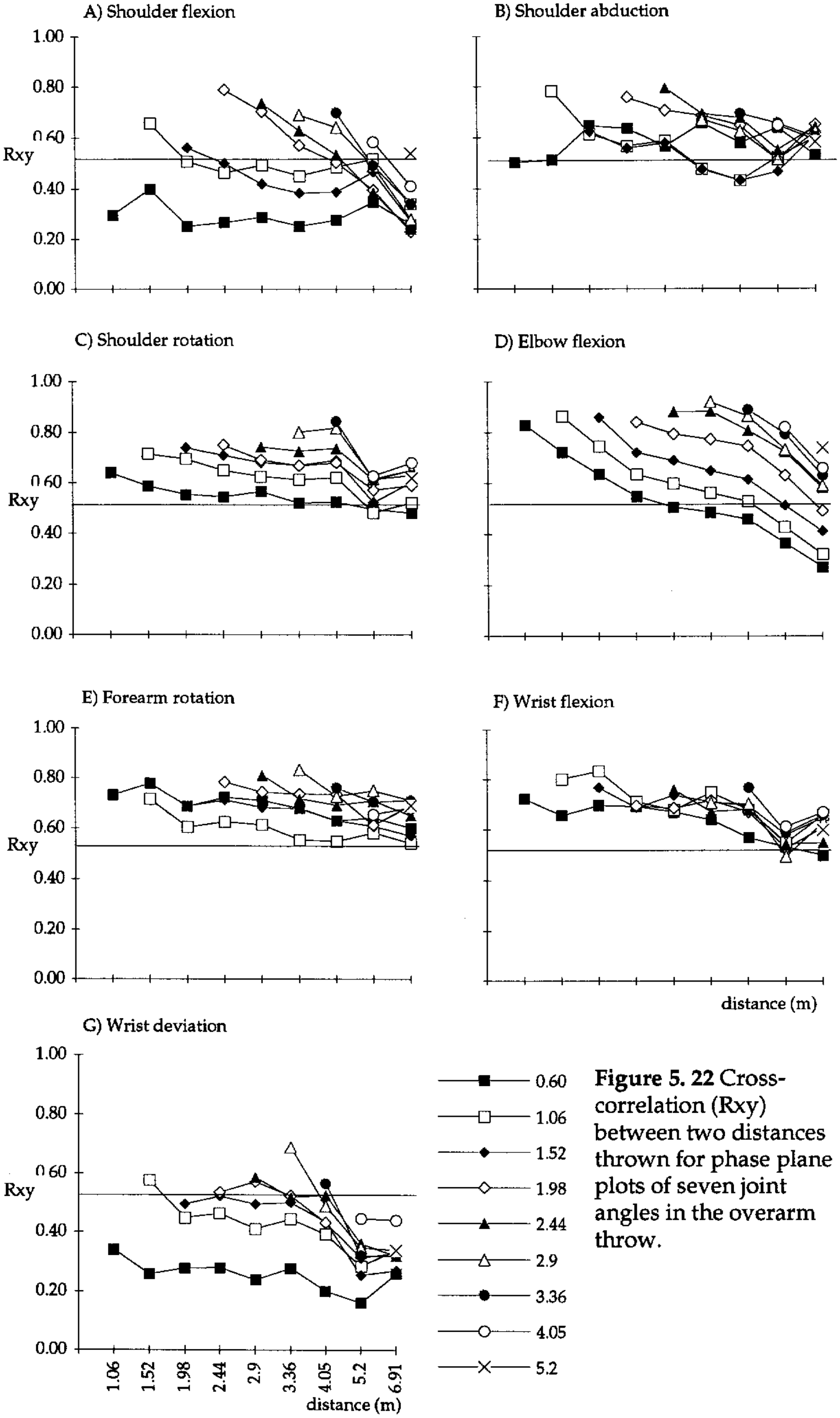
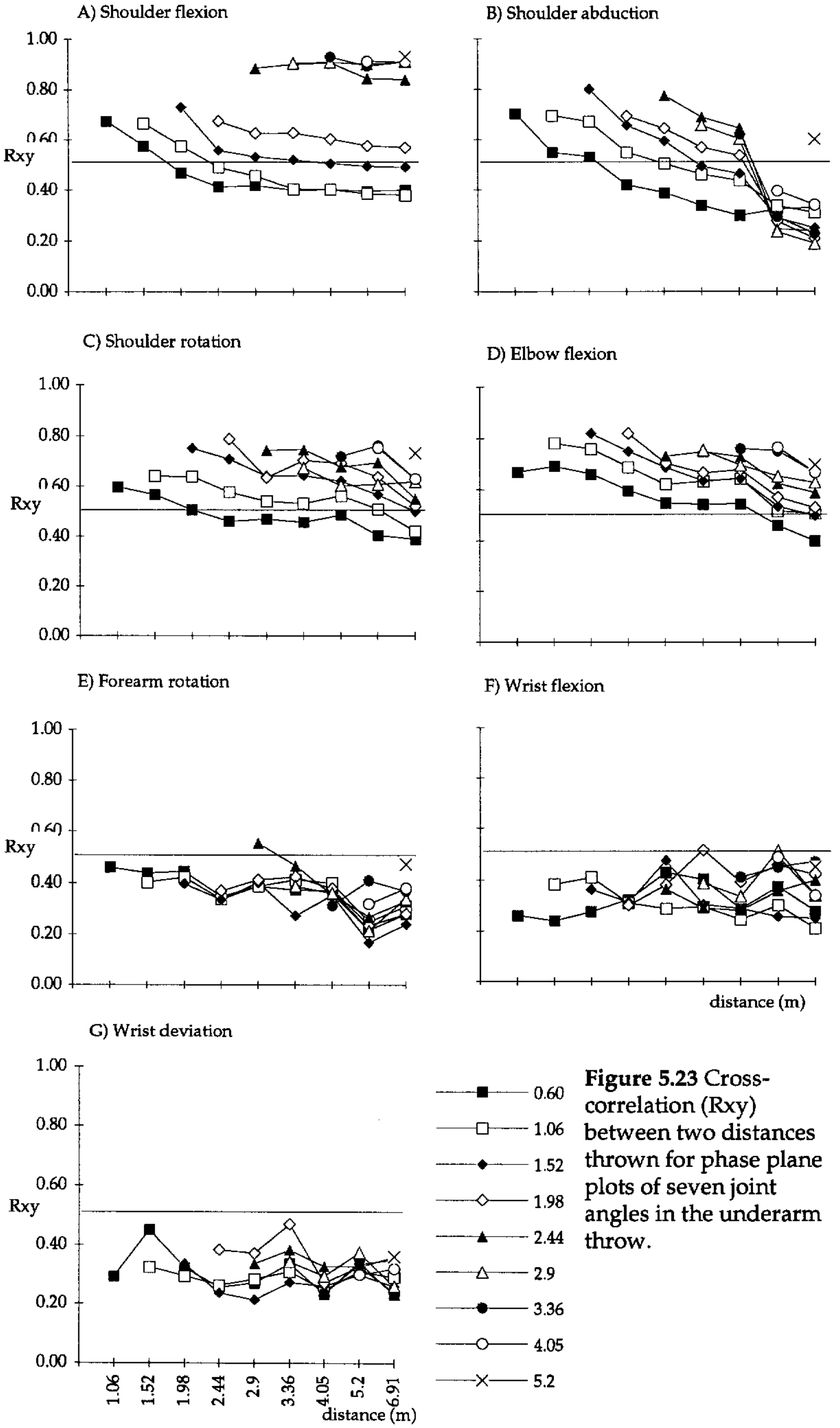


Figure 5. 22 Cross-correlation (Rxy) between two distances thrown for phase plane plots of seven joint angles in the overarm throw.



A) Shoulder flexion

B) Shoulder abduction

C) Shoulder rotation

D) Elbow flexion

E) Forearm rotation

F) Wrist flexion

G) Wrist deviation

Figure 5.23 Cross-correlation (Rxy) between two distances thrown for phase plane plots of seven joint angles in the underarm throw.

increased, whereas from the phase plane plot, all the trajectories appear visually to be the same for all distances thrown.

For the underarm throw, Rxy presents the same results when compared with direct observation of the phase plane plots. That is, only the phase plane plots of shoulder flexion and shoulder adduction (Figure 5.23 A & B) show variation across the distances thrown. However, Rxy of the phase plane plot of shoulder flexion seems to separate into two groups, the first four distances, and other distances thrown. This separation is not clearly demonstrated by visually examining the trajectories. For the phase plane plots of shoulder adduction, the two longest distances thrown show the lower Rxy when compared with the other distances thrown. This conclusion is not visually presented in the phase plane plot. Rxy of other joints, that is, shoulder rotation, elbow flexion, forearm rotation, wrist flexion and wrist deviation demonstrate an equal relationship as the distance thrown increases.

Generally, Rxy presents the same conclusions as shown in the direct observation of the phase plane plots. Rxy seems to detect more detailed differences but the dissimilarities are not necessarily meaningful when visually examined.

5.5.3 The angle-angle plot

Intersegmental coordination can be investigated by examining the trajectories of one series of joint angles plotted against those of another joint angle. The angle-angle plots can be used to show the relationship between joints.

Generally each trajectory consists of a diagonal line and a turning point. The diagonal straight line in angle - angle plots implies that the two joints are coordinated. If any change of these two joints occurs in the same direction, the line will have a positive slope. In contrast, if any change is in the opposite direction, the plot will show a negative slope. The vertical or the horizontal line means that only one joint moves while the other joint maintains its range of motion. Rounded trajectories demonstrate a phase offset or decoupled coordination or a more complex relationship. The switching of both joints to other directions simultaneously suggests a turning point synchronisation or intersegmental coordination.

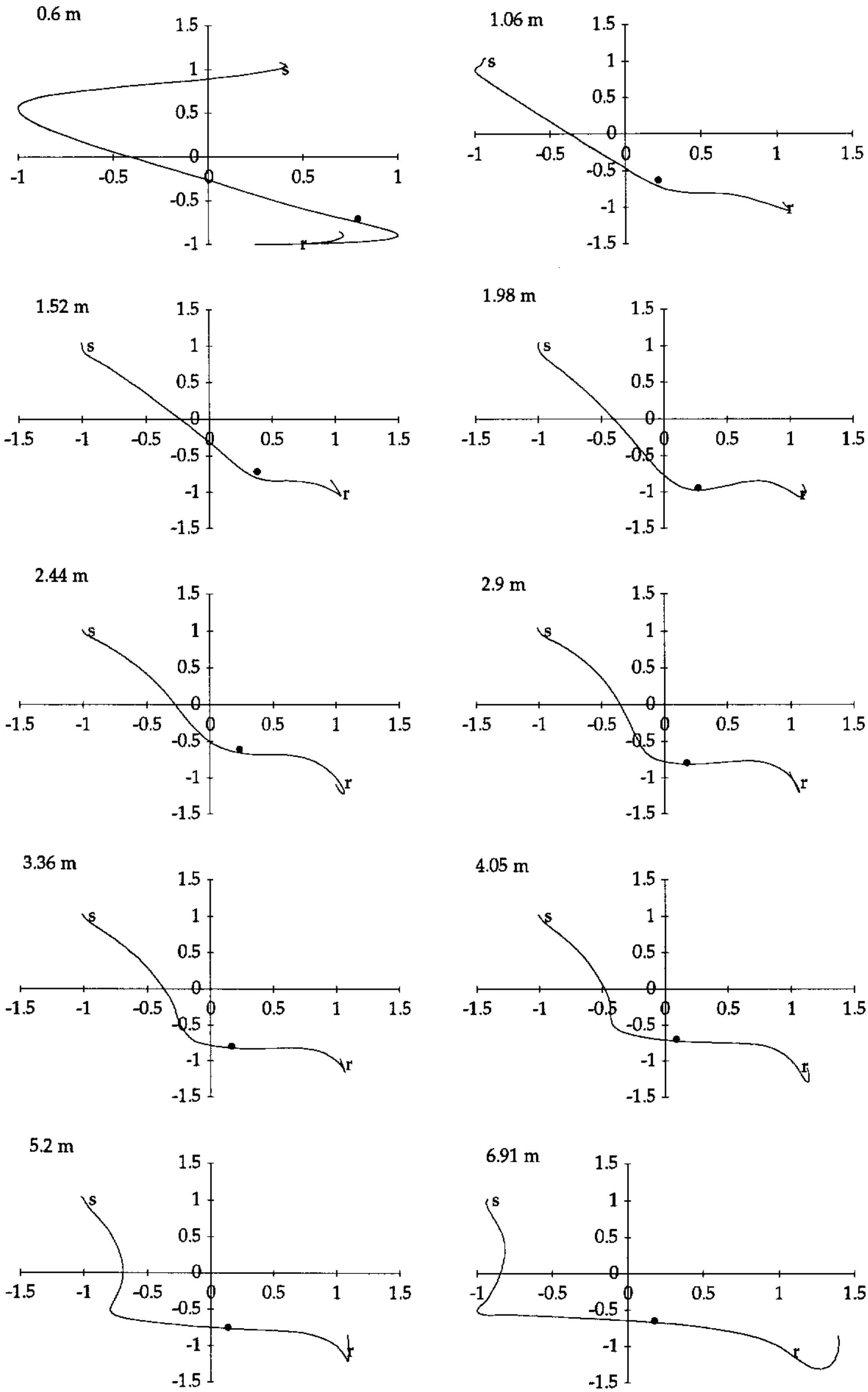


Figure 5.24 Angle - angle plot of shoulder flexion (x-axis) and shoulder adduction (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

The normalised angular displacement was used to illustrate the angle - angle plots to facilitate the comparison of coordination as the distance thrown increased.

Shoulder motions were selected to compare with other joint angles, including, elbow, radioulnar and wrist joint because shoulder movements showed the most obvious changes in both styles of throwing. Thus fifteen joint pairs for each pattern of throwing were examined. All of the angle - angle plots are displayed in Appendix E. Only three plots for each throwing pattern are presented in this section as examples.

5.5.3.1 Overarm throw

The angle - angle plots of the overarm pattern can be arranged into three groups according to the relationship between joints as the distance thrown increased. The first group (Figure 5.24) is for shoulder flexion and extension plotted against other joint actions that is, shoulder adduction, shoulder and forearm rotation and elbow and wrist movements (Figure 1 to 6 in Appendix E). This group shows different patterns between the shortest distance and other longer distances thrown. The longer nine distances in the first group demonstrate common characteristics. In the preparation phase, the trajectories between the two joints show a straight diagonal line which changes to rounded curves and horizontal segments as the distance increased. These results suggest that the relationship between shoulder flexion and extension and other joints are actively coupled and change to the decoupled state as the distance thrown increases during the preparation phase of throwing. The decoupled coordination between shoulder flexion and extension and other joints is more apparent for the three longest distances thrown. In the releasing phase, the trajectories between two joints seem to maintain their coordination except for the first distance. The profiles in the releasing phase are illustrated mainly as the diagonal straight line which suggests that shoulder flexion and extension and other joints have a coordinate relationship in this phase of throwing as the distance thrown increases. The results imply that subjects may use the sub - styles of the overarm throw for the first distance thrown since the angle - angle plots of this group are different from those for other distances. Furthermore, subjects may employ different actions of shoulder flexion related to other joints during the preparation phase for the last three distances thrown.

The second group (Figure 5.25) is shoulder adduction and abduction compared with other joints angles except shoulder flexion and extension (Figure 7 to 11 in Appendix E). The relationship between the two joints seems to be maintained over all the distances thrown. The relationship of the shoulder joint to the other joints for the shortest distance in this group is not obviously different from the other distances. Most of the trajectories consist of two segments which form a turning point. A turning point generally corresponds to the point used to divide the throw into two phases.

The last group (Figure 5.26) is that between shoulder rotation and the other joints that is, elbow, forearm rotation and wrist movements (Figure 12 to 15 in Appendix E). Generally the trajectories in this group are composed of two segments and a turning point similar to that shown in the second group. However, for the shortest distance, the plot shows a rounded curve rather than a sharp turning point or a loop. The formation of a loop occurs as the distance thrown increases. The loop in this group suggests that the movement of the two joints does not change in the same manner. Shoulder rotation starts to reverse before other joint actions and then switches to a new direction synchronously as it does over the first few distances. However, the plot between shoulder and forearm rotation does not contain a loop, instead it shows a sharp turning point as the distance thrown increases.

For the overarm throw, the plots for shoulder flexion and other joints appear to divide the overarm throw into three sub - styles. The plot for shoulder adduction and the other joints separate the throwing motion of the shortest distance from the other distances. The last group, in which shoulder rotation was plotted with other joints (except shoulder flexion), also support this assumption. However, the results are not so obvious in the last two groups. The different sub - styles of the overarm throw seem to emerge as the distance thrown increases from 0.6 to 1.06 m and then from 3.36 to 4.05 m.

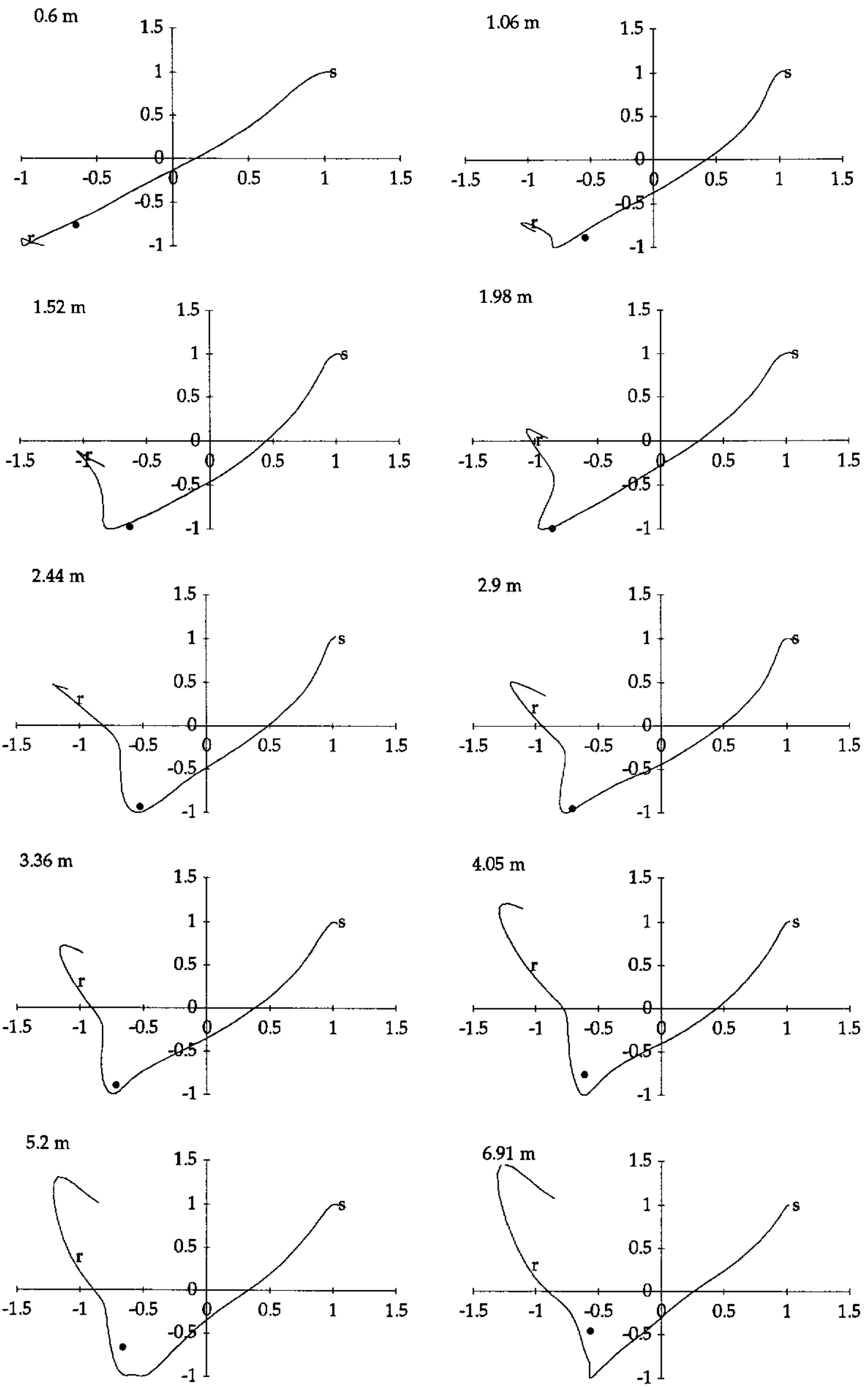


Figure 5.25 Angle - angle plot between shoulder adduction (x-axis) and shoulder rotation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

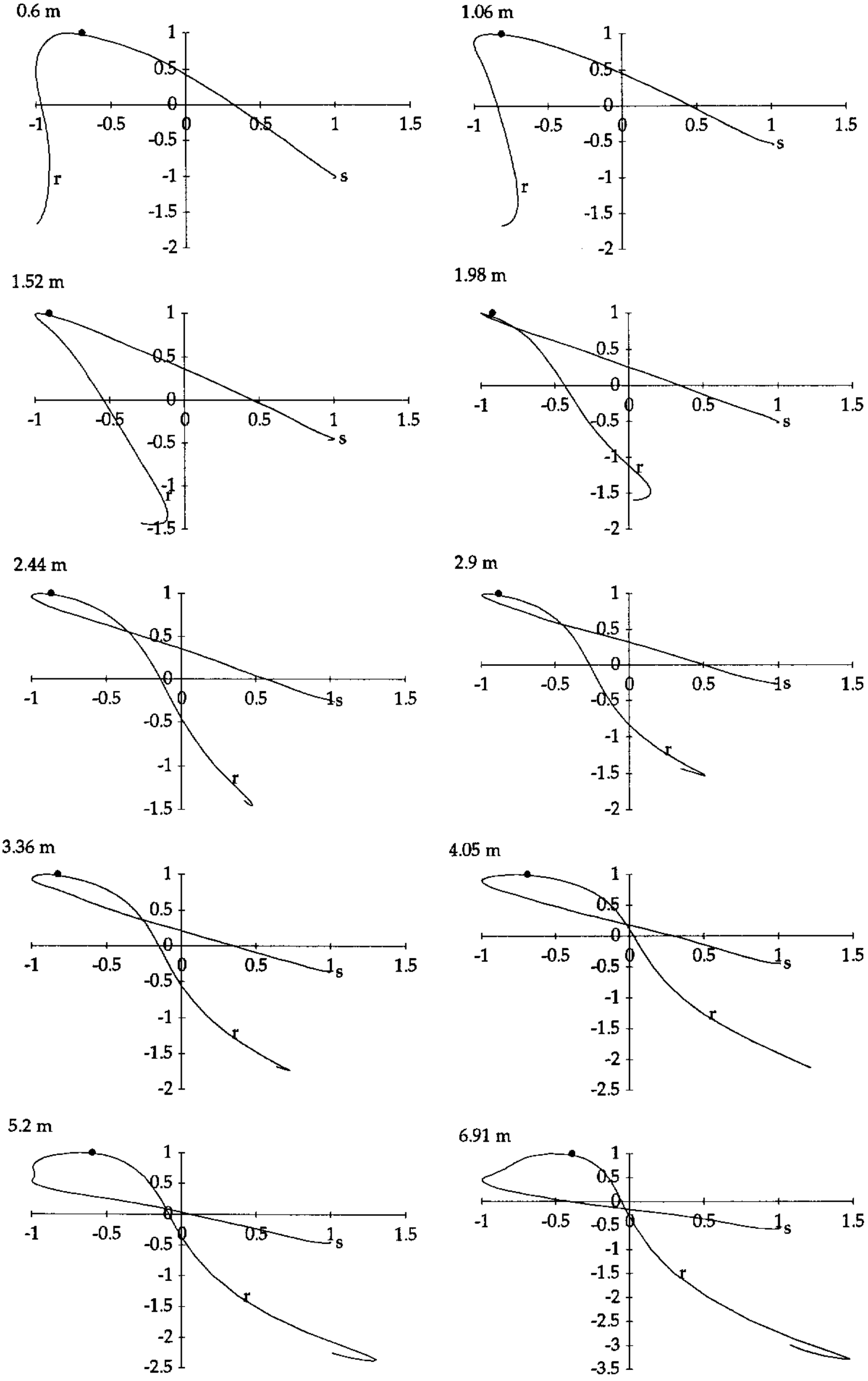


Figure 5.26 Angle - angle plot between shoulder rotation (x-axis) and elbow flexion (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

5.5.3.2 Underarm throw

The angle - angle plots of the underarm throw can also be classified into three groups. The first group (Figure 5.27) is the plot of both shoulder flexion and shoulder adduction with other joints that is, shoulder adduction, shoulder rotation, forearm rotation and elbow flexion (Figure 16 to 22 in Appendix E). This group showed variation of joint coordination as the distance thrown increased in the preparation phase. The trajectories in the preparation phase start from the diagonal straight line at the first distance and change to the rounded curves as the distance thrown increased. However, the plots between the two joint angles in this group demonstrate sharp turning points which mean a switching of both joints to other directions occurs simultaneously. The releasing phase demonstrated straight diagonal lines which implies coordination between the two joints. The differences in angle - angle plots at the shortest distance are not clearly shown, therefore, the results cannot clearly separate the underarm throw into sub - style patterns as can be done from the plots of the overarm throw.

The second group (Figure 5.28) is that between shoulder rotation and the two other joint actions, elbow flexion and forearm rotation (Figure 23 to 24 in Appendix E). The relationships among these joints are maintained over all of the distances thrown. The trajectories consist of a curved segment in the preparation phase, a straight line segment in the releasing phase and a point where movement of the two joints switches simultaneously.

The last group (Figure 5.29)is the plot between wrist movements and other joint actions, that is, shoulder flexion, shoulder adduction and shoulder rotation (Figure 25 to 30 in Appendix E). The relationships in this group are also maintained as the distance thrown increases in both the preparation and the releasing phases. The profiles show rounded curves at the period in which the motion changed direction.

For the underarm throw, neither of the plots clearly demonstrated differences in pattern as the distance thrown increased.

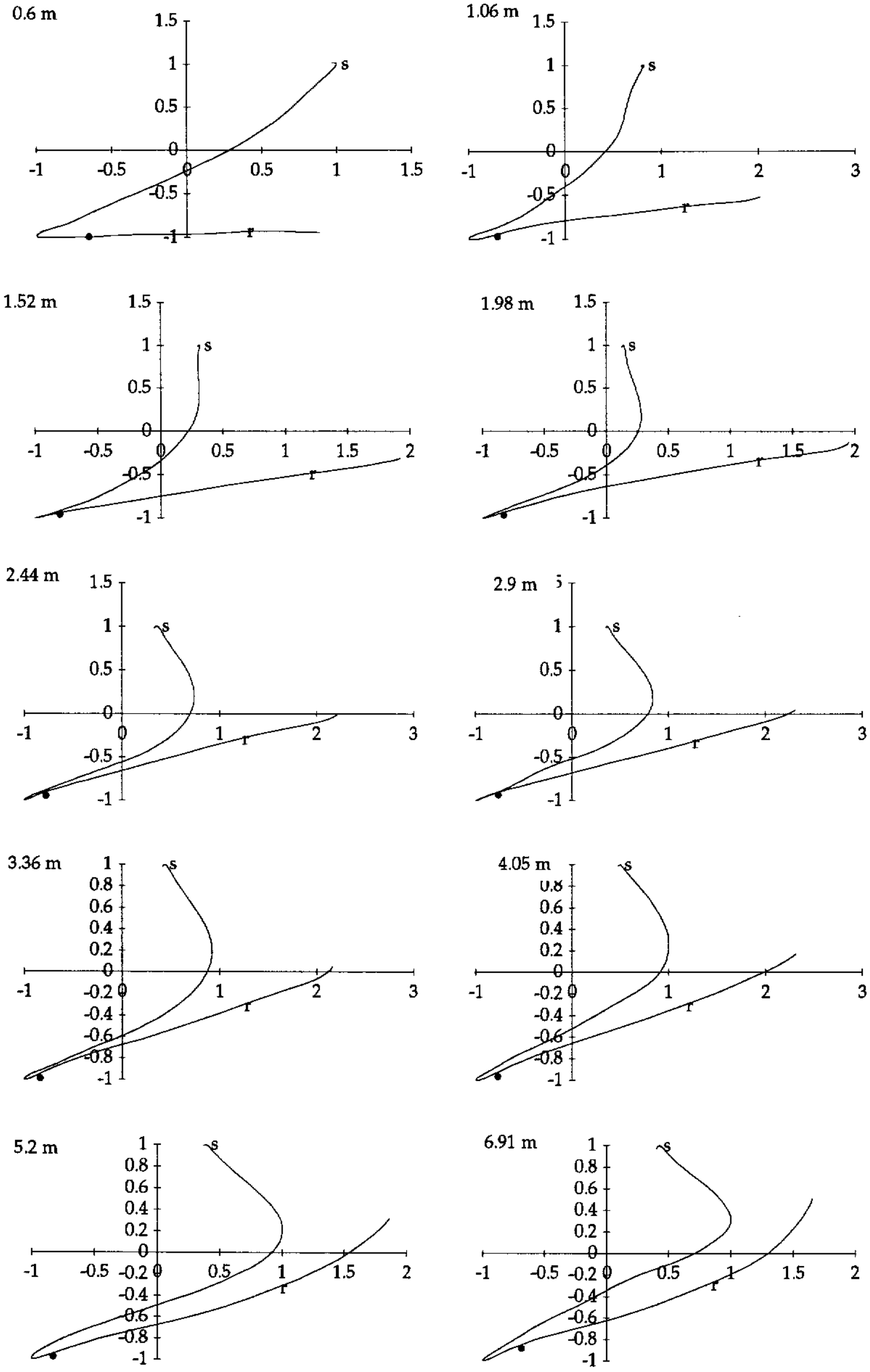
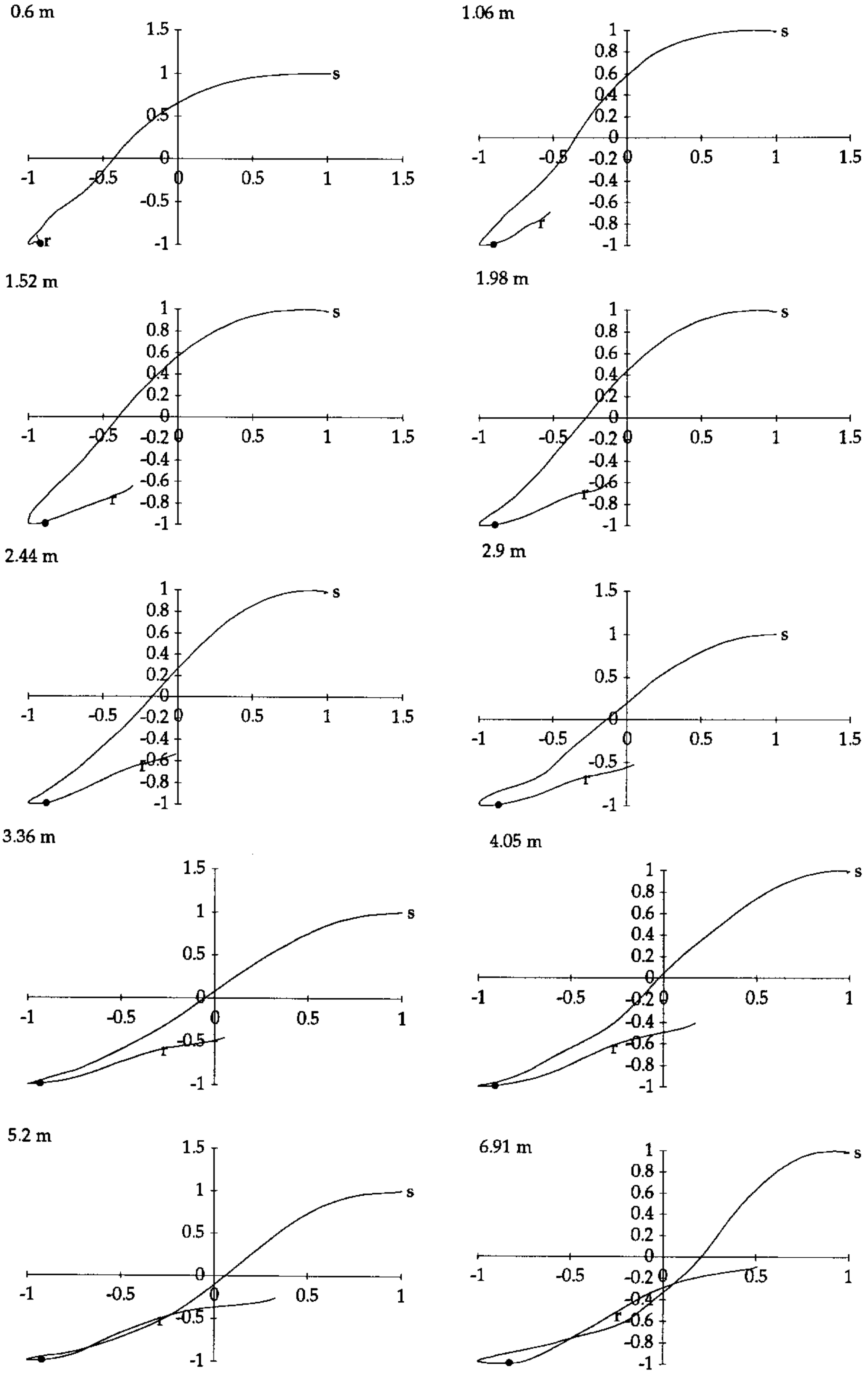


Figure 5.27 Angle-angle plot between shoulder flexion (x-axis) and shoulder rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point



0.6 m

1.06 m

1.52 m

1.98 m

2.44 m

2.9 m

3.36 m

4.05 m

5.2 m

6.91 m

Figure 5.28 Angle-angle plot between shoulder rotation (x-axis) and elbow flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

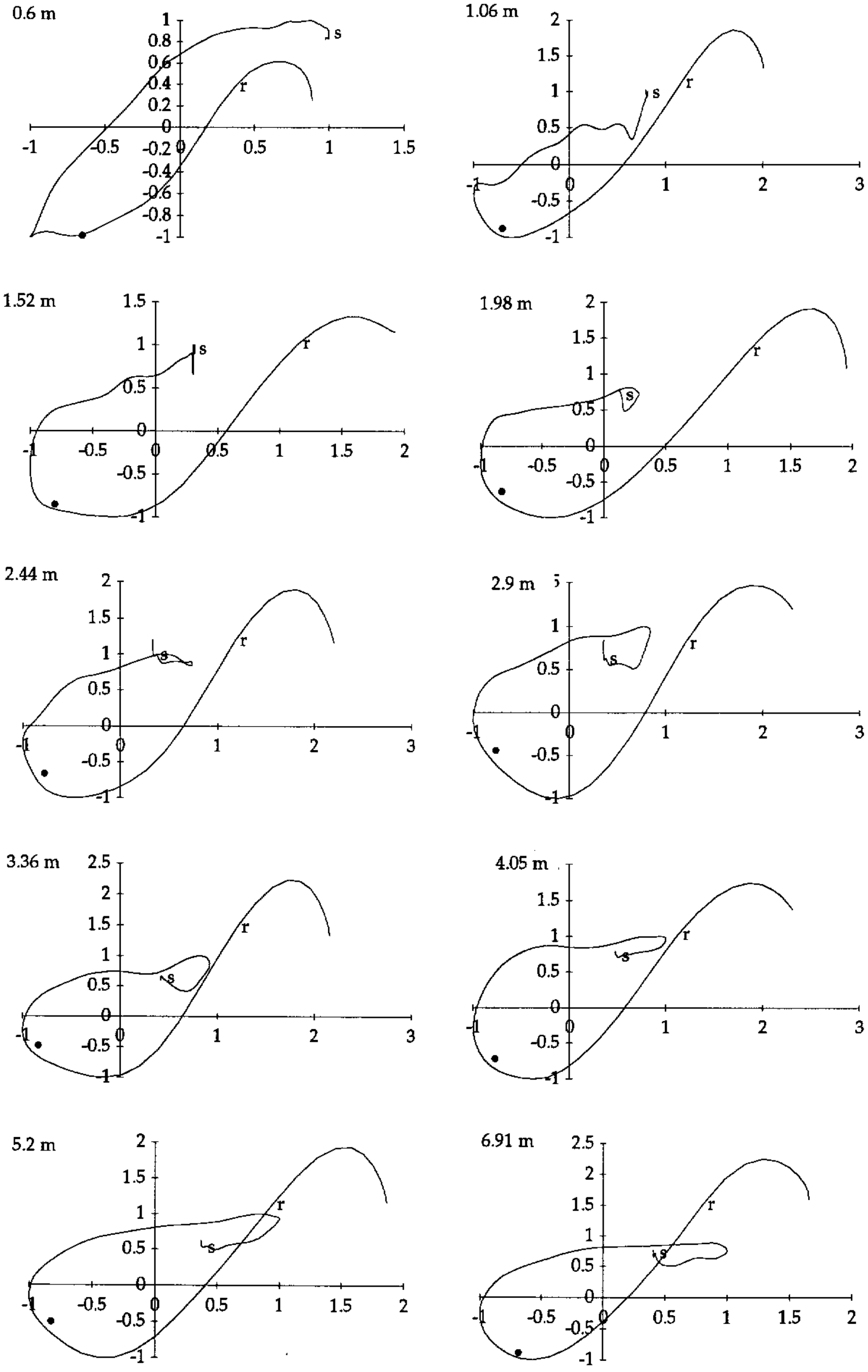


Figure 5.29 Angle-angle plot between shoulder flexion (x-axis) and wrist flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

5.5.3.3 Cross-correlation

Cross-correlation (Rxy) of the angle - angle plots for both throwing patterns are presented in groups which are not necessary similar to the classification presented in the previous sections (5.53.1 and 5.53.2). Rxy of the angle - angle plots are divided according to the level of association (Rxy) related to other distances thrown.

For the overarm throw, the results can be separated into two. The first (Figure 5.30) is the correlation of both shoulder flexion and wrist deviation with all other joint angles. This group shows the low Rxy of the shortest distance when compared with other distances thrown. Furthermore, Rxy between shoulder flexion and other joint angles at the last two distances (Figure 5.30 A to F) is less than for other distances thrown. The second (Figure 5.31) is the correlation of shoulder adduction and shoulder rotation with other joint angles except shoulder flexion and wrist deviation. This group demonstrates relatively equal correlation across all distances thrown.

The results drawn from Rxy for the overarm throw are similar to the conclusions visually observed from the angle - angle plots. That is, the relationships between shoulder flexion and other joint angles for the shortest distance and for the two longest distances thrown are different from other distances thrown.

For the underarm throw, the results of Rxy can also be classified into two. The first (Figure 5. 32) is the correlation between shoulder adduction and other joint angles. This correlation demonstrates the low Rxy at the two longest distances thrown when compared with other distances thrown. The second (Figure 5.33) is the correlation of both shoulder flexion and shoulder rotation with other joint angles except shoulder adduction. This correlation shows the relatively equal Rxy across all distances thrown.

The results of Rxy for the underarm throw mainly identify the differences in the relationships of shoulder adduction and other joint angles over the last two distances thrown. Whereas, the angle-angle plots cannot clearly demonstrate the different relationships as the distance thrown increased.

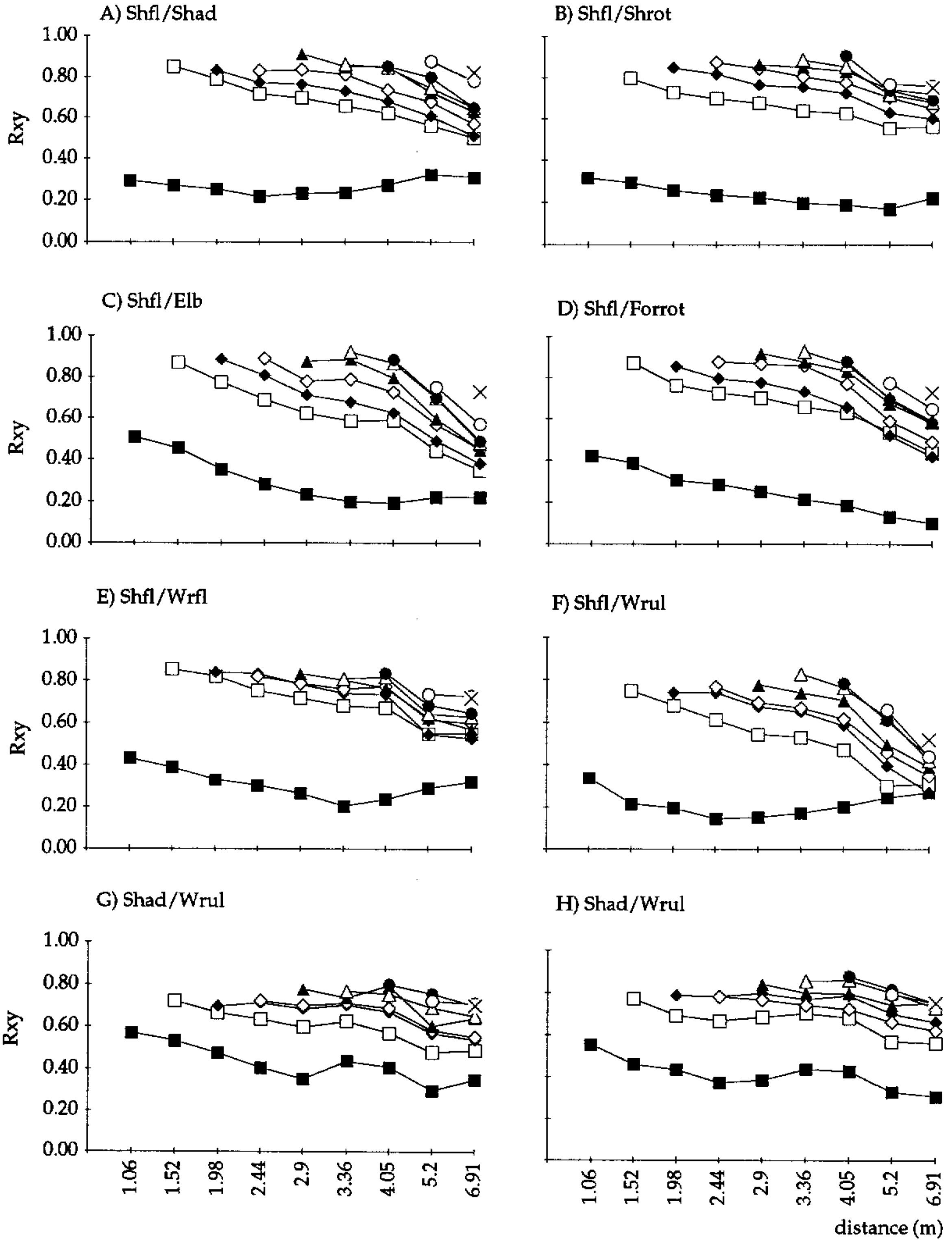


Figure 5.30 Cross-correlation (Rxy) between two distances thrown for angle - angle plots (first group) in the overarm throw. (Legend see page 201)

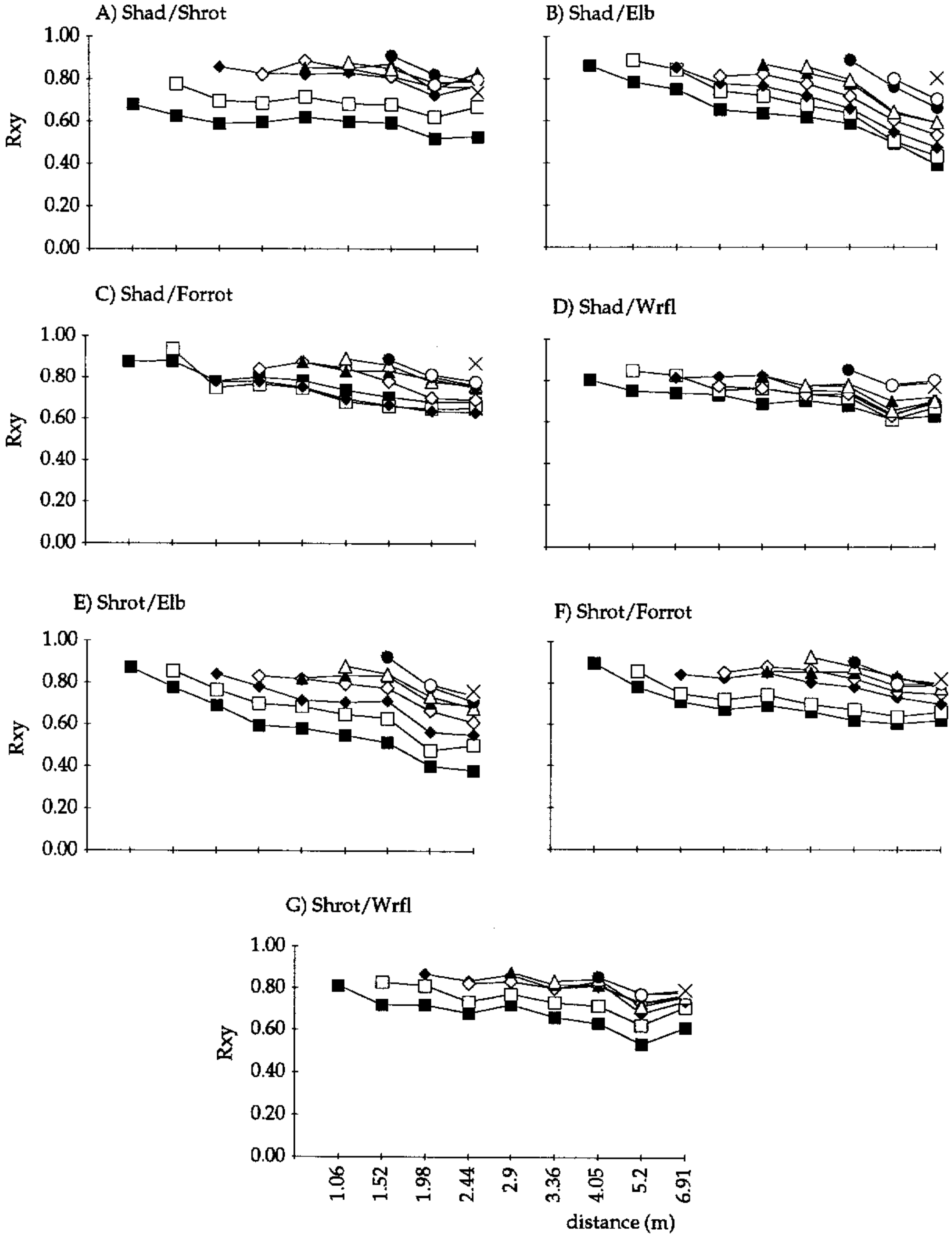


Figure 5.31 Cross-correlation (Rxy) between two distances thrown for angle - angle plots (second group) in the overarm throw. (Legend see page 201)

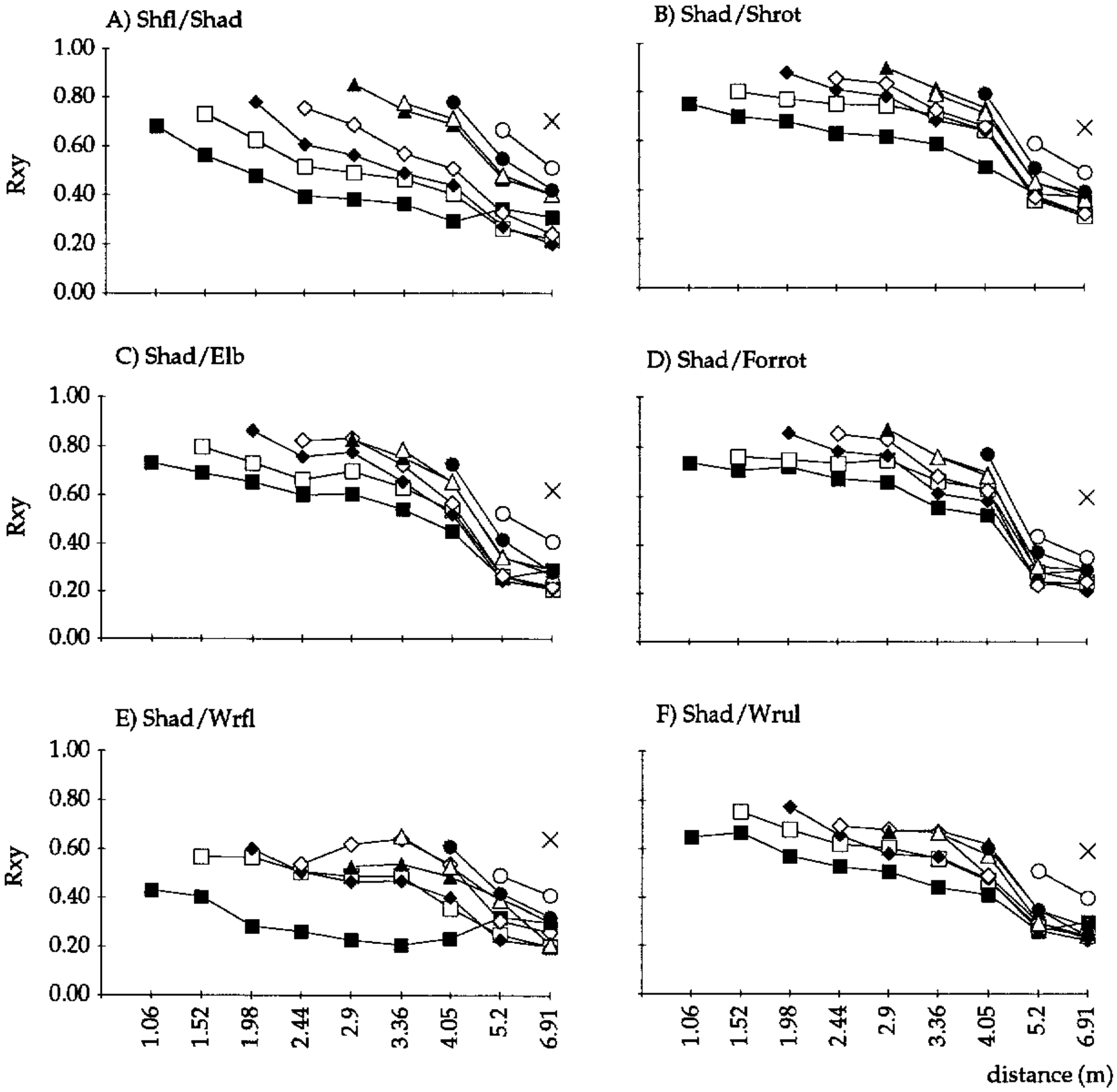


Figure 5.32 Cross-correlation (Rxy) between two distances thrown for angle - angle plots (first group) in the underarm throw. (Legend see page 201)

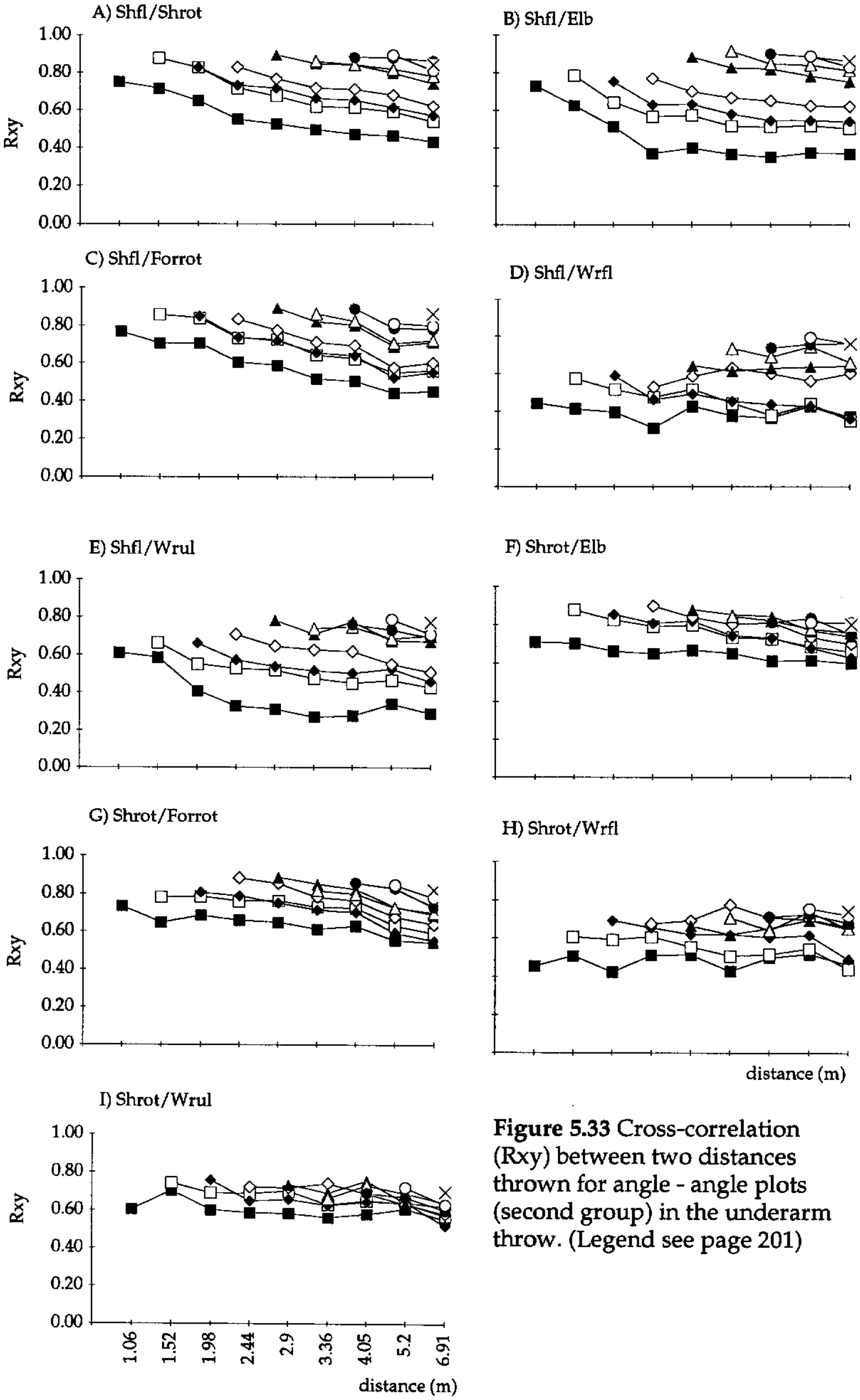


Figure 5.33 Cross-correlation (Rxy) between two distances thrown for angle - angle plots (second group) in the underarm throw. (Legend see page 201)

5.5.4 The relative phase

The arc tangent of the normalised angular displacement and angular velocity was termed the movement phase. The calculation method has been described in Chapter 4 Section 4.2.4. The difference between the movement phase of the two joints was called the relative phase. The relative phase is generally represented as an order parameter in dynamic pattern theory.

Only the relative phases (the difference in the movement phase) between shoulder flexion and shoulder rotation, shoulder flexion and elbow flexion and between shoulder flexion and forearm rotation are presented in the study. Selection of these angles was based on the results reported in Section 5.4.5. The ulnar and radial deviation of the wrist joint was not illustrated due to the high variation in the joint velocity data.

For the overarm throw, the relative phase of each pair of joint angles shows a dissimilar pattern (Figure 1 to 3 in Appendix F), especially the relative phase between shoulder flexion and forearm rotation. The relative phase of these selected pair of joint angles (Figure 5.34) also shows two types of relationships as the distance thrown increased , that is, a) distances thrown of 0.6, 1.06, 1.52, and 1.98 m and b) distances thrown of 2.44, 2.9, 3.36, 4.05, 5.02, and 6.91 m. Temporal changes of these relative phases can be seen clearly during the preparation phase. Furthermore, the relative phase of these joint angles at the shortest distance thrown (0.6 m) also demonstrates the different curve profiles during the early period of the preparation phase of throwing. For the three pairs of joint angles, the relative phase between shoulder flexion and forearm rotation seems to show the most obvious differences when compared between throwing over the short (0.6 to 1.98 m) and the long (2.44 to 6.91 m) distances thrown. Indeed, the changes of the relative phase between shoulder flexion and forearm rotation start to occur at the distance thrown of 1.98 m.

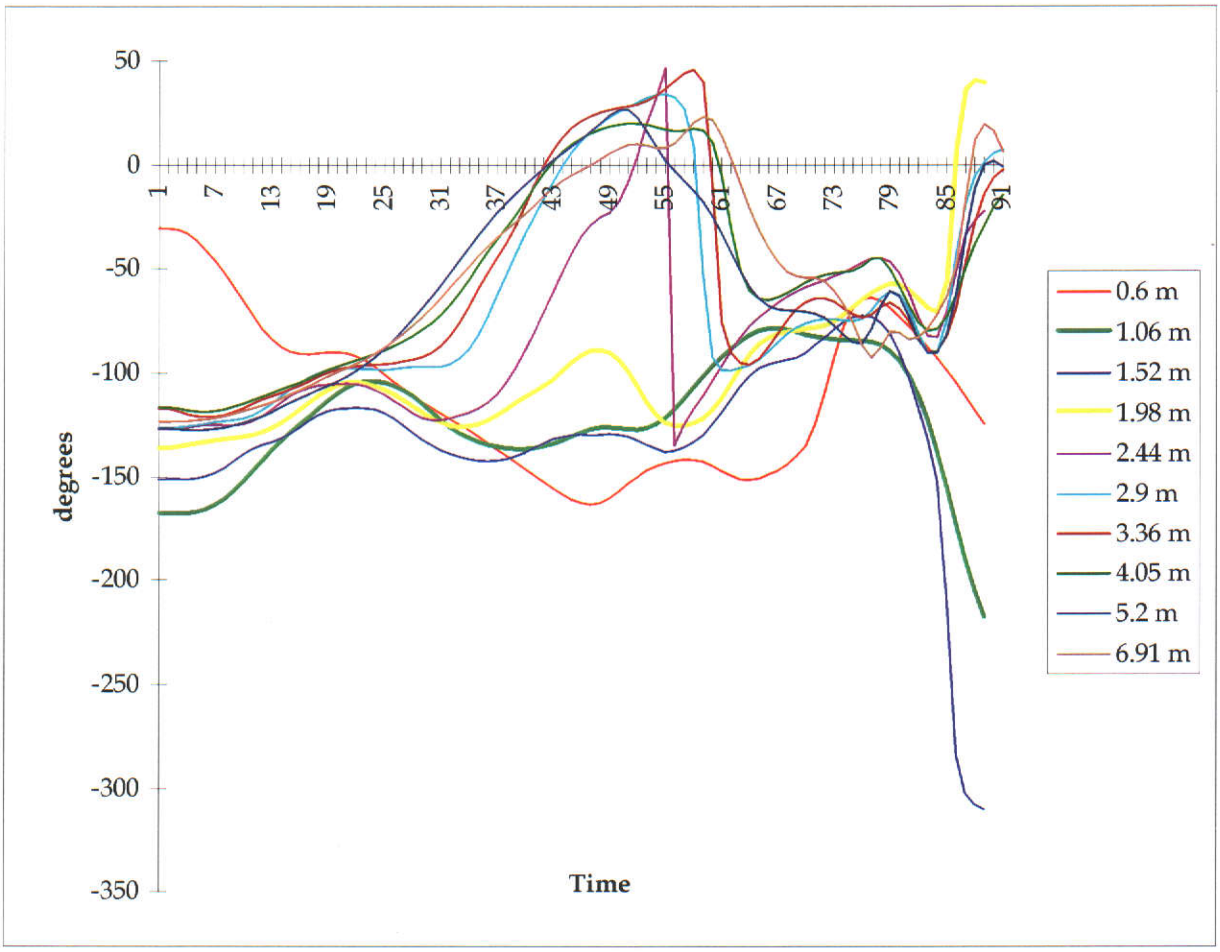


Figure 5.34 The relative phase between shoulder flexion and shoulder rotation for the overarm throw.

For the underarm throw, the relative phase of selected pairs of joint angles (Figure 4 to 6 in Appendix F) shows a rather consistent pattern over all of the distances thrown when compared with the overarm throw. Even though the different profiles of the relative phases between the short (0.6 to 1.98 m) and the long (2.44 to 6.91 m) distances can be separated same as in the overarm throw (Figure 5.35), these unlike profiles may represent the parallel changes of the range of joint motion and angular velocity rather than the temporal alteration of the relative phases as the result of increasing distances thrown.

The results of the relative phase again suggest a change of the throwing style in the overarm throw which is more apparent when compared with the underarm throw. The change seems to occur in between the shorter and the longer distances thrown, that is from the distance thrown of 1.98 to 2.44 m.

In addition to the differences of the relative phases across the distances thrown, the relative phases also demonstrates the different relationships across the patterns of throwing.

These findings supported Hypotheses Eight (a and d) and the Hypothesis Nine, which stated that:

Hypotheses 8: Order parameter

a) More than one order parameter is required to characterise the throwing pattern.

d) Relations between angular displacement and angular velocity or between angular displacement of one joint related to another joint as illustrated in phase plane plots, angle-angle plots, and relative phase plots can act as order parameters for the throwing movement.

Hypothesis 9: Measurement of coordination

Visual comparison and cross-correlation provide the same information when used to measure pattern of coordinated movement, phase plane plots and angle-angle plots, as the distance thrown increases.

Therefore these hypotheses were accepted.

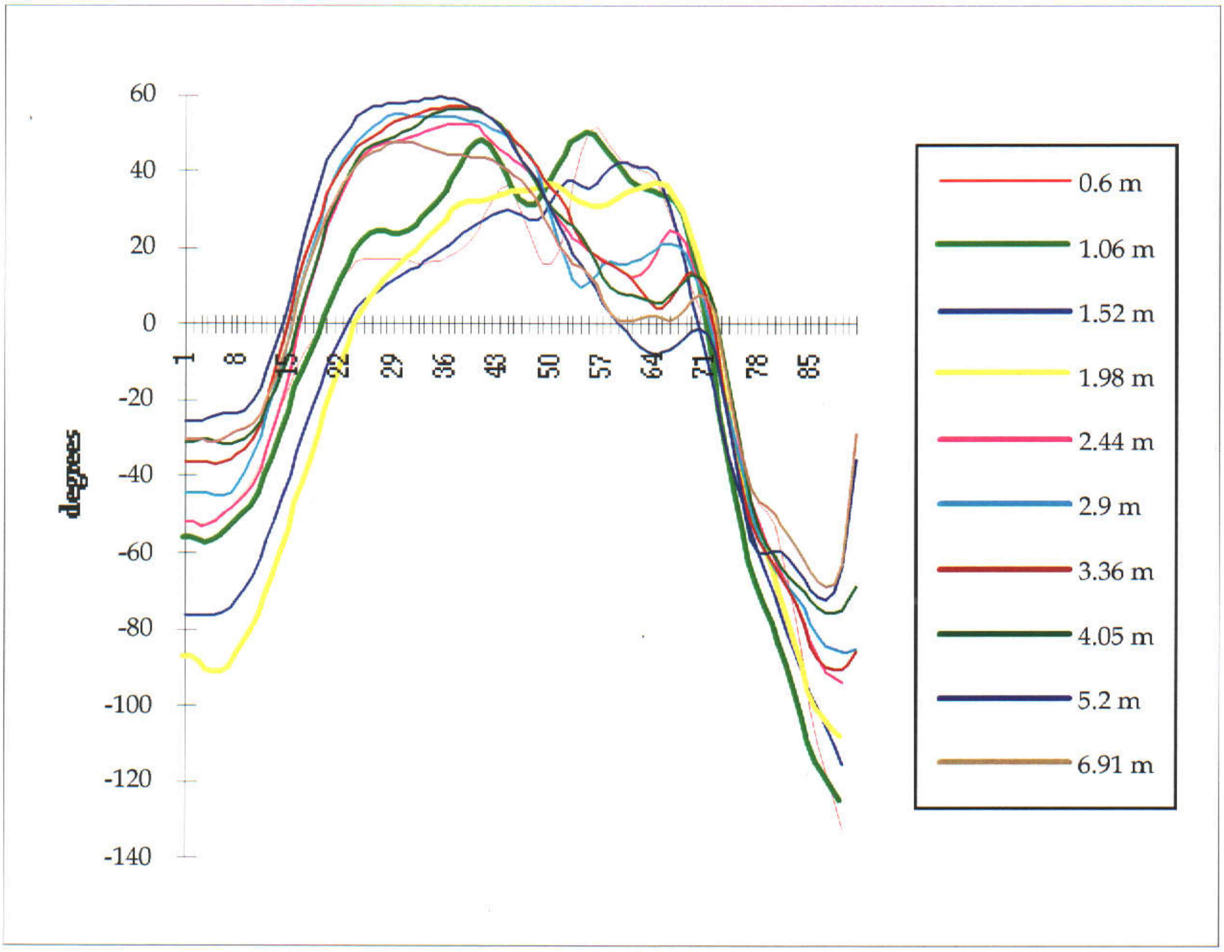


Figure 5.35 The relative phase between shoulder flexion and shoulder rotation for the underarm throw.

5.6 Mechanical work of throwing

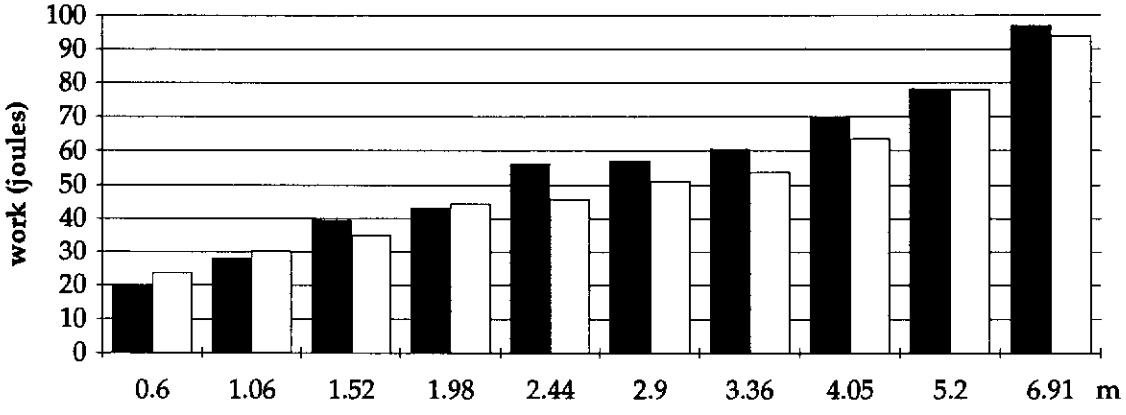
Figure 5.39 shows total, positive and negative work for the overarm and the underarm pattern as the distance thrown increased. The work of muscles indicates the amount of energy utilisation for each type of throwing pattern over a particular distance. The method of calculation of mechanical work of muscles has been described in Chapter 4, Section 4.2.6. In summary, the work done for seven joint angles was calculated separately. The summation of seven joint angles for the positive and the negative work was determined. The total work for each distance thrown was calculated from the combination of the absolute values of the positive and the negative work.

The total work done (Figure 5.36 A) by upper limb muscles during throwing for both throwing patterns is in the range of 10 to 70 joules. The amount of work done is nearly equal for both patterns for some short distances (0.6, 1.06 and 1.98 m) and the longest distance (6.91 m). The total mechanical work of muscles was greater in the overarm throw than in the underarm throw for longer throwing distances except for the longest distance thrown. However, the differences in total work done between these two throwing styles are small, within the range of 10 joules.

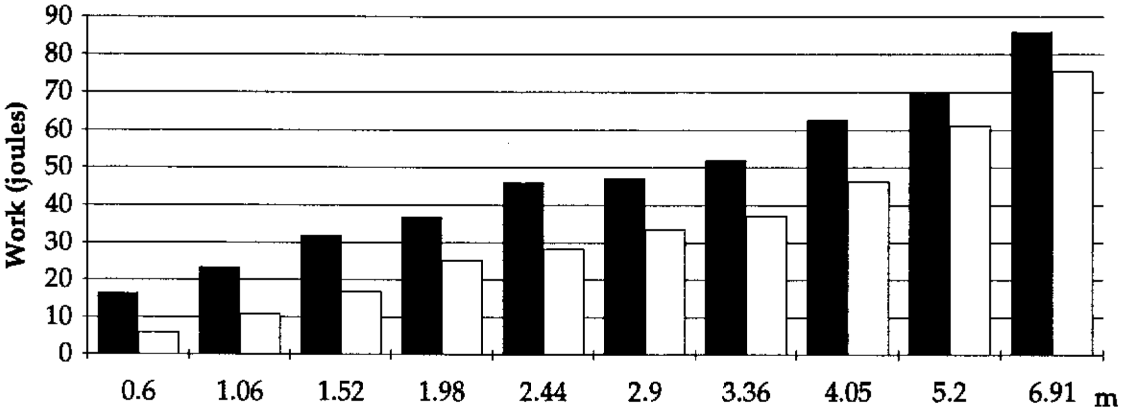
The results of the positive and the negative work which represented the concentric and the eccentric contraction of muscles respectively demonstrated different trends when compared with each type of work. There is a linear relationship between the amount of the positive work of muscles and the distance thrown for both styles of throwing. The overarm throw obviously shows higher values of work done when compared with the underarm pattern for all of the distances thrown (Figure 5.36 B).

However, the negative work of both the overarm and the underarm throws is relatively maintained as the distance changes, especially for the underarm throw. In contrast to the results for positive work, negative work is higher in the underarm throw than in the overarm throw (Figure 5.36 C). The main sources of eccentric contraction came from the elbow and the shoulder joints for both throwing patterns (data not shown).

A) Total work



B) Positive work



C) Negative work

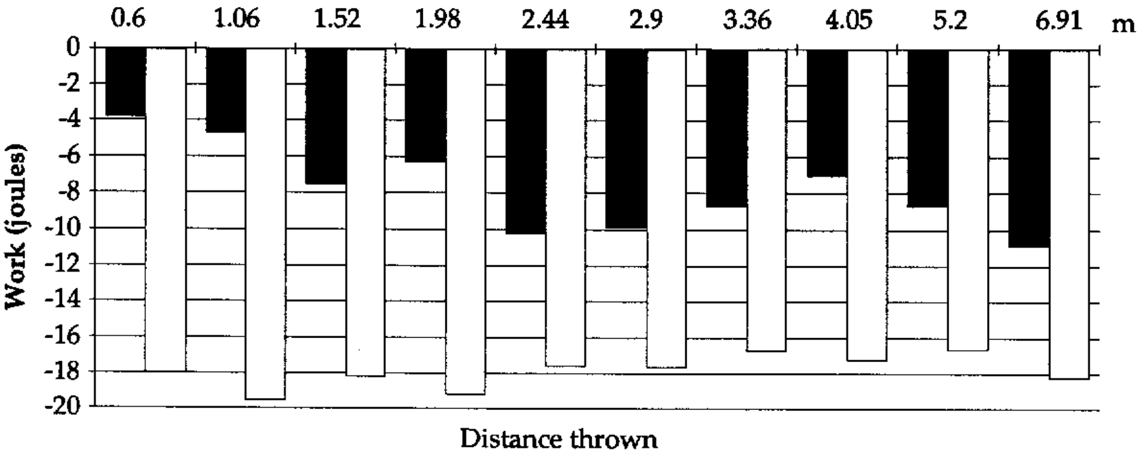


Figure 5.36 Total, positive and negative work for the overarm and the underarm throw as the distance thrown increased.

■ = Overarm, □ = Underarm

The results suggest that both throwing patterns transferred the comparable amount of the mechanical energy from muscles to the upper limb segments and the ball. Furthermore, the characteristics of the positive and the negative work of muscles as the distance thrown increased suggest that concentric contraction is necessary to accomplish throwing to targets at increasing distances. However, the significant differences cannot be tested in the mechanical energy data, because these data were derived from the mean data of joint moments.

5.7 Summary

The present study demonstrated the application of the dynamic pattern theory to throwing actions. The switching of the throwing pattern mainly occurred from the overarm to the underarm throw as the distance thrown increased. This result suggests distance thrown may be one control parameter. The overarm throw shows more evidence of this effect which implies variability within the pattern when compared with the underarm throw. That is, a) the increase in relative timing as the distance thrown increased, b) the increment in range of motion from different joint angles and c) changes in the coordination in the angle - angle plot and the relative phases between shoulder flexion and other joint angles as the distance thrown increased. In contrast to the overarm throw, the underarm throw demonstrated a more fixed pattern throughout all throwing distances. In addition, the shoulder joint seems to have the most important role in increasing the distance thrown for both throwing patterns. This assumption is based on the results of angular displacement and angular velocity as the distance thrown increased.

Chapter 6

Discussion

The difference between a flower and a weed is a judgement.

-Unknown author

6.1 Dynamic pattern theory and discrete movement

Whether dynamic pattern theory can be generalised to nonrhythmic coordinated movement is a subject of interest, however previous experimental examples of the application of dynamic pattern theory to functional discrete movements have not been found. Schöner (1990) has described the model dynamics for discrete movement. His work was based on mathematical modelling which is still difficult to apply to discrete movement in practical situations.

Other works which examine discrete motions, such as lifting tasks (Scholz, 1993a; Scholz, 1993b) or bimanual discrete tasks (Walter & Swinnen, 1990; Walter et al., 1993) have employed a repetitive motion protocol. This suggests that frequency or speed of movement was used as a control parameter for these works. In contrast, the results of the present study did not use any time constraint to induce phase transition. Distance thrown was proposed as the control parameter in the present study. Therefore, the following discussion will focus on the dynamic pattern theory as well as on the parameters which may affect the throwing distance.

6.2 Stability and variability of throwing movement

Measurements of stability have been well described in the literature (Schöner & Kelso, 1988c). Schöner (1990) has stated that for rhythmic motions, the degree of persistence and thus the degree of stability in a movement pattern can be measured because the pattern is maintained over periods of time which are much greater than the period of the relaxation time. For discrete movements the motion exists only for a short time which is not sufficient to identify an attractor and the time period of the motion is comparable to the expected relaxation time (Schöner, 1990; Walter et al., 1993). Thus pattern fluctuation cannot be used to measure stability and the relaxation time is not a suitable factor with which to measure temporal stability for discrete movements (Schöner, 1990). Schöner (1990), however, has suggested that inter-trial variability of movement parameters may be used to measure the stability of discrete movements.

In the present study, therefore, the trajectories (Figure 5.14 to 5.19) were used to indicate the stability of the system. The results demonstrated that, as the distance thrown increased, patterns of trajectories between subjects became more uniform. Variability of movement was highest when subjects threw to the shortest distance for both patterns (Figure 5.14 and 5.17). According to the dynamic pattern theory, variability of movement pattern means that the system is unstable. Thus these results suggest that as the distance thrown increased the stability of both throwing patterns increased. In addition, these results also imply an alteration of throwing pattern (sub-style of throwing).

Comparison of the stability between throwing patterns, that is between overarm and underarm throws, is difficult, because variances or standard deviations cannot be calculated from the coordinate data used to plot trajectories of movement. Stability of overarm and underarm throws might be indicated by other results, such as the results of the relative timing. A discussion on relative timing is presented in Section 6.5.5.

Moreover, according to dynamic pattern theory a stable pattern suggests the ability to stabilise the coordination of the movement while fulfilling the task requirement. It does not imply a rigid relationship of the behavioural states as the parameter values change. The overarm throw may achieve this stability by increasing the range of motion of different joint angles as the distance thrown increases. A discussion of this aspect will be presented in the following section.

According to the recruitment of task components as suggested by Kelso (1995), the system may maintain its stability by adding previous quiescent parameters into the pattern. However, a new pattern may still have the same topological form as the previous pattern. This statement suggests that the stability of the throwing pattern may be measured indirectly from the ability to recruit degrees of freedom as the distance thrown changed. The total ROM data may be used to demonstrate stability of the throwing pattern in this respect.

The total ROM data for the overarm throw (Figure 5.8) demonstrated the different roles of each joint angle for each of the different throwing distances. The flexion and extension motion of the shoulder and elbow joints seemed to be important over the three shortest distances while rotation was greatly amplified over the four longest distances thrown. Unlike the overarm throw, the underarm throw primarily showed an increase the range of shoulder flexion and extension as the distance thrown increased (Figure 5.9). Therefore, as the distance thrown increased, the coordination of flexion and extension of the shoulder joint with the rather consistent movement of the elbow, the radioulnar, and the wrist joints were required in the underarm throw. Whereas, the coordination of flexion and extension of the shoulder and the elbow joints and rotation of the shoulder and the radioulnar joints were occurred in the overarm throw. Thus the coordination of joint angles as the distance thrown increased in the overarm throw was more diverse than that occurring in the underarm throw. The overarm throw resulted from the combination of four angles (shoulder and elbow flexion and extension and shoulder and forearm rotation) whereas, only shoulder flexion and extension were involved in the underarm throw. These results suggest that the overarm pattern can recruit more joint angles than the underarm throw. In the dynamic pattern theory, the recruitment of previous quiescent degree of freedom implies the stability of the system (Kelso 1995). Thus, it appears reasonable to assume that the overarm throw is more stable than the underarm pattern.

6.3 Multistable states of throwing movements

Even though a shift from the underarm throw to the overarm throw at 4.05 m was demonstrated in the present study, each throwing pattern still exists at both the shorter and longer distances. This result suggests multistability in the throwing patterns. According to dynamical theory, the multiple stability states mean that the same tasks can be achieved using several different patterns within the same environment (Thompson & Stewart, 1986). An externally driven force is required to push the multistable system from one stable pattern to the other (Saltzman & Munhall, 1992). The changing of coordinated patterns in a multistable state is not due to the loss of stability of the previous pattern. Therefore, pattern transitions found in the present study may result from other factors rather than the instability of the system. The factors that may drive the throwing pattern from overarm to underarm may include energy utilisation, muscle strength, or stiffness of the limb. These proposed variables have been presented as control parameters in other studies (for review see Chapter 2, Section 2.2.2.2). The details of the discussion are presented in Section 6.7.

No other throwing styles, apart from overarm and underarm were identified during this study. The sidearm pattern could be considered as a throwing style which might be an intermediate strategy which may emerge between overarm and underarm throws. The absence of the sidearm throw suggests that in the context of the task examined, this is not a natural motion. Alternatively, the influence of the orientation of the forearm may prevent the selection of the sidearm throw by subjects. However, this assumption cannot be tested easily. One other explanation for the non appearance of a sidearm throw may relate to the sample size which may have been to small to detect occurrences of the sidearm throw. In fact, the presence of sidearm throw may provide additional support for the assumption of a multistable system.

The explanation given to subjects during the current study was important in considering whether other styles of throwing could have emerged. Subjects may have used only one throwing pattern over all of the distances thrown, if they were not told that they could change to any style of throwing as the distance thrown increased. The selection of the overarm or the underarm throws in the present study was left entirely to the decision of the subjects. No demonstration of how the subject should throw a ball over the various distances was offered and the instructions used encouraged variety.

6.4 Control parameter

A number of factors can affect throwing patterns, these include the mass of the implement and object to be projected, the size of the target, environmental conditions, and the strength and skill of the performer (Kreighbaum & Barthels, 1990). These factors possibly act as control parameters for throwing movements. In the present study, only the distance thrown was investigated as a control parameter. The weight of the projectile and the size of the target were examined in Stage One. They were rejected as possible control parameters in the principal study due to limitations in analysis techniques and to the fact that the conditions required to test these variables were not suitable for the study. The details of this discussion has been presented in Chapter 3, Section 3.9.7 and 3.10.7.

6.4.1 The Control parameter and the selected throwing patterns

Most of the subjects (five from nine) switched from the underarm throw to the overarm throw for a target distance of 4.05 m (Figure 5.1). Therefore, the present study suggests that the distance thrown may act as a control parameter.

In addition, the results of trajectories of movement in the present study (Figure 5.14 to 5.19) which demonstrated the stability of throwing patterns (as has been discussed in the previous section) showed high variability of the trajectories when subjects threw to the shortest distance for both throwing patterns. The pattern became uniform when the distance thrown increased. This suggests that distance thrown may also act as a control parameter for a changing of the sub-style of throwing within each throwing pattern.

In conclusion, the present study suggests the role of distance thrown as a parameter which affected throwing patterns in two aspects. That is, the distance thrown induced a phase transition between throwing patterns and within each throwing pattern. This conclusion is consistent with the interpretation of the stability of systems as described in Section 6.2. The detailed discussion of the phase transition concepts are presented in Sections 6.7.4 & 6.7.5.

6.4.2 Direction - dependent coordination patterns

Kelso and coworkers (Kelso et al., 1991) have identified that phase transitions can occur in single-limb multijoint movements. By asking subjects to flex and extend the elbow and flex and extend the wrist joint in four different conditions repetitively, they found that when the forearm is in supination, antiphase coordination (elbow flex / extend - wrist extend/ flex) switches to in-phase coordination (elbow flex / extend - wrist flex / extend) as the frequency of motion increased. However, when the forearm is in pronation, the alteration occurred in the opposite manner. Therefore, frequency of movement and spatial orientation appear to act as control parameters. Although the work of Kelso and coworkers (Kelso et al., 1991) was performed for a single limb, the task they used was still an oscillatory type. The interesting point arising from their research was the effect of the posture of forearm on the phase transition.

In the present study, for the overarm throw, the forearm generally moved to the pronated position. For the underarm throw, it was maintained in the supinated position. If the preferred coordination of the elbow and wrist joints for both types of forearm rotation as described by Kelso et al. (1991) is considered to demonstrate an easy pattern, the adoption of the results of the present study suggest that both throwing styles use the easy pattern of elbow and wrist joint interaction that is dependent on the position of the forearm. That is, for the underarm throw, the forearm is in supination thus the elbow and the wrist joints are in an inphase pattern. For the overarm throw, the forearm is in pronation so the elbow and the wrist joints are in the antiphase pattern (Figure 5.3).

In addition to the effect of orientation of the forearm on the motion of the elbow and wrist joints, the present study also found that flexion and extension of the shoulder joint demonstrated the same influence (Figure 5.3). For the overarm throw, flexion of the shoulder joint was found when the elbow and wrist joints were in the antiphase position. On the other hand, extension and flexion of the shoulder joint in underarm throw was demonstrated when the elbow and wrist joints were in an inphase mode.

The spatial orientation of the forearm and shoulder flexion and extension probably prevented the switching of the coordination pattern of the elbow and the wrist joints in the throwing motion as the distance thrown changed.

6.4.3 Elbow orthosis and identification of a control parameter

According to the dynamic pattern theory, a control parameter will not have any direct effect on the movement pattern. For example, speed of movement is a control parameter in the quadruped locomotion pattern. In Stage Three of the present study, elbow movement was limited by the application of an orthosis which maintained the elbow joint within a limited range.

Limitation of elbow movement by an elbow orthosis might not be an ideal method of examining a control parameter because the orthosis restricted the elbow joint angle which directly affected the throwing pattern. However, the restraint of the movement by an elbow orthosis identified a preference for the underarm throw at shorter distances thrown and for the overarm throw as the distance thrown increased. Furthermore, the number of subjects who used the overarm throw started to change at the distance thrown of 2.9 m in the orthosis condition, which was earlier than the shift in action noted in the without orthosis condition.

6.5 Order parameter

According to the dynamic pattern theory, an order parameter or the collective parameter characterises a movement pattern in quantitative form. Identification of order parameters for different styles of throwing, however, is not as simple as has been described for rhythmic motions. Relative phase which considers the displacement and velocity data of two joints is an order parameter frequently used by other authors. Any movement which involves only one or two joints can be described perfectly using relative phase. However, only a relative phase of one pair of joint angles may not sufficient to fully describe multijoint motions, such as throwing. The present study employed all possible measurements described in the literature to characterise the throwing movement. Trajectory of movement, phase plane plots, angle-angle plots and relative phase were investigated as order parameters for the study.

For the throwing movement examined in the present study, seven joint angles of the upper limb were involved. Appropriate joint angles had to be defined first. The essential joints which were able to differentiate the overarm from the underarm throw were selected for illustration (Chapter 5, Section 5.45). Any angular displacement which demonstrated a similar action in both throwing patterns was discarded from the analysis.

6.5.1 Trajectories of movement

The trajectories of the movements were the easiest way to observe characteristics of the throwing patterns when compared with the other proposed order parameters since only coordinate data in the xz or sagittal plane were required. This type of graph is suitable for the comparison of movement patterns among subjects. Variation of throwing patterns between subjects can be seen directly from the actual profiles of movements but cannot be described mathematically. Whereas for other order parameters (phase plane plots, angle-angle plots and relative phase), interpretation of variation can be observed from standard deviations.

For the overarm throw, the trajectories of movement demonstrated a greater variety of motion than for the underarm throw for the shortest distance thrown (Figure 5.14 to 5.19). In the present study, variations of the throwing motion within one pattern (overarm or underarm) were termed sub-styles of throwing. Variation was clearly present for the shorter distances thrown, especially the shortest distance (0.6 m). This may be due to the availability of degrees of freedom or the wide range of joint motions compared to a small range of joint motion required for throwing to the shortest distance. As the distance thrown increased, subjects may have had to use all joint angles in their full range. Therefore, increasing the distance thrown reduces the flexibility of the degrees of freedom. That is for a maximal distance thrown, only one possible interaction of joint angles can be performed. Thus, throwing to the greatest distance (6.91 m) showed relatively consistent patterns for both styles.

Determination of the averaged trajectories of all 16 subjects which represented the throwing pattern for each distance was difficult. The process of averaging trajectories required a reference point which is fixed at the same position of the recording space for all subjects. Body segments of each subject had to be normalised and a common frame of axes had to be defined. Therefore, the trajectory was not an ideal parameter with which to examine the effect of distance thrown on the movement pattern.

6.5.2 Phase plane plots

The phase plane plots of all seven joint angles of the throwing limb have been presented (Figure 5.20, 5.21 and Appendix D). These plots demonstrate movement control in terms of joint displacement and velocity for the overarm and the underarm patterns. Furthermore, these plots also differentiated the control mechanism of individual joint angles as the distance thrown increased for each throwing pattern. The differences in movement control as the distance thrown changed suggests different throwing patterns. Thus these results could be used to detect phase transition within the throwing pattern. However, a single phase plane plot which presented the control of one single joint did not represent the whole throwing movement pattern.

Comparison of the phase plane plots between the overarm and the underarm throw showed that most of the joint angles demonstrated a reversal of action. However, the opposing forces acting on joint angles for each throwing pattern did not share the same control mechanisms. That is most of the joint angles for the overarm throw demonstrated a reversal action from the sudden change of force direction, except the elbow joint which presented a smooth round curve which implied position-dependent forces. Whereas reversal motions in the underarm throw were comparable to a pendulum motion in which the magnitude of forces depend on the position and direction of movement.

Control of movement drawn from the phase plane plots for each throwing pattern at each throwing distance, demonstrated that each joint angle was regulated by the same mechanism as the distance thrown increased, except for the shortest distance thrown. The differences in the control mechanism for the shortest distance thrown were only apparent in flexion and extension of the shoulder joint and were more obvious in overarm throws than in underarm throws.

In conclusion, the results of the phase plane plots suggest differences in control of muscular forces between overarm and underarm throws. Moreover, the control of flexion and extension of the shoulder joint at the shortest distance was different compared to the control at all other distances. This suggests that a different sub-style of throwing was employed at the shortest distance thrown for both throwing styles.

6.5.3 Angle-angle plots

Only a subset of angle-angle plots were used in the present study. The shoulder joint was selected to plot against other joint angles because it showed a different action for each style of throwing and a high sensitivity to increases in throwing distance. The angle-angle plot presents the intersegmental coordination of two joint angles. The coordination between the overarm and the underarm throw and among distances thrown for each throwing style are discussed in following paragraphs.

As was the case for the phase plane plots, the angle-angle plots identified a difference in intersegmental coordination of a selected pair of joints for the shortest distance in both throwing patterns. Moreover, some of the angle-angle plots also demonstrated different relationships for the last few distances thrown. The differences were most evident in the plots of shoulder flexion with other joint angles and were more obvious in the overarm throw than in the underarm throw. Thus these results not only confirmed a difference of throwing pattern (sub-style of throwing) at the shortest distance thrown but also identified differences at the last few distances thrown for both throwing styles. The presence of sub-styles was more apparent in the overarm throw than the underarm throw.

In general, the same spatiotemporal relationships of a pair of joint angles was evident during the releasing phase of throwing. Variation in coordination mainly occurred in the preparation phase for both throwing patterns. Therefore, the control of these two phases may be different. The detail of this discussion is presented in Section 6.8.

6.5.4 Relative phase plots

For the relative phases, a subset of joint angles was selected based on the results reported in Chapter 5, Section 5.45. Shoulder flexion, shoulder rotation, elbow flexion and forearm rotation were selected because these joint angles contributed identifiably different actions in both throwing patterns. Only the relative phase between shoulder flexion and shoulder rotation, shoulder flexion and elbow flexion, and shoulder flexion and forearm rotation were presented for both throwing patterns (Appendix F, Figure 1 to 6).

Relative phase is derived from the difference between the arc tangent of the angular displacement and the angular velocity of a selected joint pair. Explanation of relative phase has been presented in Chapter 4, Section 4.2.4 and Chapter 5, Section 5.5.4. Relative phase can identify how a selected joint pair is coupled in performing the task (Scholz, 1990). Relative phase has generally been used as an order parameter in the study of oscillatory tasks and provides information about the coordination of the two joints at a particular point in each cycle of motion. Relative phase is constant for a particular speed or frequency of rhythmic motions. Thus it is a useful method for identifying the relationship between two joints as the frequency of movement increases. Manipulation of speed or frequency of movement to a critical value may change the coordination between the two joints, and thus change the relative phase of these joints changes.

In functional discrete movements such as throwing, the relative phase of a selected joint pair changes as a function of time. That is, the relative phase at the beginning of movement was not the same as at the end of motion. Changing of the independent parameter, distance thrown, created a change on the relative phase.

In conclusion, the pattern of relative phase plots demonstrated the sub-style of throwing within a throwing pattern as the distance thrown changed, especially in the overarm throw. Furthermore, the relative phase also distinguished the differences of throwing patterns. These data were used to support the information derived from other plots such as phase plane plots and angle-angle plots. A detailed description of relative phases in discrete motion requires further studies.

Relative phase confirmed the results of phase plane plots and angle-angle plots, that is, these data supported the presence of different throwing styles and sub-styles of throwing, within the same throwing pattern as the distance thrown increased. In fact, the relative phase between a selected joint pairs suggested that the sub-styles of throwing were presented in the medium distance thrown. The sub-styles of throwing were evident in the overarm throw more than the underarm throw.

6.5.5 Relative timing

Relative timing has been proposed as one of the possible invariant features. Movements belonging to the same class should have the same relative timing (Schmidt, 1991). Moreover, Schöner (1990) has suggested that relative timing may be used to capture the coordination of discrete movement.

In the present study, relative timing was calculated from the ratio of phase of throwing, preparation phase (Prep) and releasing phase (Rel), on total movement time (TMT) and also the ratio of Rel/Prep. The results for relative timing were presented in Figure 5.4. These results showed that as the distance thrown increased, the relative timing of the overarm throw increased for Prep/TMT and decreased for Rel/TMT and Rel/Prep, whereas, for the underarm throw, all the relative timings demonstrated a consistent ratio. These results suggest temporal flexibility for the overarm throw and temporal stability for the underarm throw with respect to the distance thrown.

The results for the overarm throw were in conflict with Schmidt's explanation (1991) that a particular class of movement (such as throwing overarm, throwing rapidly, etc.) is represented by a specific, rigidly defined relative timing. In the present study, only the underarm throw demonstrated the same relative timing as the distance thrown increased. The relative timing of the throws over the short distances were not considered in arriving at this conclusion since it was evident that the action was more related to dropping than throwing. Despite this, the relative timing of the overarm throw over the medium distances still showed a different ratio when compared with the throw over the longest distance. The relative timing for the longest distance in the overarm throw seemed to approach the relative timing data in the underarm throw. This tendency suggests that the relative timing of both throwing patterns may be the same over particular throwing distances, such as 6.91 m. However, this assumption needs to be further tested. The difference between the concept identified by Schmidt (1988) and the results of the present study suggest that the relative timing may not be a useful parameter with which to classify the movement. In particular, relative timing should not be used as an example of an invariant feature at least in throwing actions.

The fact that relative timing can be used to capture patterns of discrete movement (Schöner, 1990) suggests that a more uniform pattern exists within the underarm throw than within the overarm style. However, this conclusion cannot be used to support the differences in stability between the two throwing patterns, because standard deviations at the same distance thrown were relatively similar when compared between two patterns of throwing, except those for the two shortest distances thrown. The step increase of relative timing Prep/TMT and decrease of relative timing Rel/TMT and Rel/Prep without a significant increase in the standard deviation when compared with the underarm pattern suggests the adaptability of the overarm throw to the changing environmental parameters rather than the stability of the system.

Standard deviations of both throwing patterns as the distance thrown increased illustrated the same trends (Figure 5.4). That is, variation of relative timing was highest at the shortest distance and decreased as the distance thrown increased. This suggests that the variability of individual patterns was highest at the shortest distance and became more stable for longer distances. These results also confirmed the results reported for trajectories of movement as has been discussed in Section 6.5.1.

6.5.6 Summary

Different types of plots were used to present the coordinated motion of throwing. That is, phase plane plots, angle-angle plots, relative phase plots, trajectories of movement, and relative timing. More than one measure was needed to characterise the functional discrete movement. Phase plane plots and angle-angle plots seem to be helpful techniques to describe the coordination and examine the control mechanism. Both of the plots are easy to process and comprehensible when compared with the relative phase plots. However, event markers were essential to a full understanding of the data. In addition, phase plane plots, angle-angle plots and the relative phase were derived from the time and amplitude normalised data. Therefore, the plots could only be used to compare the form or pattern of that particular parameter.

Trajectories of movement and relative timing appear to be useful in determining the variability and stability of the pattern of motion. The quantitative measurement of stability can be identified using the standard deviations of the relative timing.

6.6 Angular displacement at the releasing point

The releasing position of most of joint angles for the underarm throw were approximately the same as the distance thrown increased, except for that of shoulder flexion and extension and shoulder adduction and abduction. However, the differences were evident only over the three shortest distances. The releasing posture for the underarm throw was relatively the same when the distance thrown was greater than 1.52 m. For the overarm throw, the releasing angles of shoulder motions changed as the distance thrown increased. Even though the alteration of releasing angles generally occurred over the first few distances thrown, shoulder adduction and abduction showed a step increase over all of the distances thrown and shoulder flexion, shoulder rotation and forearm rotation also demonstrated a significant difference between the 5.2 m distance and the longest distance thrown. Therefore, the releasing position of the throwing limb for the overarm throw was not constant as the distance thrown increased. The differences were evident mainly at the shoulder joint over the shortest distances and over the longest distance thrown.

6.6.1 The consistency of the releasing angle data and the phase plane plots

The releasing posture of the overarm throw showed slight variation in the motion of the shoulder joint as the distance thrown increased. The variability occurred mainly over the first few distances thrown and over the last distance thrown. Therefore, for the overarm throw, the end posture states appear to be separated into three groups as the distance thrown increased. This result was consistent with the phase plane plots. The phase plane plots of most of the joint angles showed different patterns mainly at the first distance, the phase plane plot for shoulder flexion and extension demonstrated these different patterns at the shortest and at the last few distances thrown.

The releasing posture for the underarm throw showed the change only over the first two distances thrown in shoulder flexion and extension. Other joint angles demonstrated a fixed releasing position over all of the target distances. The phase plane plots for the underarm throw also displayed the difference at the first distance thrown in shoulder flexion, shoulder adduction and wrist flexion. The relationship was maintained in other joints over all of the distances thrown. Thus the results suggest that different sub-styles may be introduced only at the first distance thrown.

6.7. Movement transition

Results of control and order parameters suggest that there are two types of movement transition in the present study.

The first type of transition occurred between the pattern of throwing, that is from the underarm throw to the overarm throw. No results could directly illustrate the period of transition, for example, the results which demonstrated the instability of the underarm throw at the distance 4.05 m. This may be due to the fact that:

a) measurement of stability in discrete movement is difficult. Proposed concepts which can be applied in rhythmic motion could not be used in functional discrete movement as has been discussed in Section 6.2;

b) phase transition in a multistable system are not the result of instability in the previous pattern (Thompson & Stewart, 1986).

However, some of the results presented indirect evidence, eg. hysteresis, which implies a phase shift between throwing patterns.

The second type of phase shift occurred within each individual throwing pattern from one sub-style of throwing to another. Results of phase plane plots, angle-angle plots and relative phase confirmed this assumption. Furthermore, results of trajectories of movement, total ROM, angular displacement at the releasing point, and the relative timing also supported this statement. Details of this discussion will be presented in subsequent sections of this discussion.

6.7.1 Hysteresis

Hysteresis is an important phenomenon which suggests the coexistence of the behavioural states for the parameter values (Kelso, 1995). In the present study, alteration from an underarm to an overarm throw was the apparent trend. Despite the fact that one subject changed her styles from the underarm to overarm and reversed back to the underarm throw in the normal condition (without elbow orthosis), this subject also altered her throwing styles three times in the elbow limitation condition. That is she moved from the underarm to overarm throw then reverted to underarm and finally reversed to overarm again. Therefore, the preferred direction of phase transition in throwing the pattern appears to be in the direction of the overarm throw. However, the present study did not test for any alteration of pattern when subjects were asked to throw from the longest to the shortest distance thrown, that is in the reverse distance order. Therefore, this result can only suggest the presence of the hysteresis phenomenon as has been described by Kelso (1995).

6.7.2 Recruitment of joint angles as the distance thrown increased

Kelso (1995) has suggested that previously quiescent motions can be spontaneously recruited to gain stability during a movement while flexibly adapting to environmental requirements. The findings of the present study related to the joint angles employed in the overarm and underarm throws show a difference in the total range of motion data. The overarm throw recruited the greatest range of motion in the sagittal plane then added actions which occurred in the transverse plane (shoulder and forearm rotation). Conversely the underarm throw increased the range of motion mainly through flexion and extension of the shoulder joint.

The higher degree of recruitment in the overarm throw suggests the shifting of the pattern to a new form (sub-style of throwing) as the distance thrown increased.

6.7.3 Energy expenditure for each throwing pattern

According to the dynamic pattern theory, any system tends to organise a new form of movement so that the energy required in performing the movement is reduced (Kelso, 1984). In the present study calculation of energy expenditure was not performed directly. An estimate of energy was determined by extrapolation from the total mechanical work of the muscles involved in the throwing pattern. However, the calculation of mechanical work was derived from the moment data which were computed using a number of assumptions as has been described in Chapter 4, Section 4.2.6. The results of joint moment data are subject to error due to the lack of accurate prediction of the position of joint centres. Calculation of joint moments assumed that the markers represented the joint centre positions. Therefore results related to moment and work of muscles require careful interpretation and need to be confirmed. In spite of these reservations, these results were included because the data for both throwing patterns were derived using the same calculation procedures. That is both patterns were subject to the same error in joint centre approximation.

6.7.3.1. The extrapolation of energy utilisation from the mechanical work of muscles

Positive and negative work represents concentric and eccentric contraction respectively (Winter, 1990). Oxygen consumption is known to be much lower during eccentric exercise than in comparable concentric exercise (Kaneko, Komi, & Aura, 1984). The relationship between net energy expenditure and mechanical work has been presented by Kaneko, Komi, and Aura (1984).

From the results of the present study (Figure 5.39), the overarm throw showed a greater amount of positive work over all of the distances thrown when compared with the underarm throw. The underarm throw demonstrated a higher level of the negative work over all of the distances thrown when compared with the overarm throw. The amount of positive work increased as the distance thrown increased whereas, the value of the negative work was maintained or varied very little. However, the difference of total energy work between these two throwing patterns was very small.

The total mechanical work in the overarm and the underarm throw in the present study was in the range of 10 to 100 joules. The low level of mechanical work required for both styles and the fact that these two throwing patterns utilised relatively the same amount of work, suggest a non-significant effect when considered in terms of energy consumption.

In conclusion, the total mechanical work required for both throwing patterns was small and might not have had any significant effect on the phase transition observed.

6.7.4 Movement transition from the overarm to the underarm throw

This finding suggests that coordination of throwing may be affected by the use of multistable states. In effect, increasing the throwing distance may change the environment of the system so that the overarm throw becomes the preferred pattern. There are several possible explanations of the underlying mechanisms which could account for the change from the underarm throw to the overarm throw.

1) The greater flexibility of the overarm throw when compared with the underarm throw. This flexibility suggests that the overarm pattern may have the capacity to adjust to the new environment (increasing distance) to a greater extent than the underarm pattern.

2) The stability of the system may be more easily maintained in the overarm throw than in the underarm throw. This assumption is based on the evidence of the recruitment of additional ranges of joint motion as the distance thrown increased in the overarm throw. According to the dynamic pattern theory, the recruitment of the increasing degrees of freedom suggests a shift to a new pattern while maintaining the stability of the system.

3) Based on purely mechanical reasons, the overarm throw resembles a rotational movement while the underarm throw is much more like a pendular motion. The moment of inertia is higher in pendular movement than is the case for rotational motion. The underarm throw is therefore limited in its ability to sequentially increase rotation when the only choice is to increase the range of flexion of the shoulder and elbow joints. Such a course of action might displace the projectile in a vertical or posterior direction rather than the required forward direction.

4) Comparisons of the energy expenditure between the two throwing patterns showed no significant difference. While the overarm throw may use more energy when compared with the underarm throw, the amount of energy required in both styles of throwing was at a very low level, within the range of 10 joules. In fact, Kreighbaum and Barhtels (1990) have indicated that for a given muscular torque, the wheel-axle system produces higher angular acceleration than the lever system. This implies that the overarm throw may create a higher angular acceleration than an underarm throw. Since the distance of throwing depends on the velocity and acceleration of movement, selection of overarm throw may fulfil the required velocity for a particular distance with the least muscular effort.

6.7.5 Movement transition within a throwing pattern

For the overarm throw, alteration of the sub-styles of movement within the same throwing pattern seemed to take place between the shorter distances thrown, that is from an action which may be described as a dropping action to one involving a throwing pattern.

Dropping can be separated from throwing by considering of the phase of movement data. Subjects moved their bodies forward in the direction of the target and let the ball go at the releasing point in dropping, whereas in the throwing motion, subjects increased the flexion of the shoulder in order to develop maximum potential energy before accelerating the arm forward to the target then releasing the ball in the throwing action.

At the longest distance thrown, another sub-style of throwing appeared to arise. This action may be comparable to the throwing movement of a baseball pitch in which sequential motions are apparent and the shoulder joint demonstrates a fully external rotated posture in the preparation phase.

For the underarm throw, most of evidence supported the existence of a sub-style of throwing at the shortest distance. However, the differences in the relationship between the shortest distance thrown and other distances were not as obvious as in the overarm throw. The movement may be described as a dropping action as was identified in the overarm throw, however, the forearm was positioned in supination which was the opposite to the action used in the overarm throw.

At the longest distance thrown, only the result of the relative phase plots demonstrated the different coordination of selected joints (Appendix F, Figure 11 and 12). However, simple observation of the underarm throw from the video tape did not show any meaningful difference in the pattern when compared with the motion used for the next shortest distance thrown.

Results that suggest the alteration of sub-style of throwing are summarised as follows:

1) Based upon the relative timing, large standard deviations at the two shortest distances suggest variability of motion when compared with other distances thrown. This result was demonstrated in both throwing patterns.

2) The total ROM data indicated that in the overarm throw, the contribution of the joint angles was not the same when compared among the short and the long distances thrown.

3) The data which described the angular displacement at the releasing point showed differences in releasing angle which was demonstrated mainly at the shortest distance thrown especially for the shoulder motions. The difference in the releasing angles was more apparent in the overarm throw.

4) The results of the trajectories of the movement, showed clearly in both throwing patterns that variation of the trajectories was high at the shortest distance thrown and became uniform as the distances thrown increased. The trajectories at the shortest distance thrown were also different from those of the longest distance thrown.

5) The phase plane plots also showed interesting results. The phase plane plot of flexion and extension of the shoulder joint demonstrated a different control mechanism when compared with other distances. This result could be seen in both throwing patterns. The differences were also present at the last few distances thrown in the overarm throw but were not as obvious as in the shortest distance.

6) Information derived from the angle-angle plots, showed that for shoulder flexion there was a difference in intersegmental coordination at the shortest distance thrown. Variation of coordination was also apparent as the distance thrown increased but this variation was mainly in the preparation phase of throwing. Similar evidence was not obviously demonstrated in the underarm thrown.

7) Based upon the relative phase data, the presence of sub-styles of throwing at the shortest was shown only in the overarm throw. The differences mainly presented in the preparation phase. Furthermore, the changes of the relative phase also demonstrated between the distance thrown of 1.98 to 2.99 m. For the underarm throw, a difference in relative phase was not evidently demonstrated as in the overarm throw.

6.8 Control of throwing movement

For both throwing patterns, the preparation phase demonstrated variability of movement when compared with the releasing phase. These changes could be seen from the angle-angle plots between shoulder flexion and other joint angles.

Control of throwing may be relatively more important at the beginning of the movement (preparation phase). Selecting and recruiting all degrees of freedom for a particular throw (suitable for the required distance) may occur in the preparation phase. The coordinated motion in the releasing phase is probably, the result of the preparation position which was organised initially to meet the requirements of the end position.

Furthermore, it appears that the control of throwing motions during the preparation phase occurs mainly as a result of movements of the shoulder joint. This conclusion seem to be confirmed by the fact that most of the significant data in the present study are associated with the shoulder joint, for example, the results from the phase plane plots, angle-angle plots, and joint angle at the releasing point. Therefore, the shoulder joint may play a major role in the throwing action employed in this study and its control is probably independent of the control of the elbow and wrist joint. This conclusion is consistent with the assumption presented by Soechting and Lacquaniti (1983) based upon the examination of a pointing movement .

Soechting and Lacquaniti (1983) found that the wrist joint was controlled separately from motion at the elbow and shoulder joint in a pointing task. Because the requirements in a pointing movement are relatively minimal compared with the throwing motion, adjustment of the limb segments to achieve the goal is likely to be different from those of throwing. Control of both shoulder and elbow joints is required to position the wrist joint and hand to the specified position. For the throwing motion, the full length of the upper limb is required at the releasing point. Transferring of energy from the proximal parts to the distal end effector (hand) is one of the important goals in throwing. Only one mechanism is available to produce maximum force for the elbow and wrist joints, that is through the execution of rapid extension of the elbow joint and flexion of the wrist joint. This assumption was confirmed by the increase angular velocity at the releasing point of flexion and extension of the shoulder, the elbow, and the wrist joints as the distance thrown increased. The ulnar and radial deviation components of the wrist joint were not found to contribute to the development of force in the present study, since the direction of movement required of the projectile was directly forward to the target and there was no need for any change direction of the ball. Thus, it appears that the shoulder joint action was the most important to the movement and required most control because of the three degrees of freedom present at the shoulder joint. The control of the shoulder joint seems to be different from that of the elbow and wrist joints in the throwing motion studied here. It is evident that if movement of the torso and lower limb are limited control of the shoulder joint is the major component required as was the case in the present study. In other throwing situations, for example, a baseball pitch or a hammer throwing, points of control are probably concentrated more on the movement of the lower limb and trunk.

6.9 Alteration of throwing movements from other motor control perspectives

The fact that dynamic pattern theory emphasises manipulation of independent parameters to induce a phase transition, provides a different perspective from other motor control theories. This outcome is supported by the comments of Newell (1989) who stated that the use of a task goal that requires manipulation of environmental conditions to induce phase transitions of coordinated patterns has been very limited in motor control experiments. While dynamic pattern theory provides a model to investigate methods which induce a change of pattern in motor control experiments, other motor control models do not have any assumptions relating to the changes in pattern. According to the generalised motor program theory and the concept of invariant features (Schmidt, 1988), the overarm and underarm throws are located in the same class of movement and performed by the same motor program. This proposition does not explain phase transitions in the throwing patterns observed in the current study as the distance thrown increased.

In fact, the results of the relative timing in the present study, for example the ratio of preparation time to total movement time, showed different values for overarm throws as the distance increased but were unchanged for the underarm pattern.

To explain throwing movements based on mechanical characteristics, Kreighbaum and Barthels (1990) divided rotation which occurs in throwing motions into two types, that is, lever and wheel-axle rotations. The overarm throw (a so-called throwlike action), demonstrates a wheel-axle rotation, whereas the movement in which segmental rotations occur simultaneously (the so-called pushlike action), behave as a leverlike movement. In the principal study, an overarm throw was matched with the throwlike action since the segmental motions operate in the wheel-axle rotation system. On the other hand, underarm throw can be considered to be a pushlike action because the movements of the limb act like a lever system. This conclusion may be confirmed by the temporal position of the peak angular velocity of the shoulder, elbow, and wrist joints (Figure 5.13). From the present data it is evident that overarm throws demonstrated a higher degree of sequential motion than underarm throws.

The differences in the rotational mechanism between the overarm and underarm throws suggest that different amounts of energy would be used in the two different styles. For the same amount of muscular torque, the overthrow which acts like a wheel-axle system can produce higher angular acceleration than the underarm throw, which behaves like a lever system (Kreighbaum & Barthels, 1990). Energy utilisation appears to have been one of the factors responsible for the alteration of throwing patterns as the distance increased (Section 6.7.3).

However, for an overarm throw, two subjects who had difficulties in throwing to the greatest distance could not accelerate segments of the upper extremity in sequential motion (data not shown). They demonstrated simultaneous motion of all segments rather than a sequential pattern. This was found through observation of their overarm throws using the video tape. This discrepancy may be due to a lack of skill or muscle strength (Kreighbaum & Barthels, 1990). For the overarm throw, only a small amount of elbow extension is required (Feltner & Dapena, 1986) and this added to the fact that all subjects were normal and in the same age range and the projectile used in the present study weighed 500 g suggests that a lack of skill may have been responsible for the simultaneous motions found in these subjects. However, this conclusion needs to be confirmed by measures of muscle strength of the shoulder rotator muscles of subjects and comparison of throwing patterns (overarm) after subjects are taught how to throw and allowed a period of time to practice.

6.10 Measurement of coordination

6.10.1 Three-dimensional motion analysis

A significant advantage of three-dimensional motion analysis using videography is that the kinematics of motion can be accurately detected for the whole motion. However, the validity of the results remain open to question. In addition, the time required for digitisation may be a major obstacle if the requirement is for rapid turn around on the data.

6.10.2 Cross-correlation and visual comparison

In general, the present study used visual comparison to measure the similarity between two coordinated plots. For the results of the phase plane plots and angle-angle plots, cross-correlation was also employed. The results from both techniques, that is vision and cross-correlation, were consistent. However, there is a problem of the significant difference between these two techniques. The differences in cross-correlational values identified as the distance thrown increased may not have any significant meaning when compared directly with the curves derived from the respective plots.

6.11 Summary

An examination of throwing was performed using the dynamic pattern theory. The throwing motion was analysed three dimensionally using the videography method. Seven joint angles of the throwing limb, that is, shoulder flexion and extension, shoulder adduction and abduction, shoulder rotation, elbow flexion and extension, forearm pronation and supination, wrist flexion and extension and wrist ulnar and radial deviation, were calculated using Euler's method. Other parameters were also determined such as the angular velocity, relative timing, the joint angle at the releasing point, the phase plane plot, the angle - angle plot and the relative phase.

The study demonstrated an alteration of the throwing pattern in one direction, that is from an underarm to an overarm throw as the distance thrown increased. This transition of the throwing pattern may be due to various factors. These included the possibility for increasing the flexibility of the overarm throw, the ability to maintain the required stability as the distance thrown increased, and mechanical reasons related to the nature of the throwing movement. In addition, the amount of energy required and the differences of each throwing pattern in producing muscular torque in both throwing patterns have also been discussed.

Furthermore, the study also suggested an alteration of the throwing style within each throwing pattern (overarm and underarm throws), which was defined as a sub-style of the movement. The results suggest the existence of at least three sub-styles of the overarm throw and two sub-styles of the underarm throw which become apparent as the distance thrown increases. This assumption is based on the results of the total range of motion, the releasing joint angles, the phase plane plot, the angle - angle plot and the relative phase. While these data did not identify the exact distance at which the sub-styles of throwing were able to be separated, they demonstrated trends toward such an identification.

The following conclusions may be drawn from the study.

6.11.1 Distance thrown as a control parameter of throwing

1) The overarm and the underarm throw were the two most common throwing patterns

2) There was a tendency towards alteration the pattern of throwing as the distance thrown increased.

3) Switching of the throwing style occurred mainly in the direction of the overarm throw from the underarm throw.

4) The transition of the throwing pattern from underarm to overarm occurred at a distance thrown of 4.05 m.

5) There was a change in the throwing style when comparisons were made between a throw over the shortest distance and the longer distance thrown. This change might be defined as the difference between the action of dropping and a true overarm throw.

6.11.2 The relative timing

1) The relative timing of throwing movements in the same class may not be equal

2) The relative timing of the overarm throw changed as the distance thrown increased.

3) The relative timing of the underarm throw was maintained over all of the distances thrown.

4) The relative timing of the overarm throw approached the value of the underarm throw as the distance thrown increased.

5) Variation among subjects in pattern production, which was presented by standard deviations was greater for the shortest distance than for other, longer distances. This suggests variability of the throwing pattern.

6.11.3 The angular displacement as the distance thrown increased

1) As the distance thrown increased, the increase in the range of motion changed from one joint angle to another in the overarm throw.

2) As the distance thrown increased only shoulder flexion and extension showed a step increment in the underarm style.

3) The amplification of joint motion in the overarm throw changed from flexion and extension to rotation as subjects threw over the various distances, commencing with flexion and extension at the shorter distances and moving to rotation over the longer distances.

4) The overarm throw seemed to show a higher degree of joint recruitment when compared with the underarm throw.

6.11.4 The angular displacement at the releasing point

1) As the distance thrown increased, the releasing angles of the shoulder joint changed for both throwing patterns.

2) For the underarm throw, the differences in the releasing angles mainly occurred at the three shortest distances thrown.

3) For the overarm throw, shoulder adduction and abduction appeared to increase in range throughout all of the distances thrown, while shoulder flexion and extension and shoulder rotation mainly demonstrated changes over the first few distances thrown.

4) The position of the elbow, radioulnar and wrist joints at the releasing point seem to be the same as the distance thrown increased in both throwing patterns.

6.11.5 The angular velocity as the distance thrown increased

1) Angular velocity of the shoulder joint demonstrated a step increase as the distance thrown increased in both the preparation and the releasing phases.

2) The increase in the angular velocity for other joints, that is, the elbow, radioulnar and wrist joints mainly occurred during the releasing phase as the distance thrown increased.

3) The angular velocity of the elbow, radioulnar and wrist joints in the preparation phase was relatively similar over all of the throwing distances.

6.11.6 The phase plane plot

1) For the overarm throw, the phase plane plots of shoulder flexion and extension, shoulder adduction and abduction and shoulder rotation showed a different relationship when compared between the shortest and the longer distances thrown.

2 For the overarm throw, the phase plane plot of forearm rotation, elbow and wrist motions appeared to maintain their relationship over all of the distances thrown.

3) For the underarm throw, the phase plane plot of shoulder flexion and extension, shoulder adduction and abduction and wrist flexion and extension showed a different relationship when compared among the shortest and the longer distances thrown.

4) For the underarm throw, the phase plane plot of shoulder rotation, forearm rotation, elbow flexion and wrist deviation seemed to retain the relationship over all of the distances thrown.

6.11.7 The angle - angle plot

1) Only the plot between shoulder flexion and the other joints in the overarm throw showed any difference at the shortest distance when compared with the longer distances thrown.

2) The angle - angle plots between shoulder flexion and other joints in the overarm throw demonstrated a change in the relationship from coupled to the decoupled coordination in the preparation phase as the distance thrown increased whereas the relationship was maintained in the releasing phase.

3) The angle - angle plots in the underarm throw did not change as the distance thrown increased.

4) Apart from the switching of throwing pattern at a distance of 4.05 m, the results also suggest an alteration of the pattern in between the short distances.

6.11.8 The relative phase

1) The relative phases of the overarm throw identified a change in throwing patterns at the shortest distance thrown and in between the distance thrown of 1.98 to 2.99 m.

7) The relative phases of the underarm throw suggested that the alteration of the throwing pattern might occur at the medium distance thrown same as in the overarm throw. However, the results did not obviously presented when compared with the overarm throw.

6.11.9 The mechanical work of muscles

1) The total work of muscles in the overarm throw was slightly higher than that which occurred in the underarm throw.

2) The overarm throw showed greater positive work when compared with the underarm throw over all of the distance thrown.

3) Positive work increased as the distance thrown increased in both throwing patterns

4) The underarm throw showed the highest negative work when compared with the overarm throw over all of the distances thrown.

5) Negative work was maintained over all of the distances thrown in both throwing patterns.

Chapter 7

Conclusions

Every end is a new beginning

-Unknown author

This is one of the first study that has applied dynamic pattern theory to a functional, single-limb, discrete movement. Most of the parameters proposed by the theory have been calculated, including phase plane plots, angle-angle plots and the relative phase. Although the study did not demonstrate an abrupt change in the relative phase at the distance thrown where the pattern transition occurred, some characteristics such as hysteresis and the recruitment of degrees of freedom were identifiable. Furthermore, the results also imply that the dynamic system involved in throwing is in a multistable state.

Examination of the angular displacement results and the order parameters suggested that the shoulder joint is the crucial point of control. Additionally the control appears to occur during the preparation phase of throwing. For the throwing motion in the present study, only movements of the upper limb were allowed, position of the shoulder joint and selection of all other joints involved may be determined during the preparation phase, the movement of other joint angles during the releasing phase occur automatically, determined by the preparation position.

The number of joints involved in each throwing pattern were not the same for the overarm and the underarm throw. The overarm throw requires movement of the shoulder (flexion, adduction and rotation), elbow, radioulnar, and wrist joints, whereas the underarm throw requires movement mainly of the shoulder (only flexion) and the wrist joints. The number of joints that have to be controlled may act as a major determinant in the alteration of the throwing pattern. Reduction of the number of moving joints indicates a decrease in the number of degrees of freedom that have to be controlled. Thus the underarm throw may be easier to control than the overarm throw. This may explain the preference for the underarm throw at the shorter distances thrown.

Although the distance thrown was the only manipulated control parameter, other factors may have been also involved, for example, the muscular forces. As the distance thrown was increased, other parameters such as the torque of muscles were automatically manipulated in order to accelerate the upper limb segments to the required velocity. Interactive effects of these control parameters may have acted as a driving force to shift the throwing pattern to another style. Transition of the throwing pattern to the overarm throw may be one of the solutions. This may have been due to the fact that the overarm pattern can recruit more joint angles and the rotational mechanism is more suited to generating larger amounts of muscular torque.

However, measurement of stability and identification of suitable order parameters of a discrete motion need to be further examined before the dynamic of throwing motion can be understood. In addition, the concepts of and the relationships among stability, variability, flexibility, and a new pattern need to be redefined. Precise and sensitive order parameters are necessary to differentiate variability within movements from new movement patterns since similar types of the movement coordination may arise from different types of sub-systems.

The present study has provided some insight in the dynamic of throwing motion. The results implied that movement of the shoulder joint during the preparation phase of throwing is the key point of control. It would be interesting to test this concept in the training strategies of throwing by controlling motion of the shoulder joint at the early phase. Furthermore, additional rotation components of the shoulder and the radioulnar joints found in the overarm throw as the distance thrown increased but not in the underarm throw also implied that alteration of movement pattern can be elicited from the changes in physical parameter of the environment (increase of the distance thrown in the study). The same conclusion has also been demonstrated in the locomotion and repetitive motion, such as flexion and extension of the wrist joint by increase speed of movement. Therapists should become aware of this concept and try to modify physical parameters of movement (which does not have a direct influence on movement pattern) and observing the changes in patients' performance. However, the ability to recruit more degrees of freedom of a motion has to be determined first, because a particular movement might have employed all the components of the movement system and cannot alter the pattern as the physical parameters have changed. For example, the contribution of joint motions of the upper extremity in the underarm throw was hardly changes as the distance thrown increased.

Future research and suggestions

1) Future studies should test the changing of the throwing pattern in two directions, that is, subjects should be asked to throw from the shortest to the longest distances and also in the opposite direction. It is expected that the results would be different. Alteration of the throwing pattern from the underarm to the overarm throw should be demonstrate only when subjects throw from the shortest to the longest distances. Phase transition may be detected at the different distances thrown, if subjects throw from the greatest to the shortest distances. However, there may be more subjects who fail to strike the target area at the longer distances with the underarm throw than those who use the overarm throw. The results from a protocol such as this could demonstrate whether the direction of progression of the target distances (from the shortest to longest or vice versa) can affect phase transition and produce a full example of the hysteresis phenomenon.

2) To test the concept of direction dependent coordination patterns, the experiment may be performed by determining the relationship of the starting posture of the forearm in supination, neutral, and pronation and a style of throwing. The expected results are that if the movement starts from supination of the radioulnar joint, more subjects may select an underarm throw rather than the overarm styles. The opposite results will be detected, if the forearm is in pronation at the starting position. The use of the neutral position of the forearm may result in a similar number of subjects selecting each throwing style. Experimental protocol of defining the starting position of the forearm should perform indirectly, for example, giving a ball above and underneath subjects' hand should facilitate supination and pronation of the forearm respectively.

3) Determination of the relationship between throwing styles and measurement of muscle power especially for the muscle groups involved in rotational components, for example, the internal and external rotators of the shoulder joint and the supinator and pronator of the radioulnar joint.

Muscle strength may be one of the control parameters which influence the throwing pattern.

4) In the present study, measurement of energy utilisation for each throwing pattern was calculated from the mean results of angular displacement and angular velocity and the calculation processes of moment data based on some assumptions. The results may not truly present the energy required for throwing motion. Thus further study which measures the energy consumption of throwing is essential to clarify the alteration of the throwing motion as the distance thrown increased. This may be performed using inverse kinetics.

5) Repeating the experiment with a heavier projectile, such as a shot put ball. The purpose of using a very heavy ball is to push the system to the point at which the transition takes place. The alteration of the throwing pattern may occur at shorter distances if the projectile is sufficiently heavy.

6) Repeating the experiment for children with immature throwing skills comparing these with the subjects who have skills in throwing. The points of interest would be the selected patterns of throwing and alteration of throwing patterns as the distance thrown is increased.

7) Repeating the experiment with a different starting position, such as in a sitting posture which limits motion of the lower limb but allows movement of the trunk and upper limb and in the standing posture in which all body segments can take part in the throwing motion. This protocol may be able to verify the concepts of control of throwing which have been implied from the results of the present study.

Studies of motor control based on dynamic pattern theory need to be performed using more functional discrete movements than has been the case in the past. Additionally, the examination should also place emphasis on the measurement of intention which is likely to play a major role in the observed pattern. Common results suggested from different type of task may provide the necessary information which can elucidate the underlying control mechanism of the variety of movements which can be described as throwing.

In short it would appear that it is possible to apply dynamic pattern theory to the task of throwing at least under the controlled environmental conditions needed in the present study. From this information base it would be useful to move forward and further examine the range of actions described as throwing. It would also be of benefit in the development of a greater understanding of a variety of functional and discrete movement. Such increased in understandings are likely to be of major benefit in assisting all those who work with people who display movement disorders to better understand the problems presented and the likely solutions.

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Appendix A.

Consent form

Subject no. ________

Curtin University of Technology
School of Physiotherapy

An examination of selected upper extremity functional activity from the perspective of the Dynamic Pattern Theory of motor control

You are invited to participate in this project. The purpose of the study is to investigate factors that may affect upper limb function based on a theory of the control of movement. The measurements will be carried out at the School of Physiotherapy at Shenton Park. The measurement for the study will be performed as follows:

1. Measurement of kinematic variables of simple of functional hand tasks using a video motion analysis system.
2. Small adhesive markers will be placed on the bony prominence of each of the joints of the upper limb.
3. You will be asked to perform the desired activities under different conditions, for example throwing a ball to different distances.
4. Subjects will be identified on the video tape only by number.

All personal data will be considered confidential and will be anonymously presented. Your decision whether or not to participate in this study is up to you. You are free to withdraw from the testing at any time. The measurements will be performed once only and will take about sixty minutes. As the data captured on video tape will be a valuable resource, the School of Physiotherapy would wish to retain it for possible further use. A record of the match of the subjects name and number will be maintained in a locked file by the Co-ordinator of Graduate Studies in the School of Physiotherapy. Should there be a need to derive further data from these video tapes, the Co-ordinator of Graduate Studies will approach the subjects again seeking their permission for this possible future use.

If you wish to participate in this study, please sign the attached form. Thank you for your time and cooperation.

I, ________________________ have agreed to participate in the research being undertaken by Jonjin Ratanapinunchai, under the supervision of Professor Joan Cole

I certify that:

The procedures have been clearly described to me. I am willing to participate in this study and I can withdraw from the study without penalty at any time.

Participant Signature____________________ Date____/____/____

Researcher Signature____________________ Date____/____/____

Participant address________________________________

Tel (H)______________ (W) ______________

Appendix B.

Anthropometric data

Anthropometric data were calculated from the average height, body weight and the upper extremity's length of 16 subjects, which were 1.64 m, 57.6 kg and 0.72 m respectively. All the values are expressed in percentages.

Location of centre of mass for arm segment (m)	0.14
Location of centre of mass for forearm segment (m)	0.11
Location of centre of mass for hand (m)	0.09
Ixx for arm (kg m^2)	0.0132603
Iyy for arm (kg m^2)	0.0127561
Izz for arm (kg m^2)	0.0018784
Mass of arm segment (kg)	1.61
Ixx for forearm (kg m^2)	0.0057626
Iyy for forearm (kg m^2)	0.0055727
Izz for forearm (kg m^2)	0.0006589
Mass of forearm (kg)	0.92
Ixx for hand and ball (kg m^2)	0.0003702
Iyy for hand and ball (kg m^2)	0.0003702
Izz for hand and ball (kg m^2)	0.0003702
Mass of hand and ball (kg)	0.85
Length of arm (m)	0.32
Length of forearm (m)	0.25
Length of arm (m)	0.18

All the anthropometric data were derived from Winter (1990), except the moment of inertia data. The moment of inertia data were computed from the equation of Chandler (1975).

Appendix C

Graphs of direction-dependent coordination for both throwing patterns

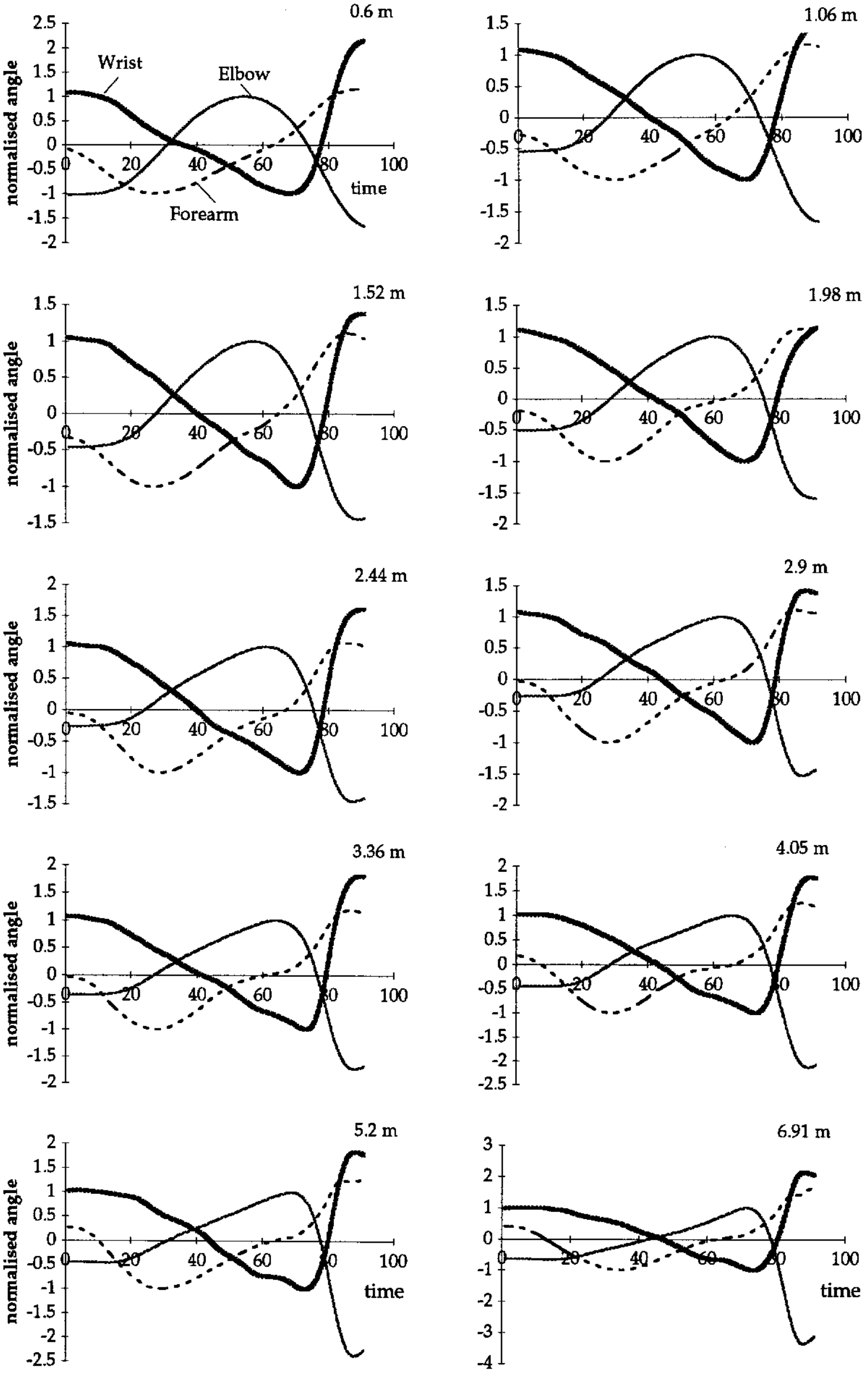


Figure 1 Normalised angular displacement of elbow and wrist flexion and forearm rotation for the overarm throw as the distance thrown increased.

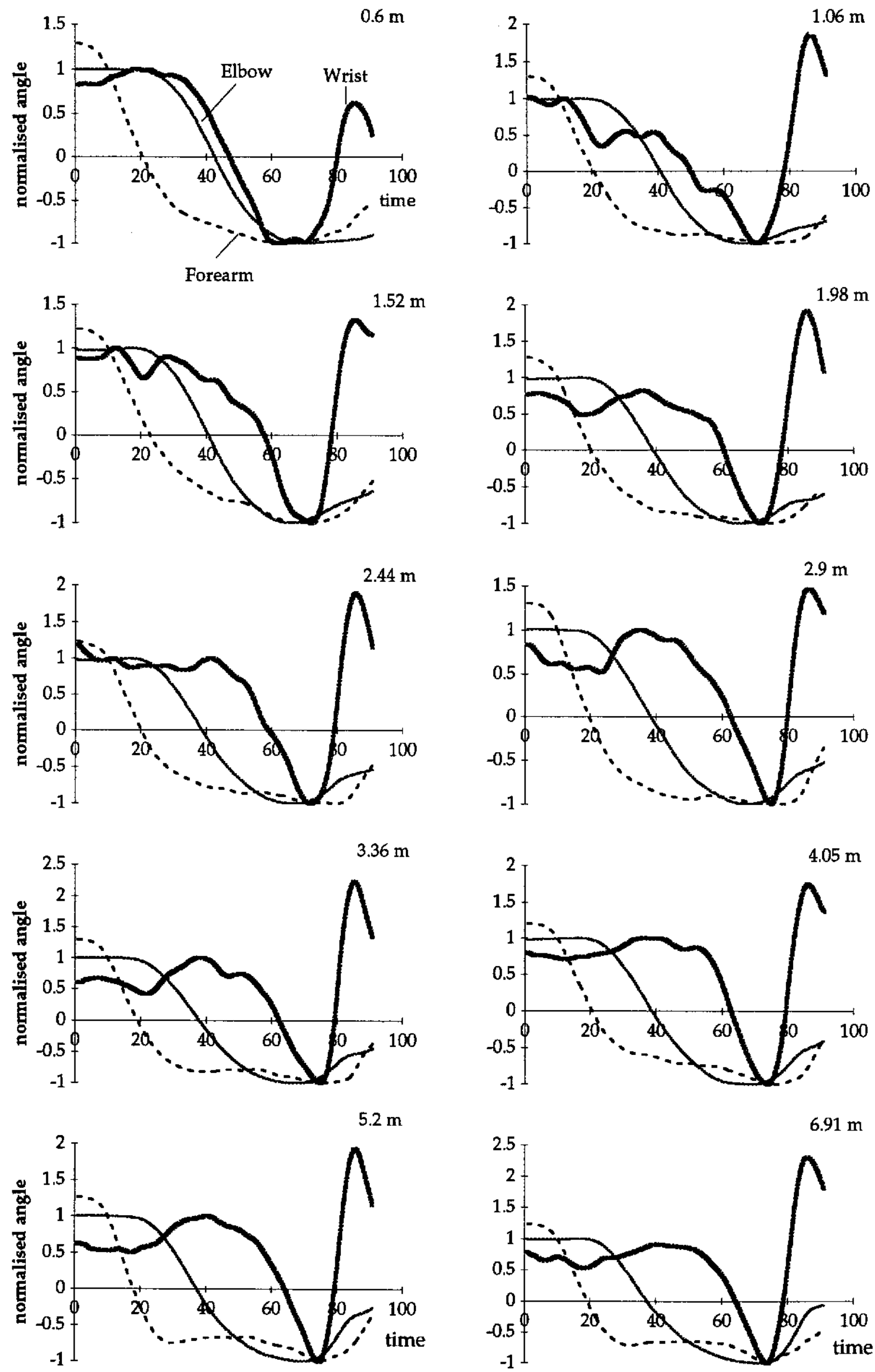


Figure 2 Normalised angular displacement of elbow and wrist flexion and forearm rotation for the underarm throw as the distance thrown increased.

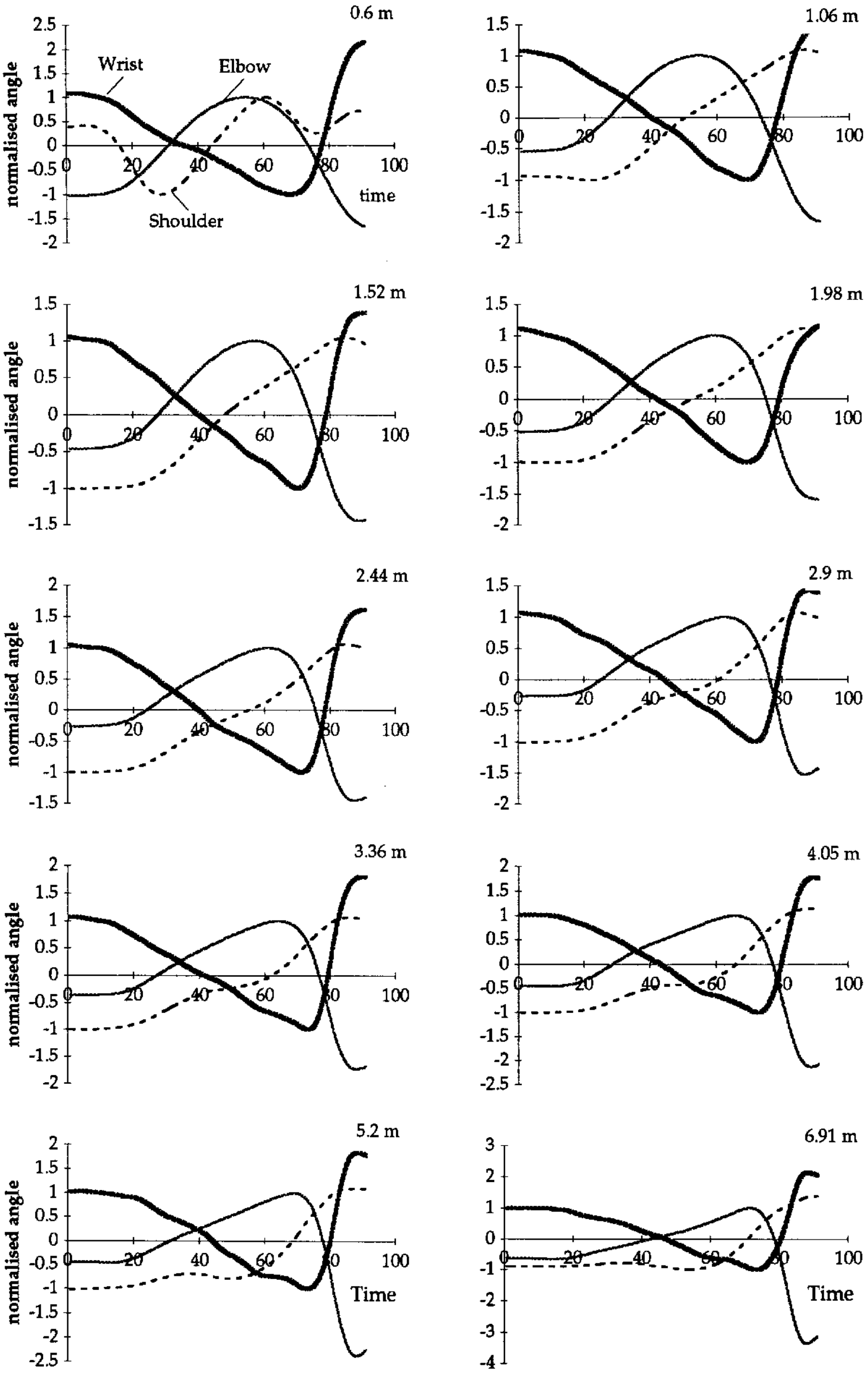


Figure 3 Normalised angular displacement of shoulder, elbow and wrist flexion for the overarm throw as the distance thrown increased.

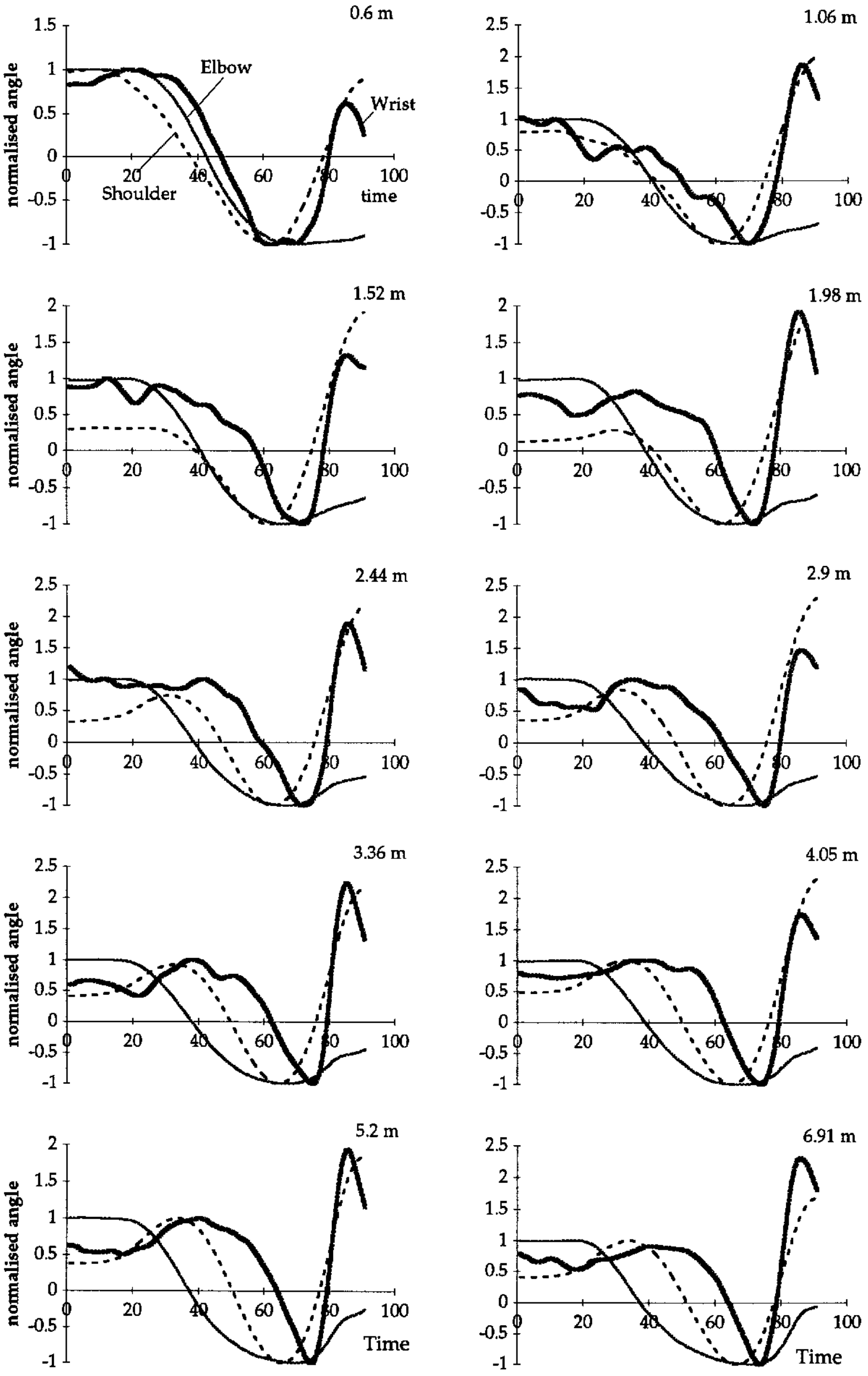


Figure 4 Normalised angular displacement of shoulder, elbow and wrist flexion for the underarm throw as the distance thrown increased.

Appendix D

Graphs of phase plane plots for both throwing patterns

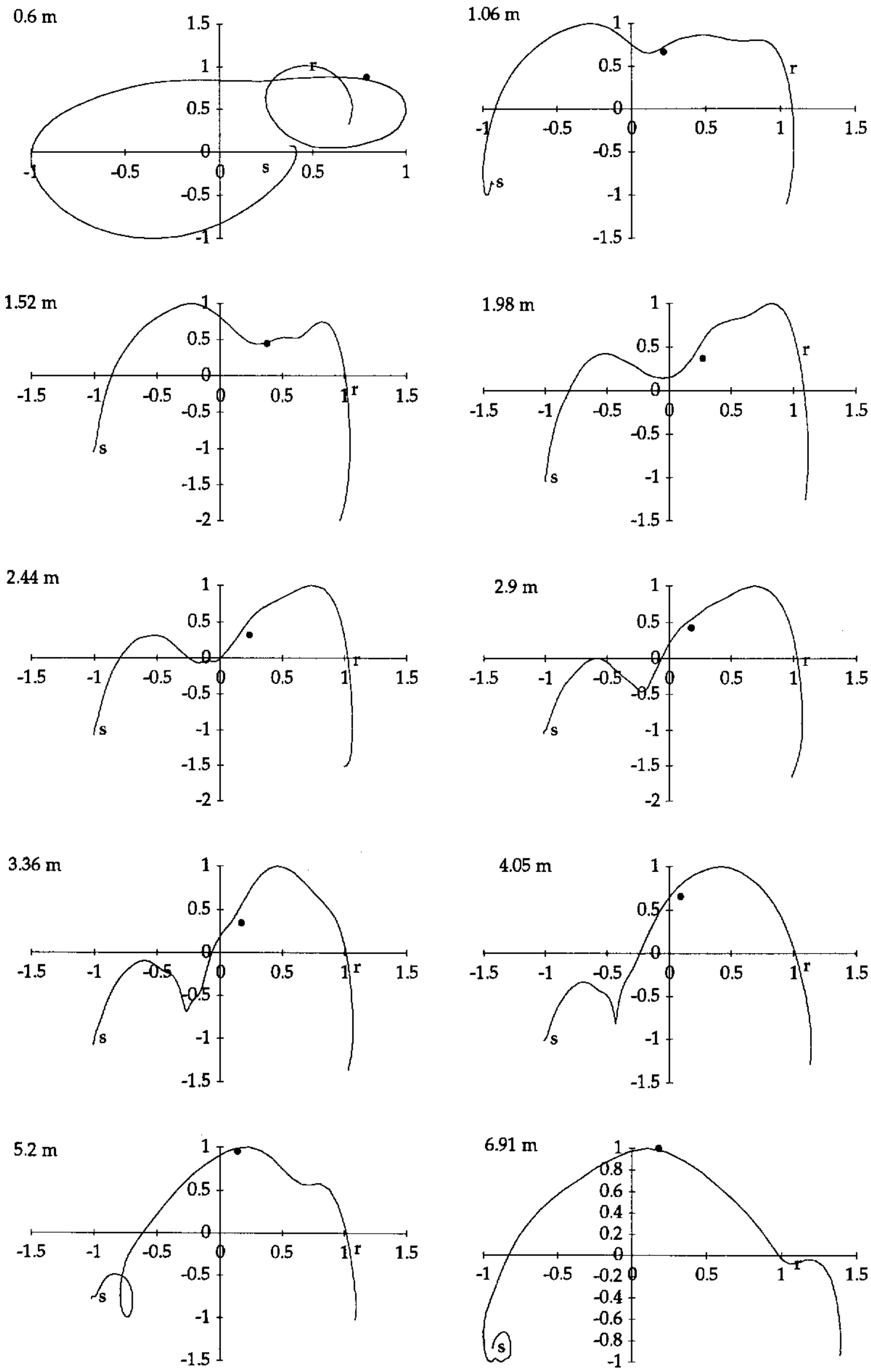


Figure 1 Phase plane plot of shoulder flexion and extension of the overarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

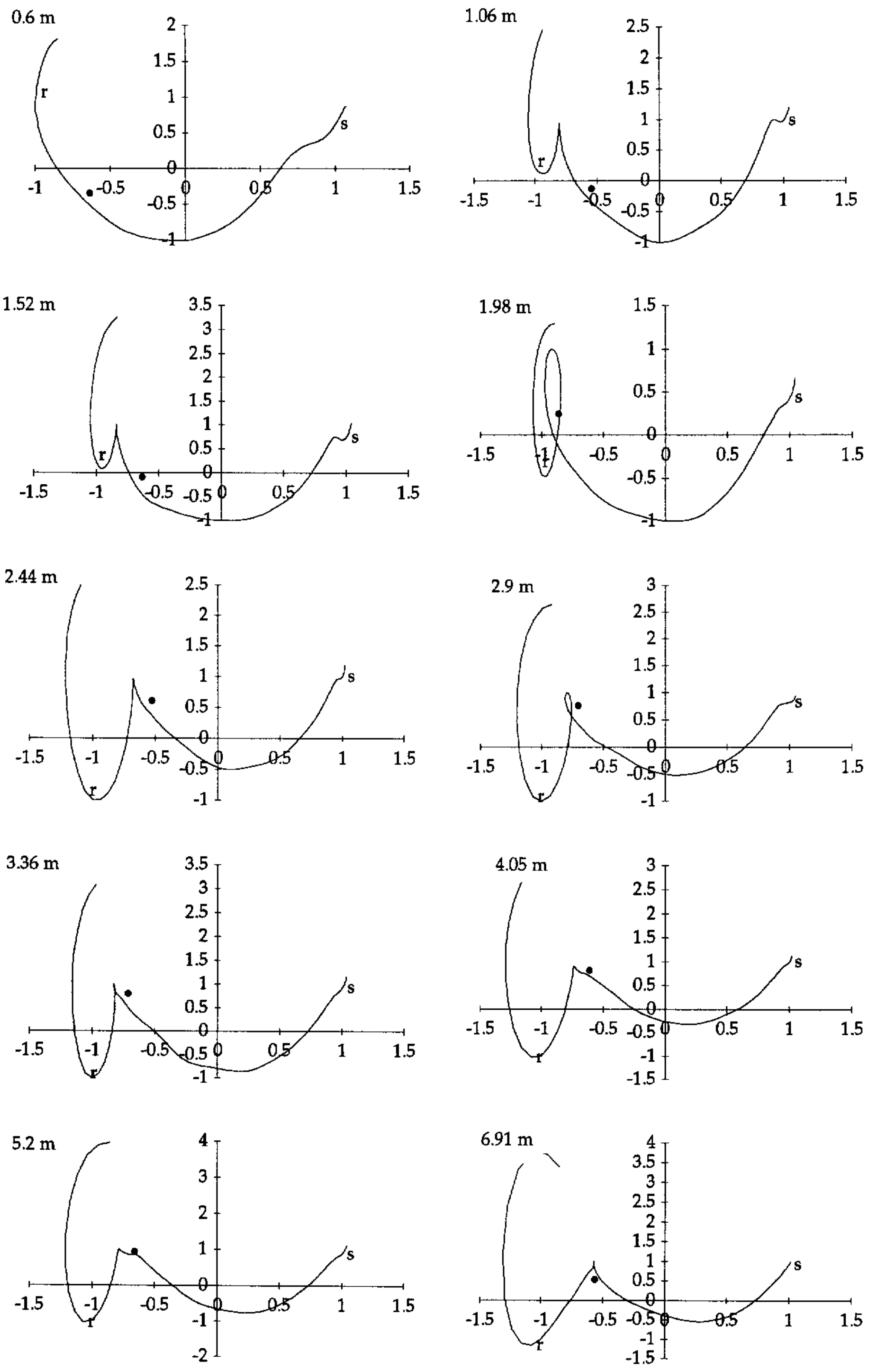


Figure 2 Phase plane plot of shoulder adduction and abduction of the overarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

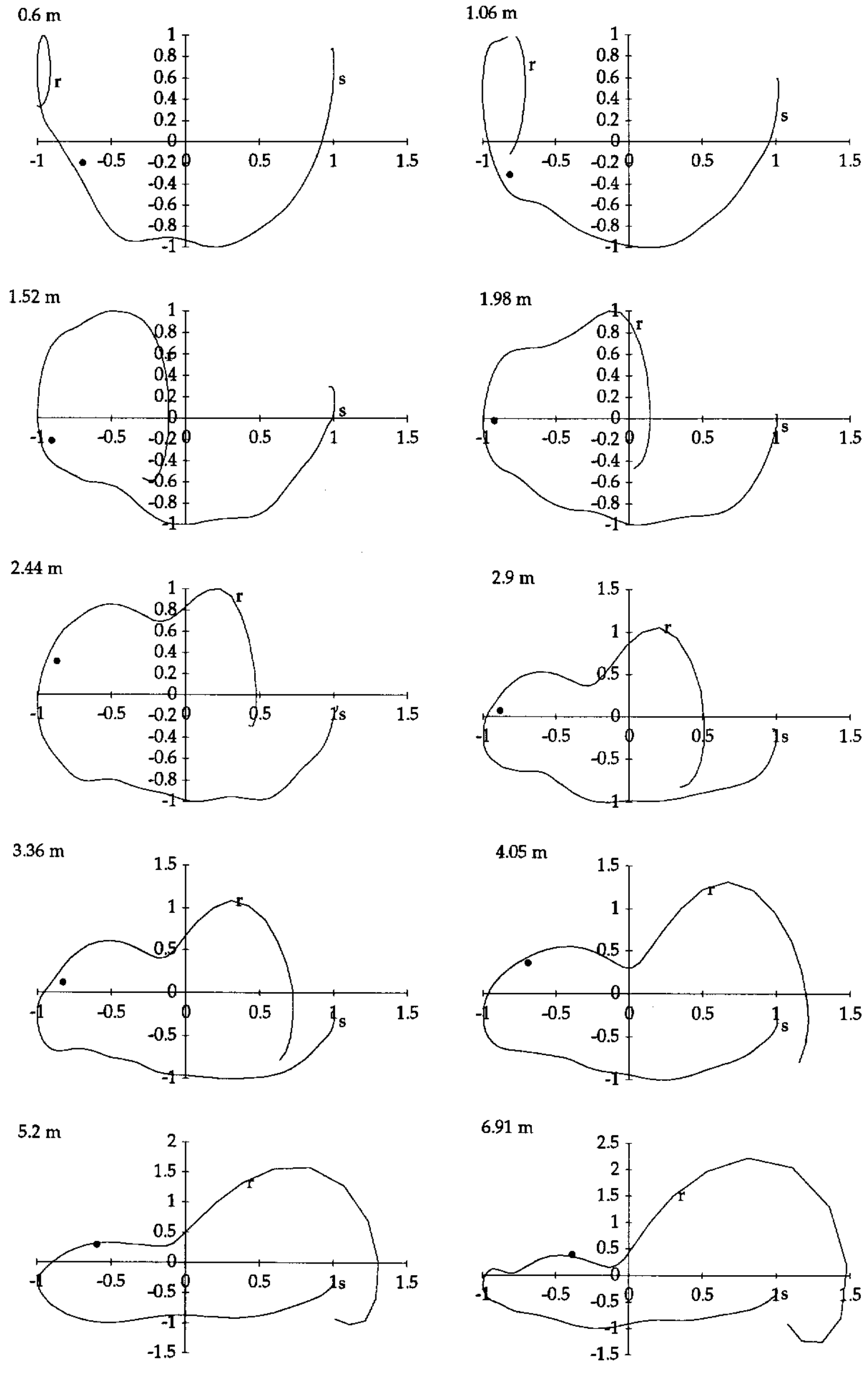


Figure 3 Phase plane plot of shoulder rotation of the overarm throw. s = starting point, r = releasing point, •= phase dividing point, x-axis = degree, y-axis = degree/sec

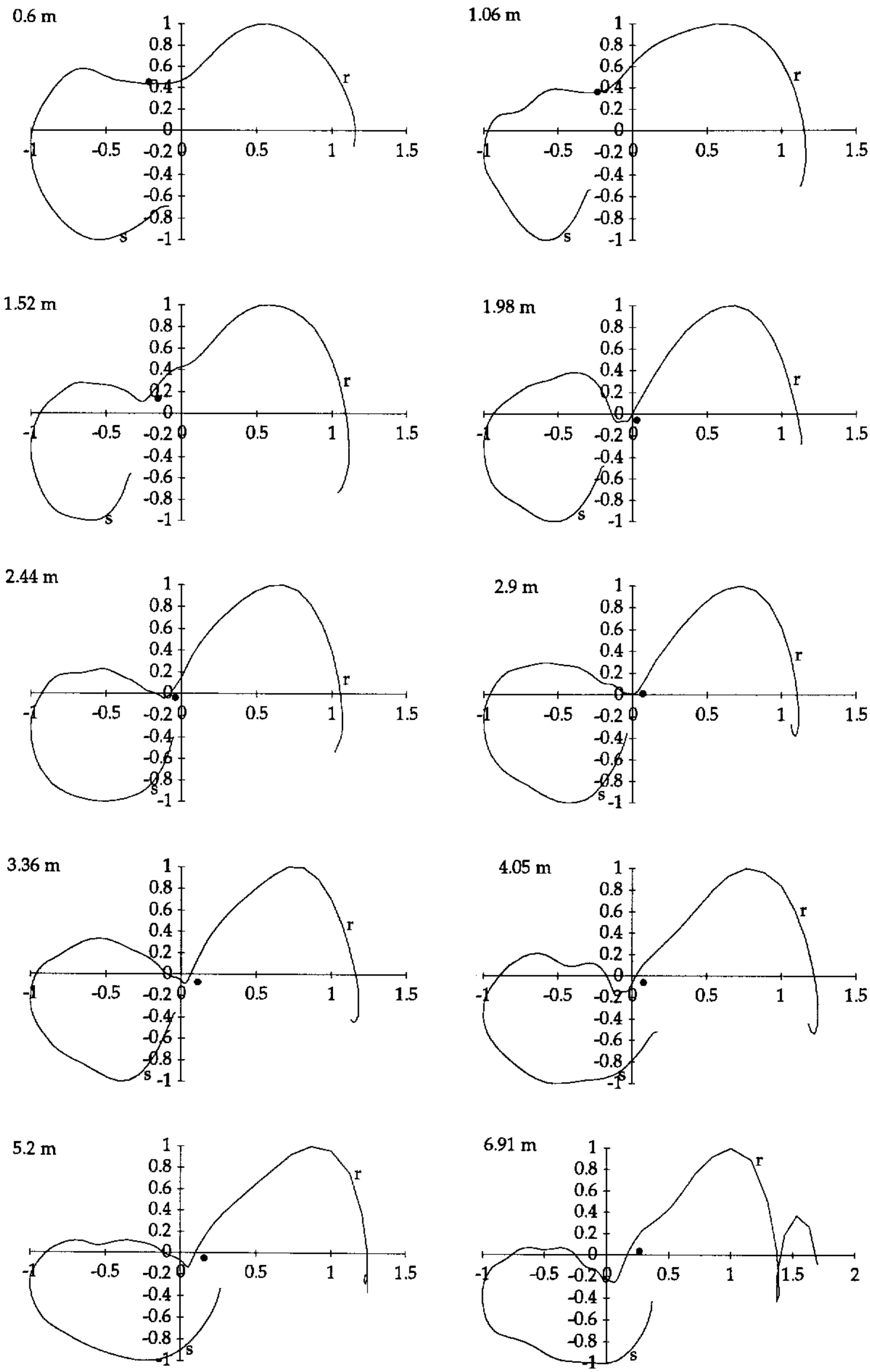


Figure 4 Phase plane plot of forearm rotation of the overarm throw. s = starting point, r = releasing point, •= phase dividing point, x-axis = degree, y-axis = degree/sec

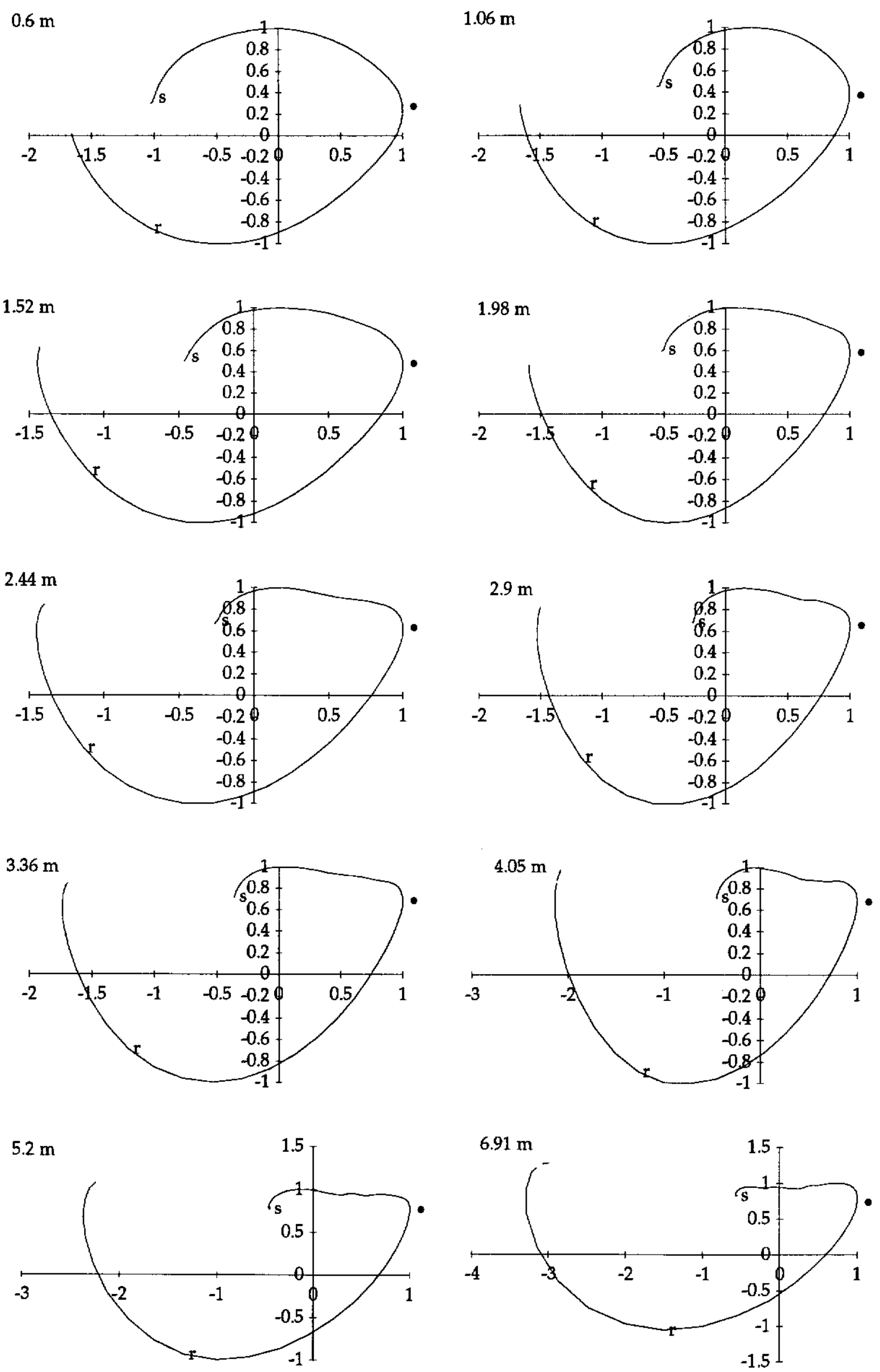


Figure 5 Phase plane plot of elbow flexion and extension of the overarm throw. s = starting point, r = releasing point, •= phase dividing point, x-axis = degree, y-axis = degree/sec

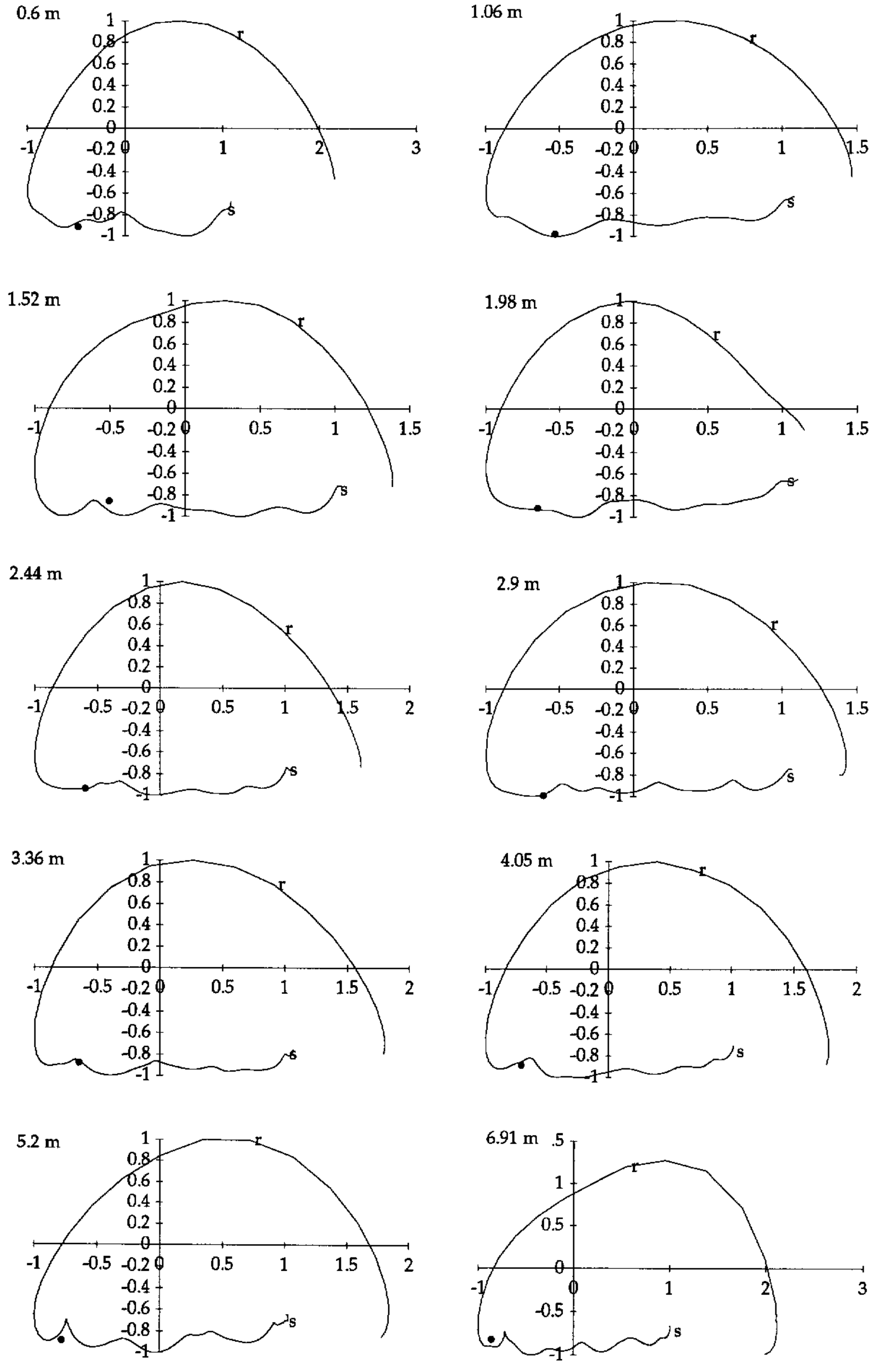


Figure 6 Phase plane plot of wrist flexion and extension of the overarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

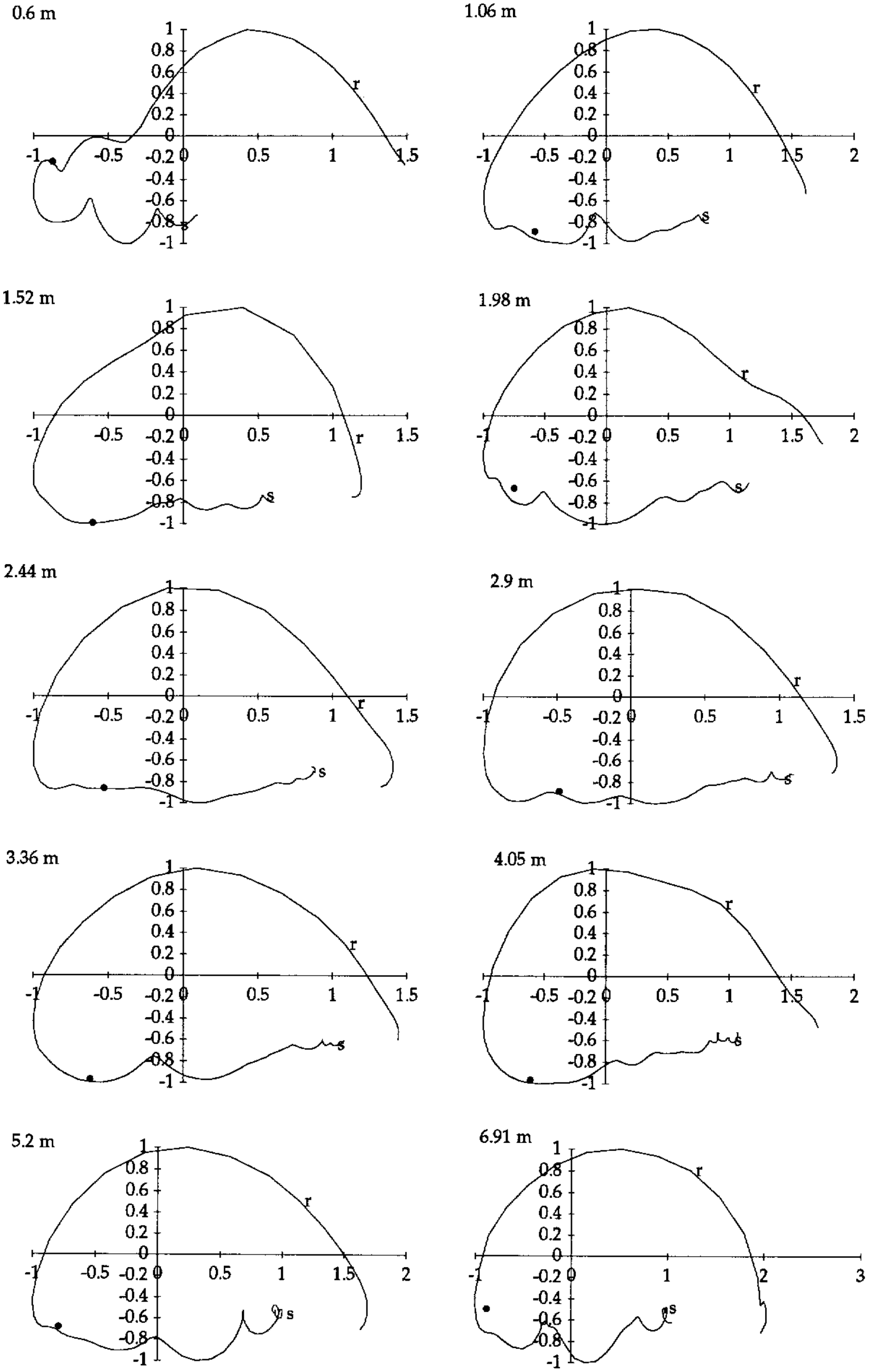


Figure 7 Phase plane plot of wrist ulnar and radial deviation of the overarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

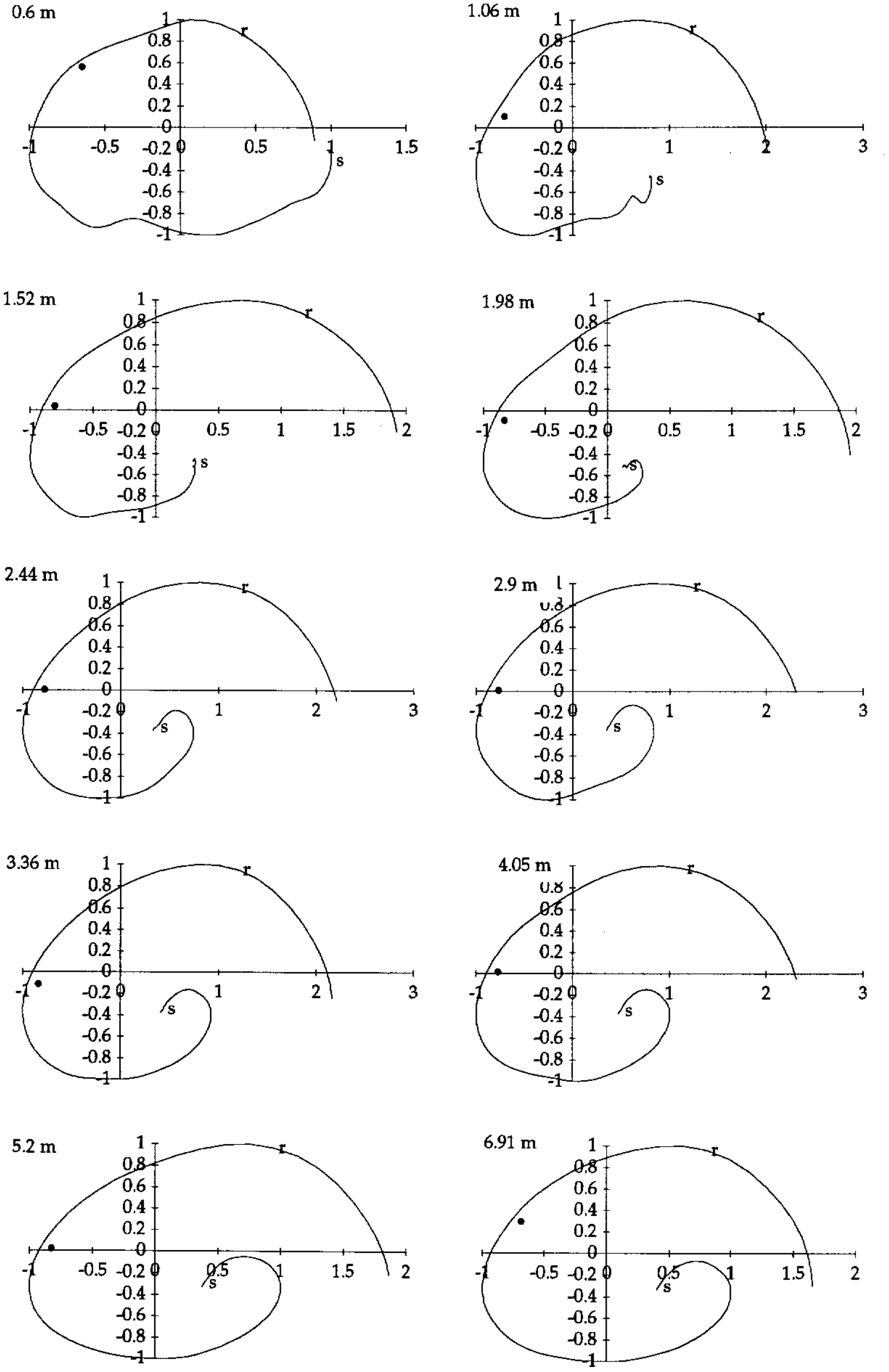


Figure 8 Phase plane plot of shoulder flexion and extension of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

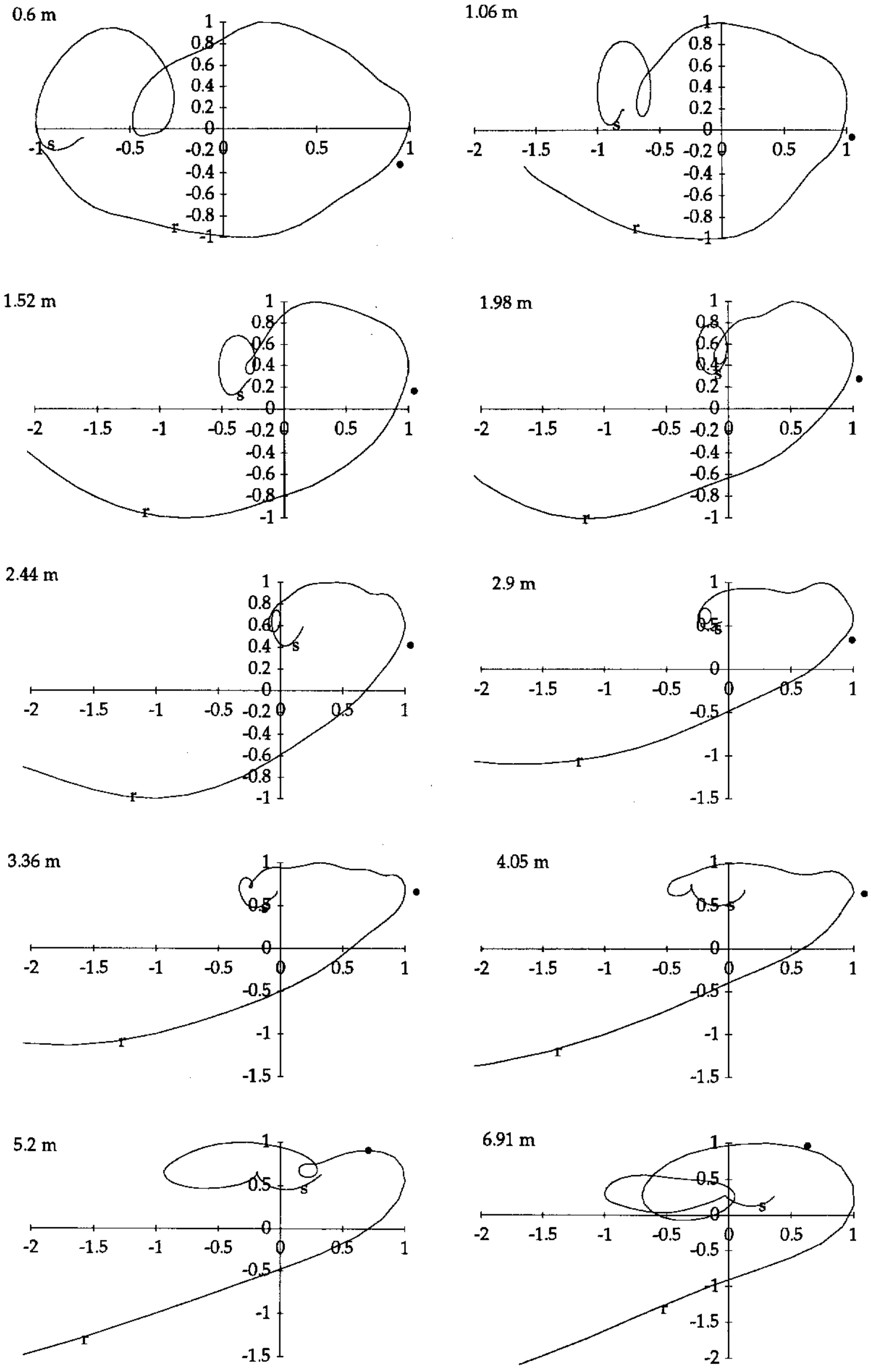


Figure 9 Phase plane plot of shoulder adduction and abduction of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

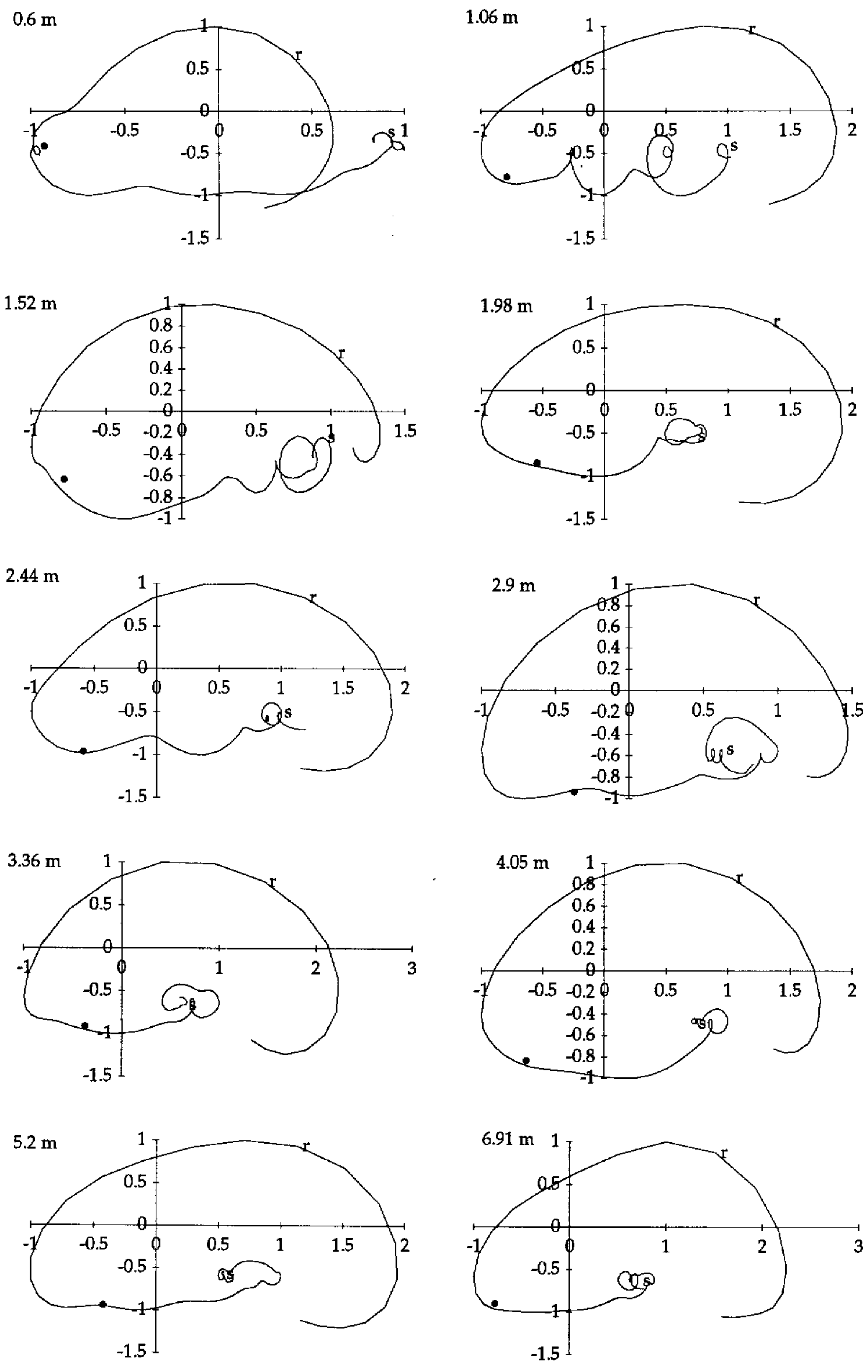
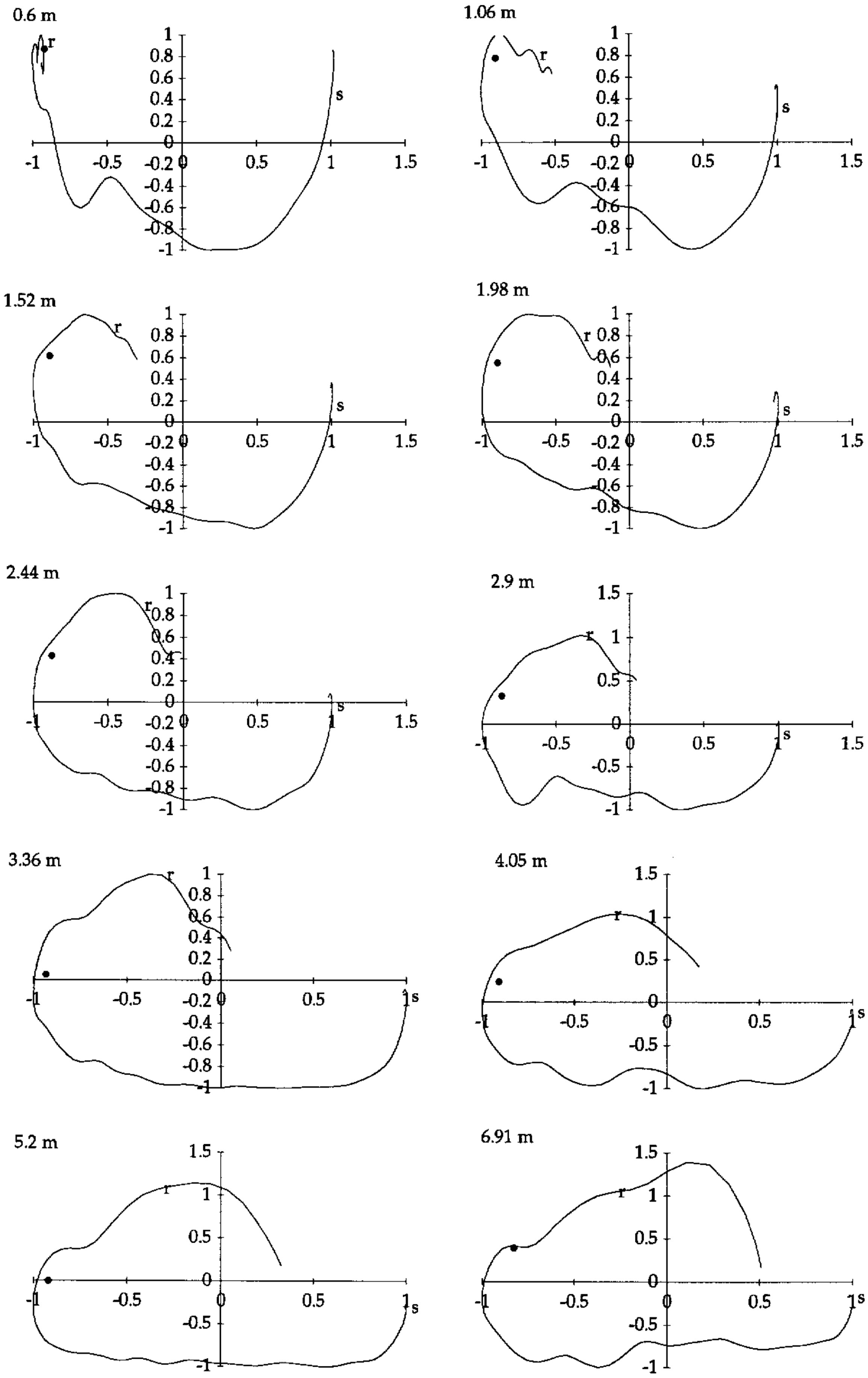


Figure 10 Phase plane plot of wrist flexion and extension of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec



0.6 m

1.06 m

1.52 m

1.98 m

2.44 m

2.9 m

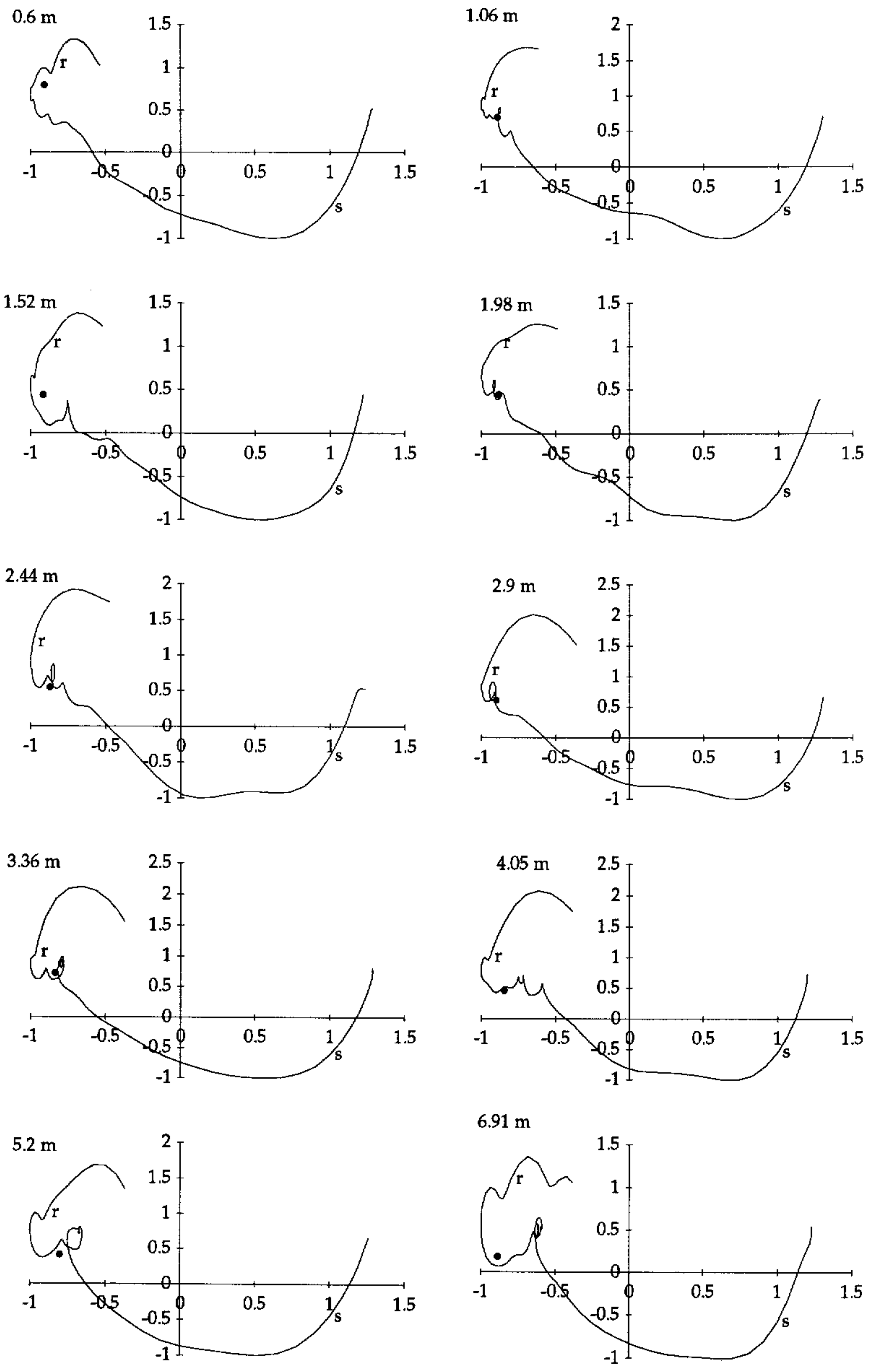
3.36 m

4.05 m

5.2 m

6.91 m

Figure 11 Phase plane plot of shoulder rotation of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec



0.6 m

1.06 m

1.52 m

1.98 m

2.44 m

2.9 m

3.36 m

4.05 m

5.2 m

6.91 m

Figure 12 Phase plane plot of forearm rotation of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

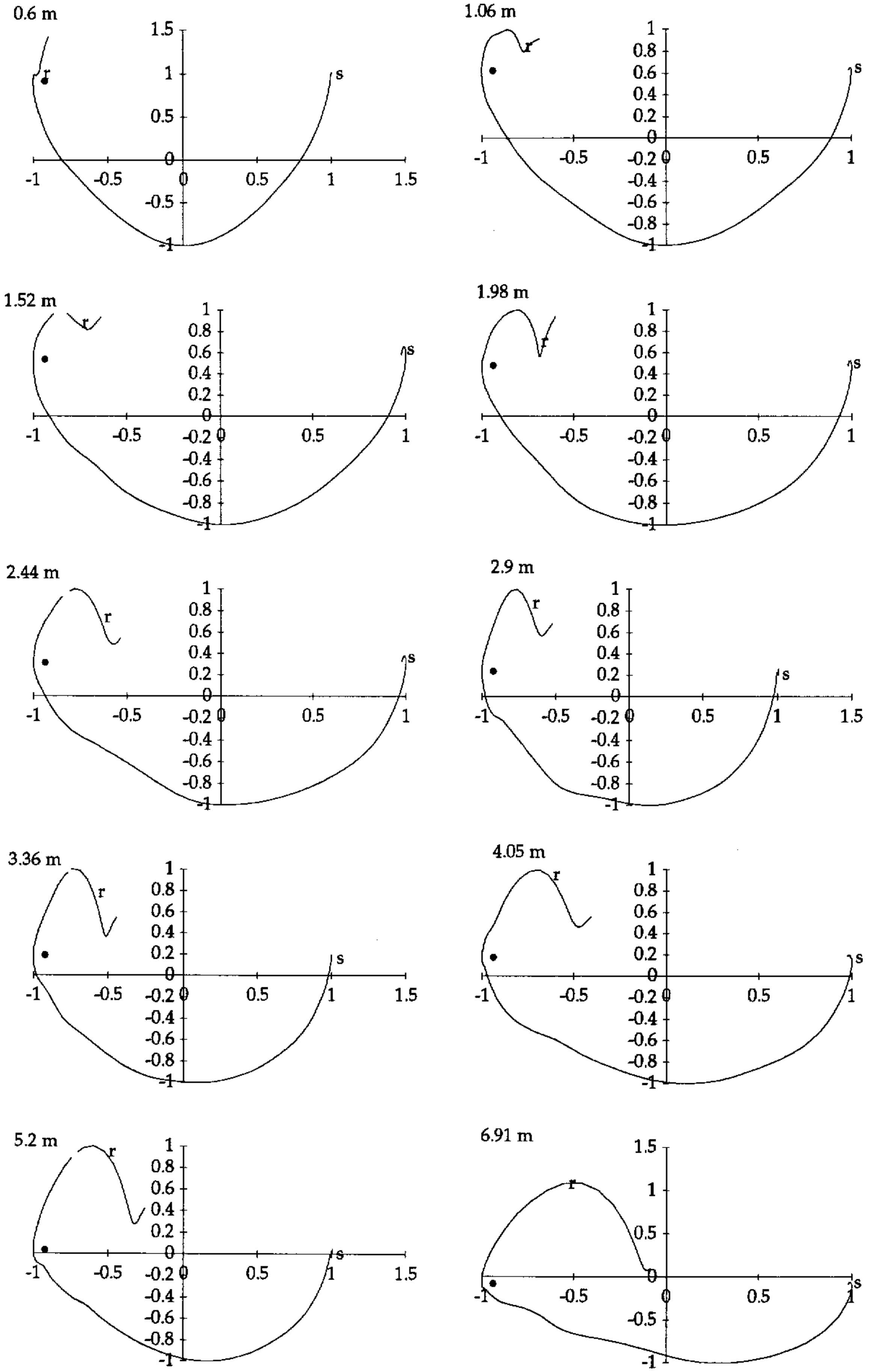


Figure 13 Phase plane plot of elbow flexion and extension of the underarm throw. s = starting point, r = releasing point, • = phase dividing point, x-axis = degree, y-axis = degree/sec

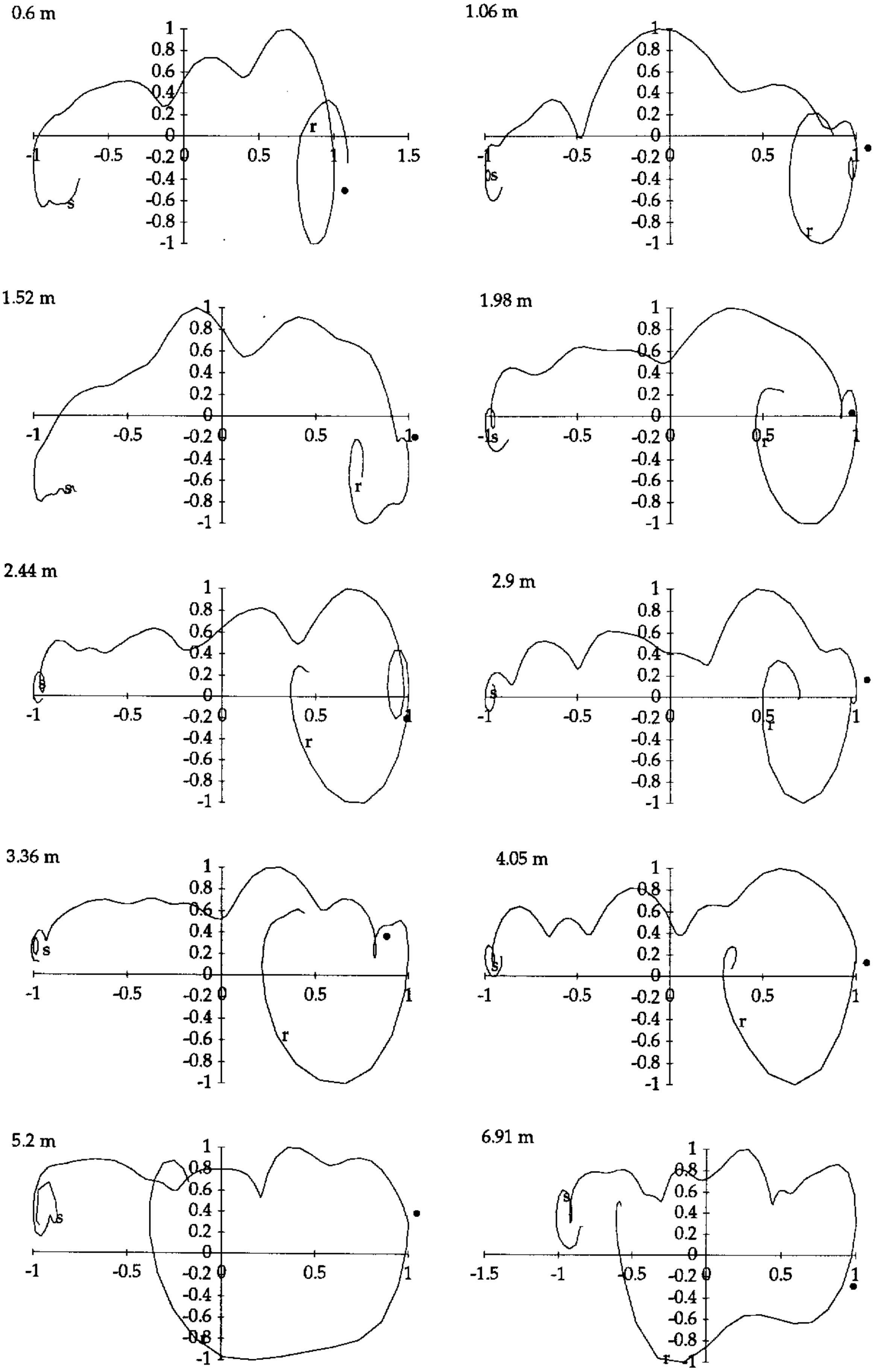


Figure 14 Phase plane plot of wrist ulnar and radial deviation of the underarm throw. s = starting point, r = releasing point, •= phase dividing point, x-axis = degree, y-axis = degree/sec

Appendix E

Graphs of angle - angle plots for both throwing patterns

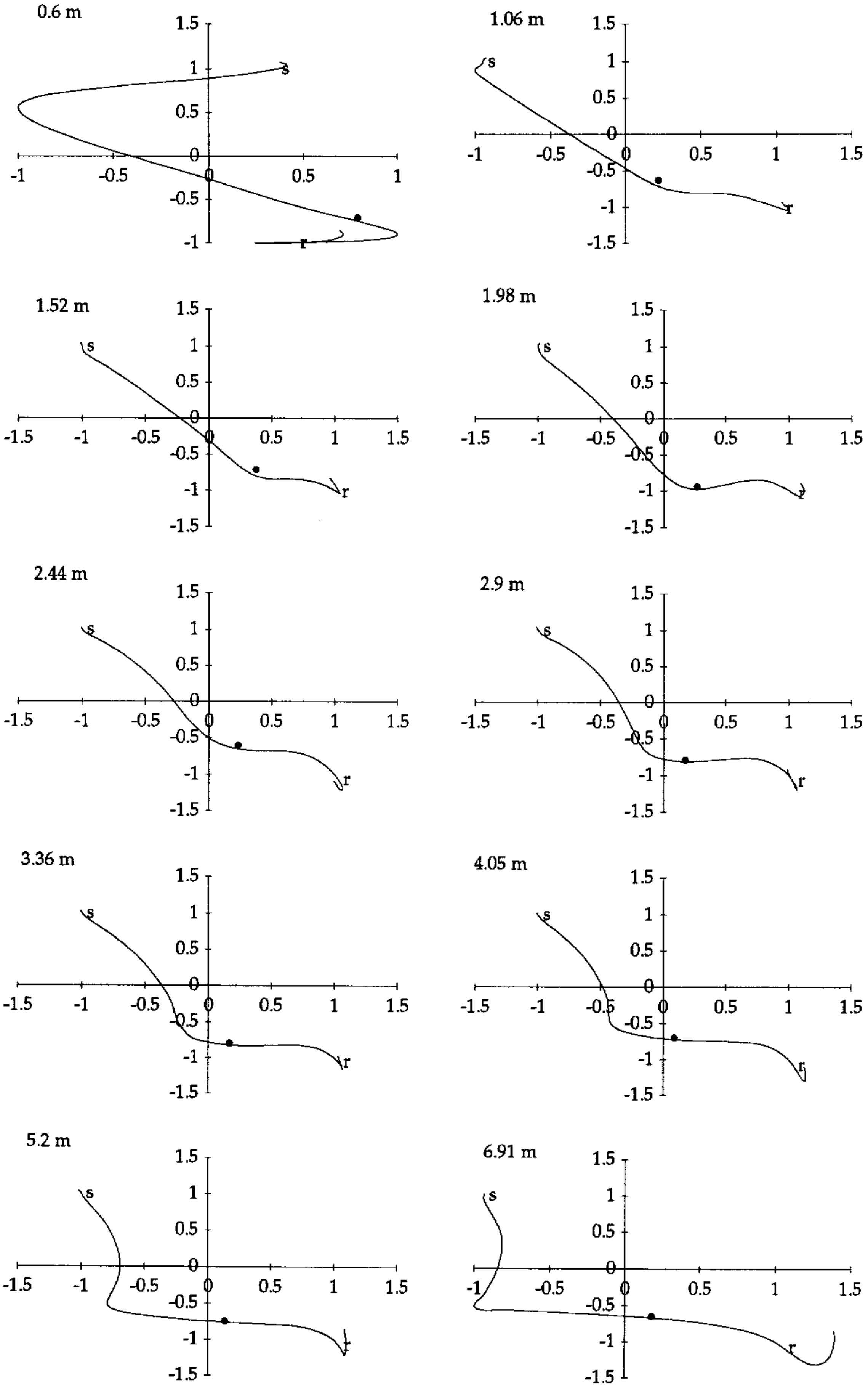


Figure 1 Angle-angle plot of shoulder flexion (x-axis) and shoulder adduction (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

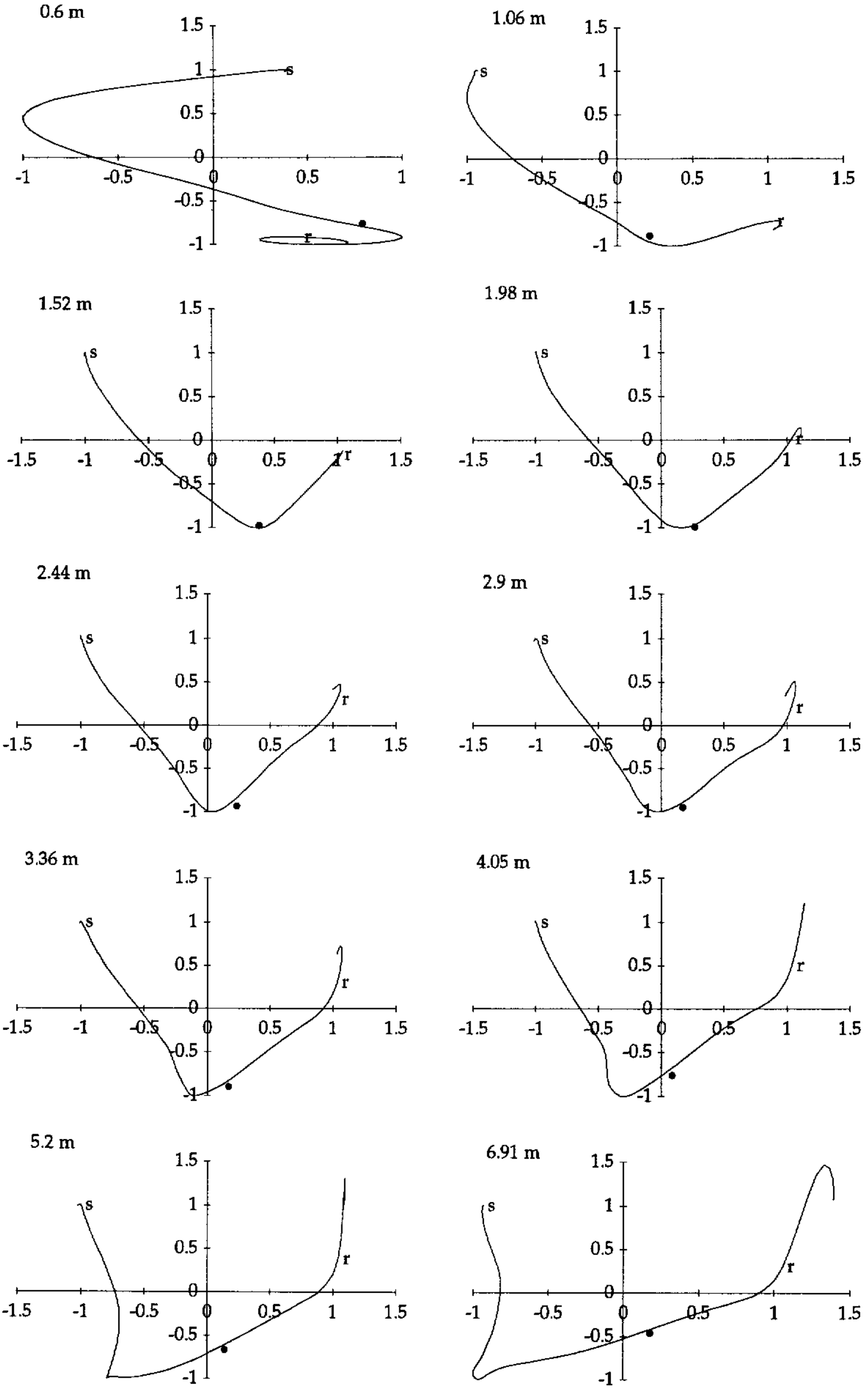


Figure 2 Angle-angle plot between shoulder flexion (x-axis) and shoulder rotation (y-axis) of the overarm throw. s = starting point, r = releasing point, • = phase dividing point

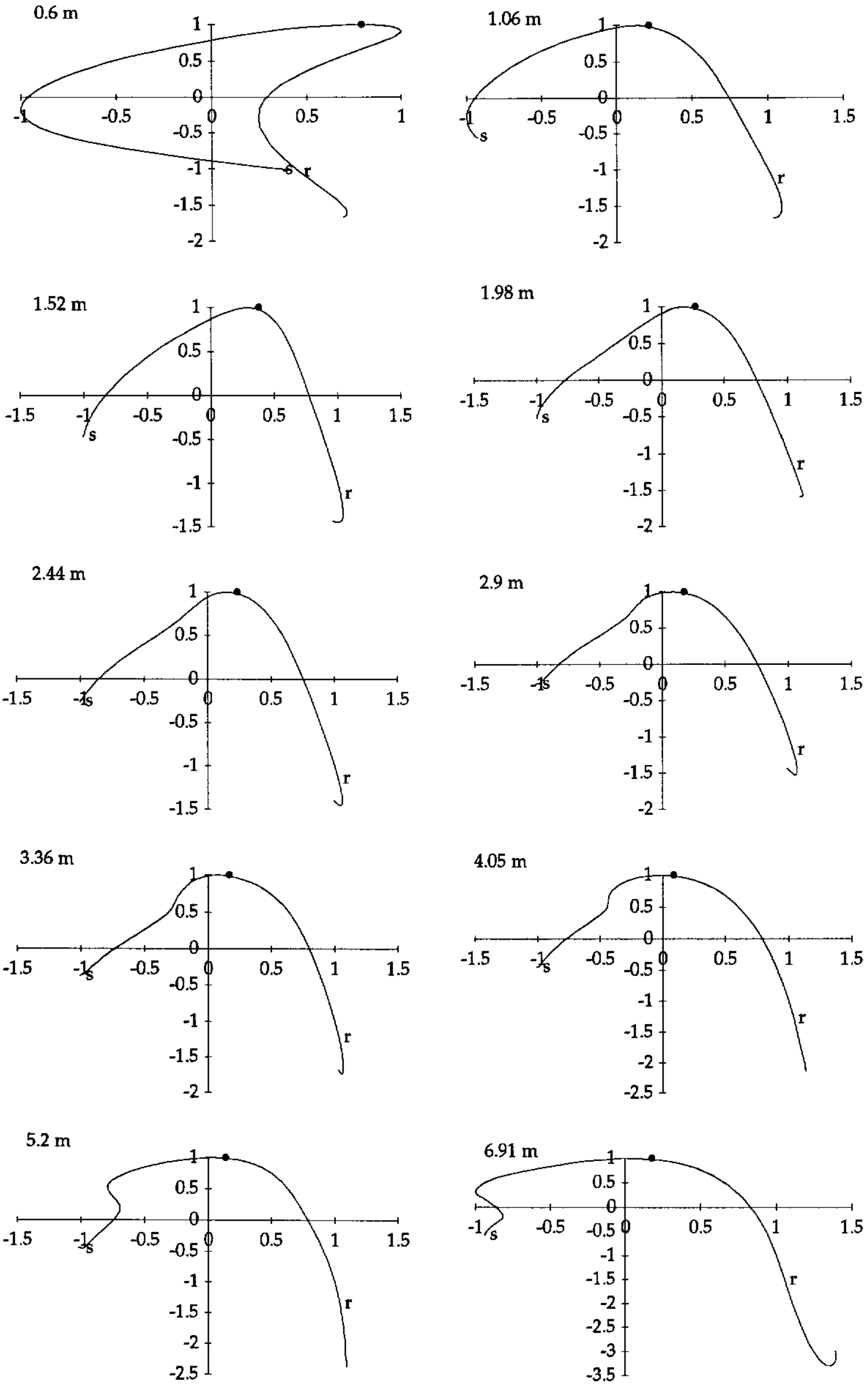


Figure 3 Angle-angle plot between shoulder flexion (x-axis) and elbow flexion (y-axis) of the overarm throw. s = starting point, r = releasing point, • = phase dividing point

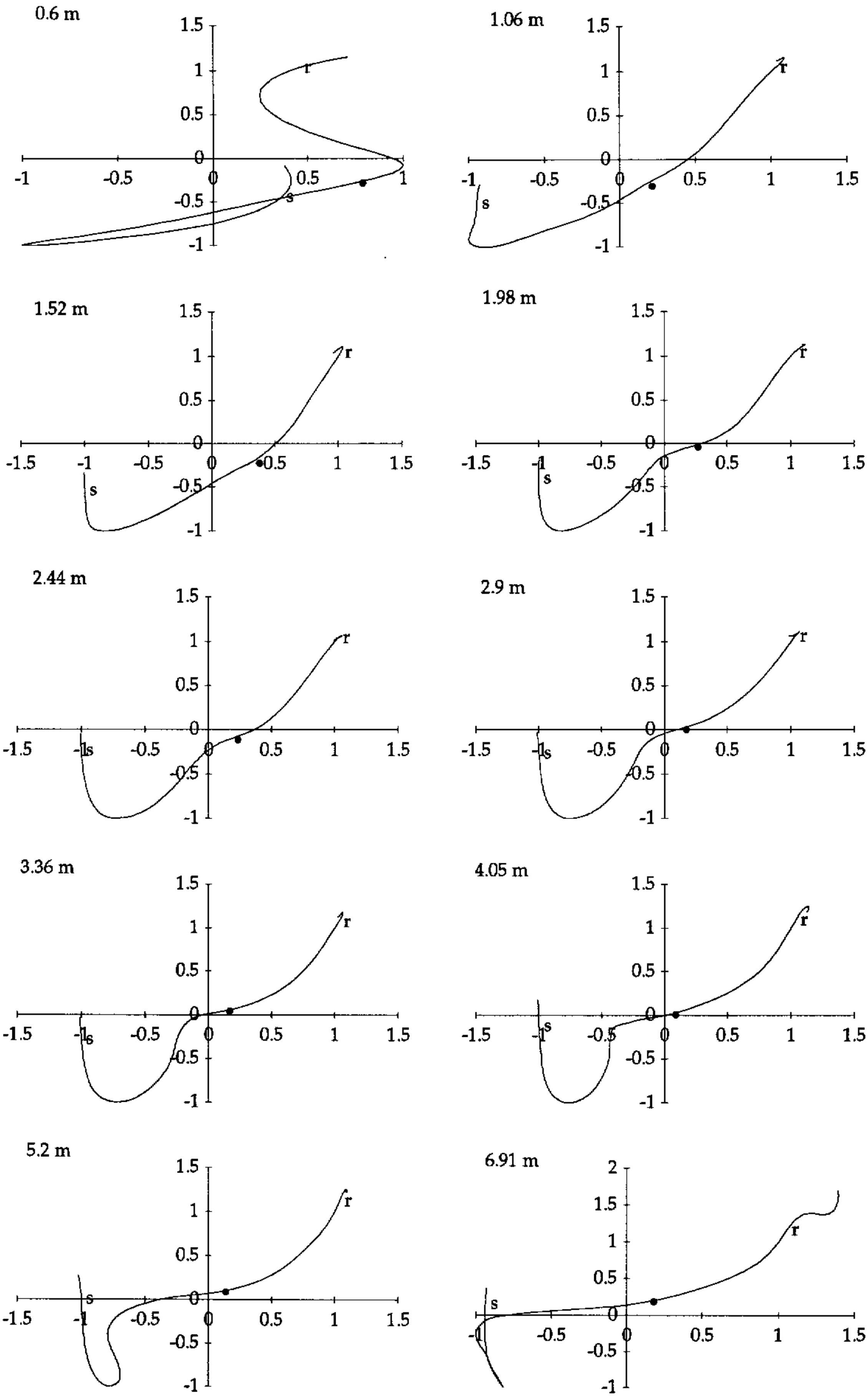


Figure 4 Angle-angle plot between shoulder flexion (x-axis) and forearm rotation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

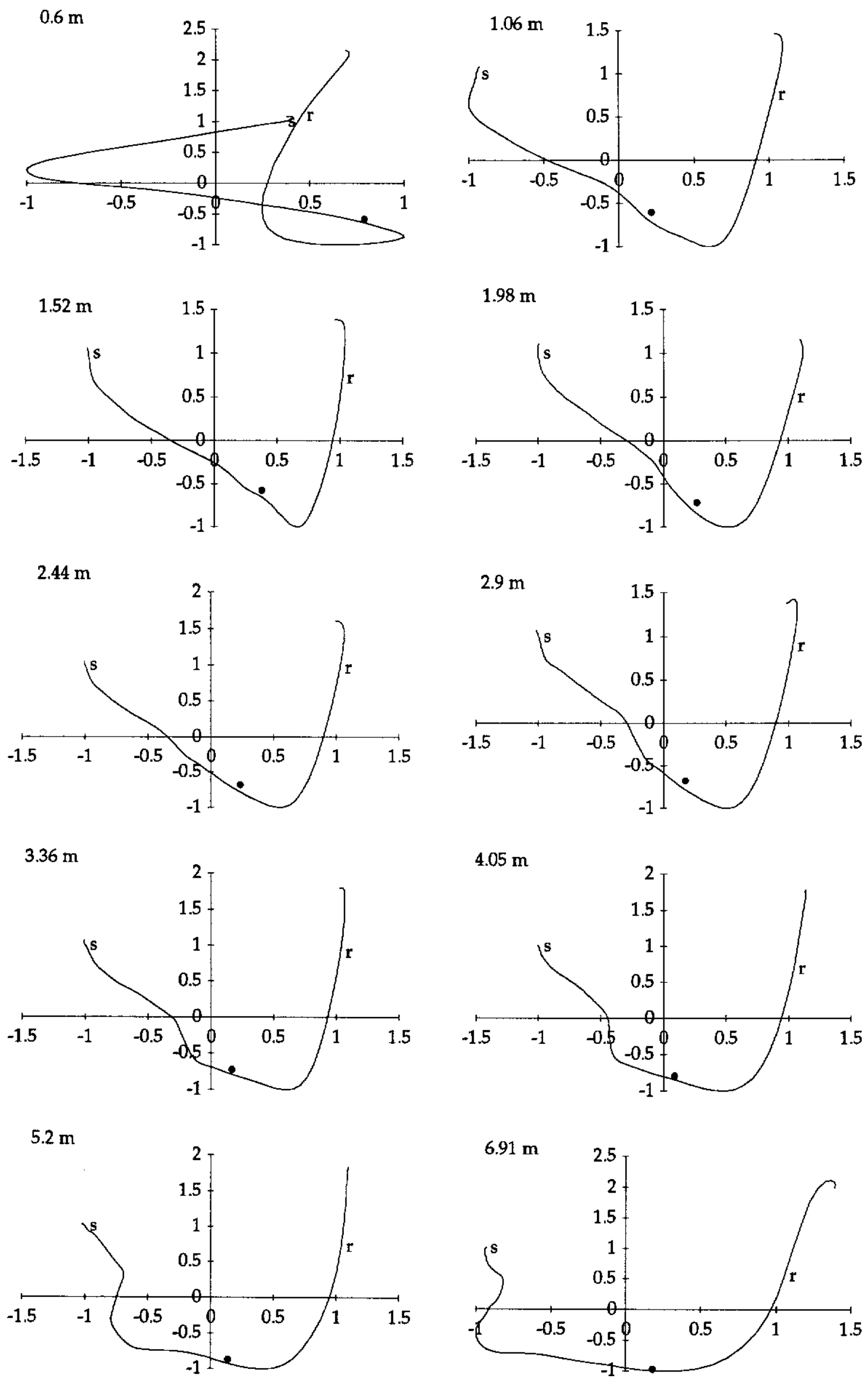


Figure 5 Angle-angle plot between shoulder flexion (x-axis) and wrist flexion (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

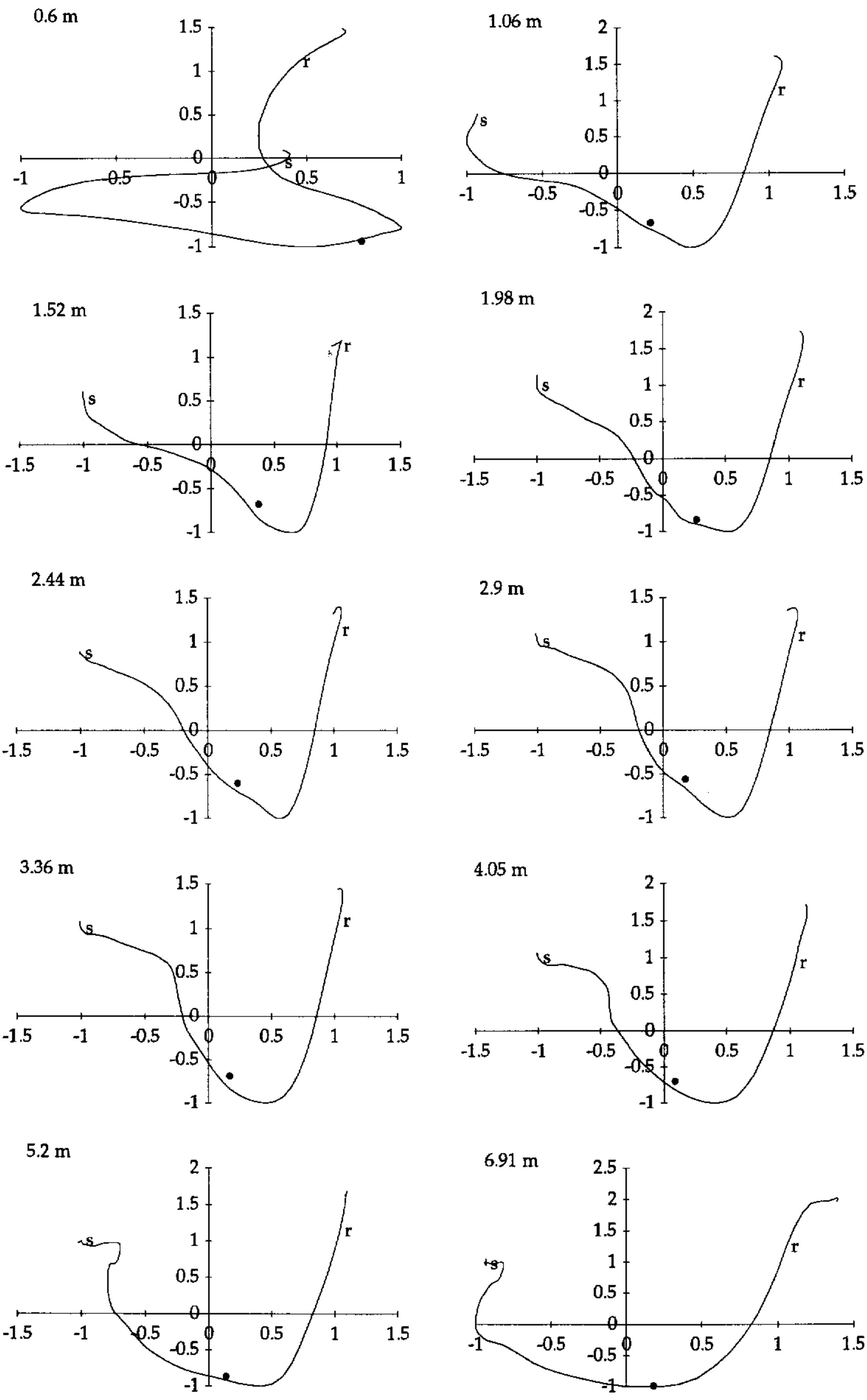


Figure 6 Angle-angle plot between shoulder flexion (x-axis) and wrist ulnar and radial deviation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

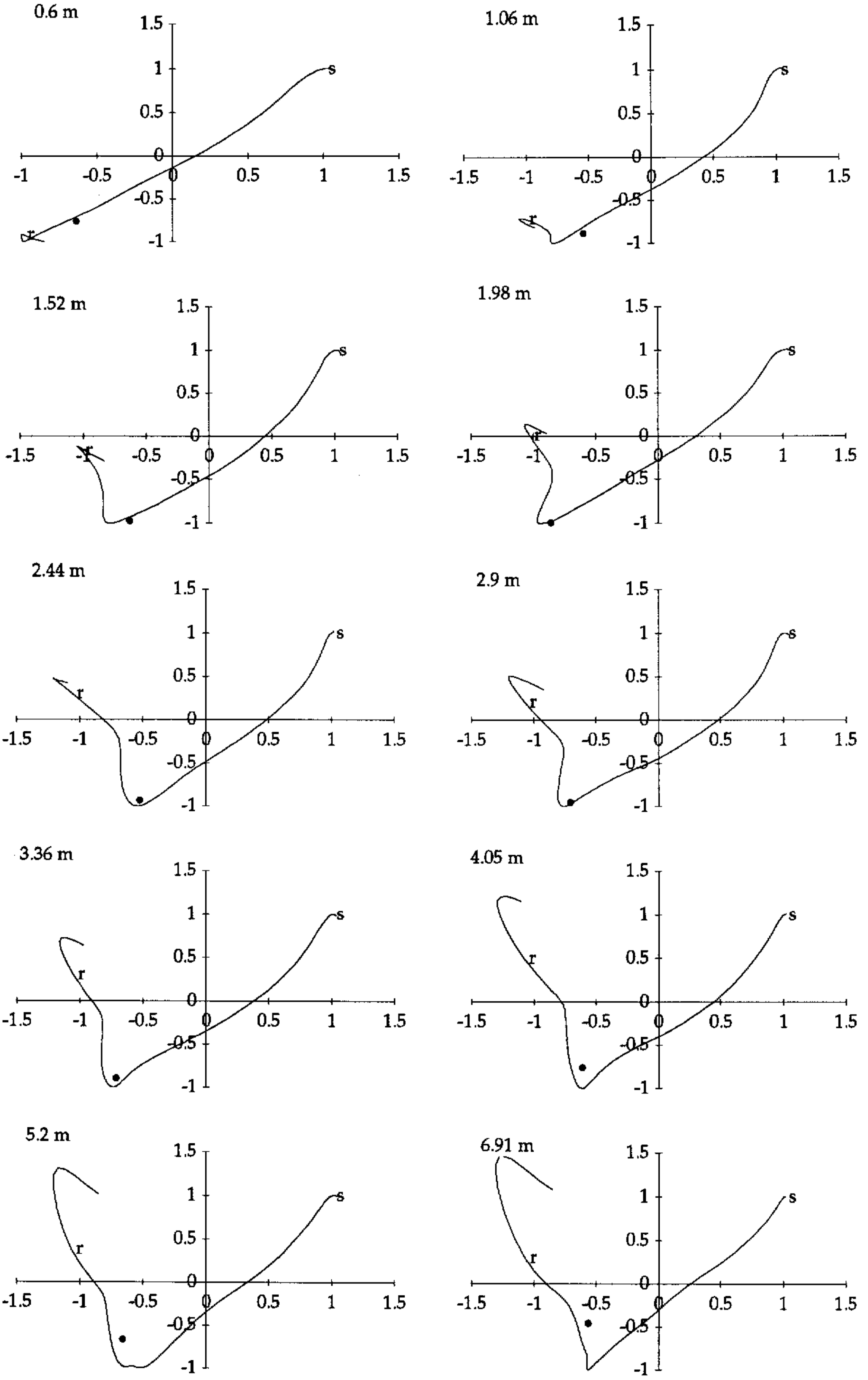


Figure 7 Angle-angle plot between shoulder adduction (x-axis) and shoulder rotation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

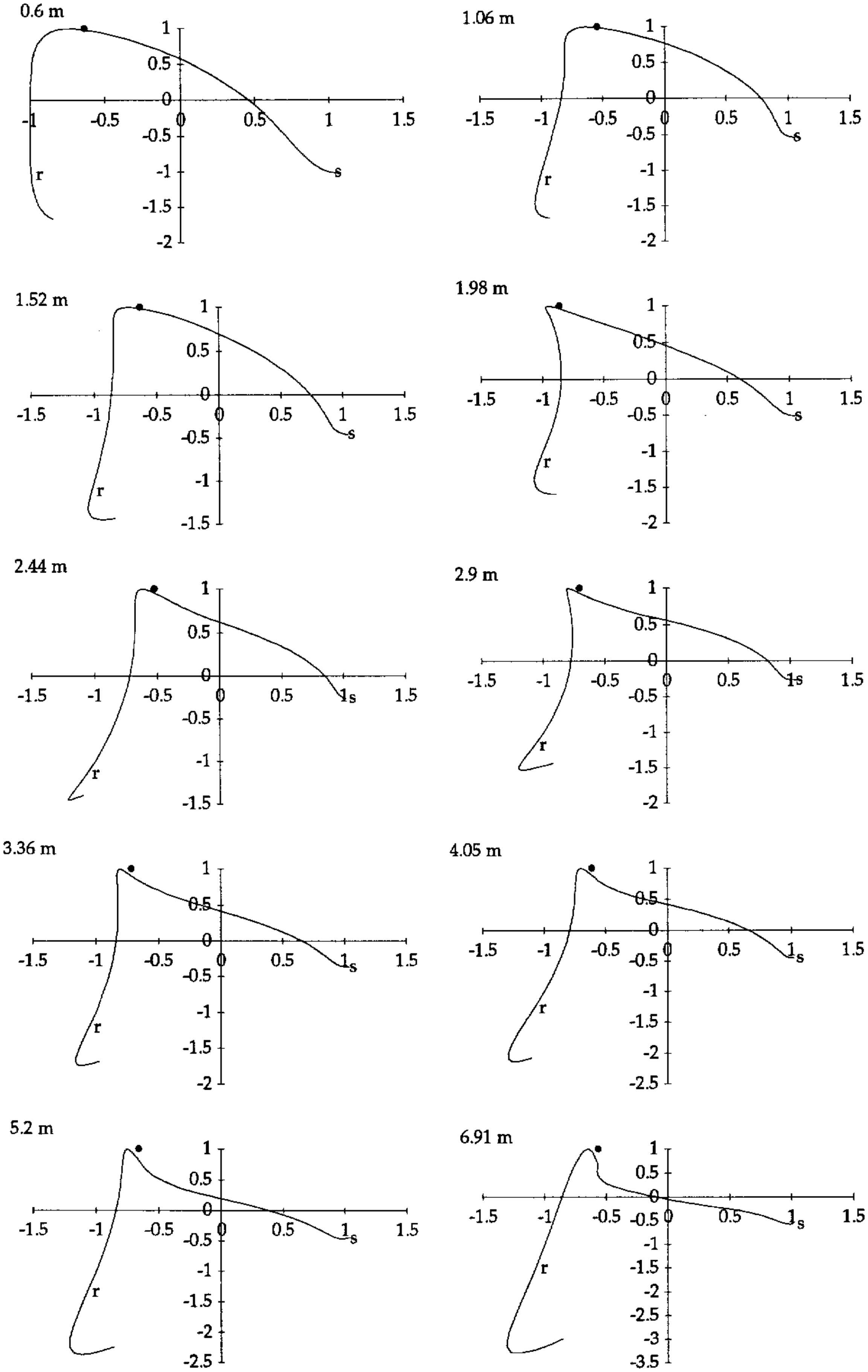
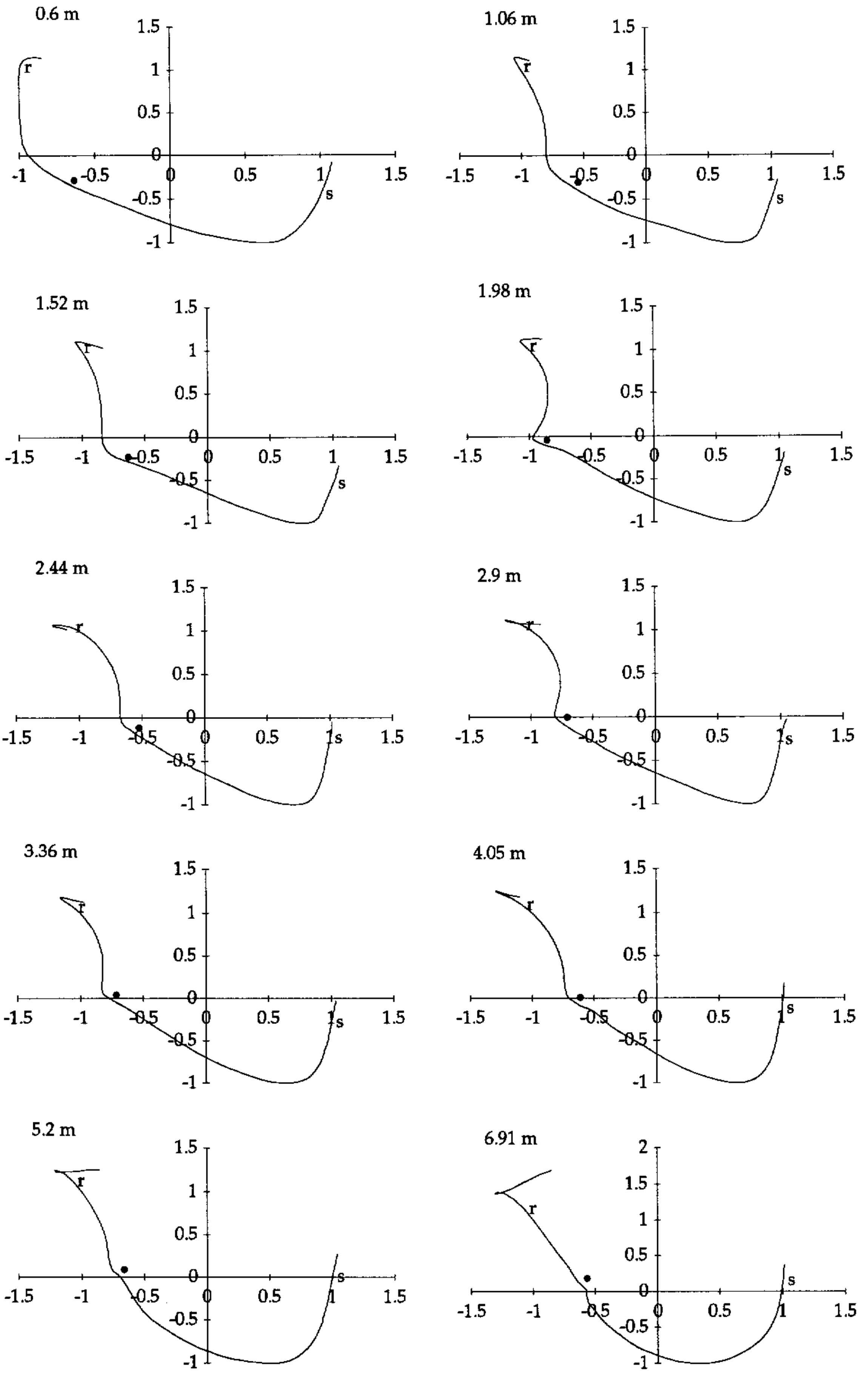


Figure 8 Angle-angle plot of shoulder adduction (x-axis) and elbow flexion (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point



0.6 m

1.06 m

1.52 m

1.98 m

2.44 m

2.9 m

3.36 m

4.05 m

5.2 m

6.91 m

Figure 9 Angle-angle plot between shoulder adduction (x-axis) and forearm rotation (y-axis) of the overarm throw. s = starting point, r = releasing point, •= phase dividing point

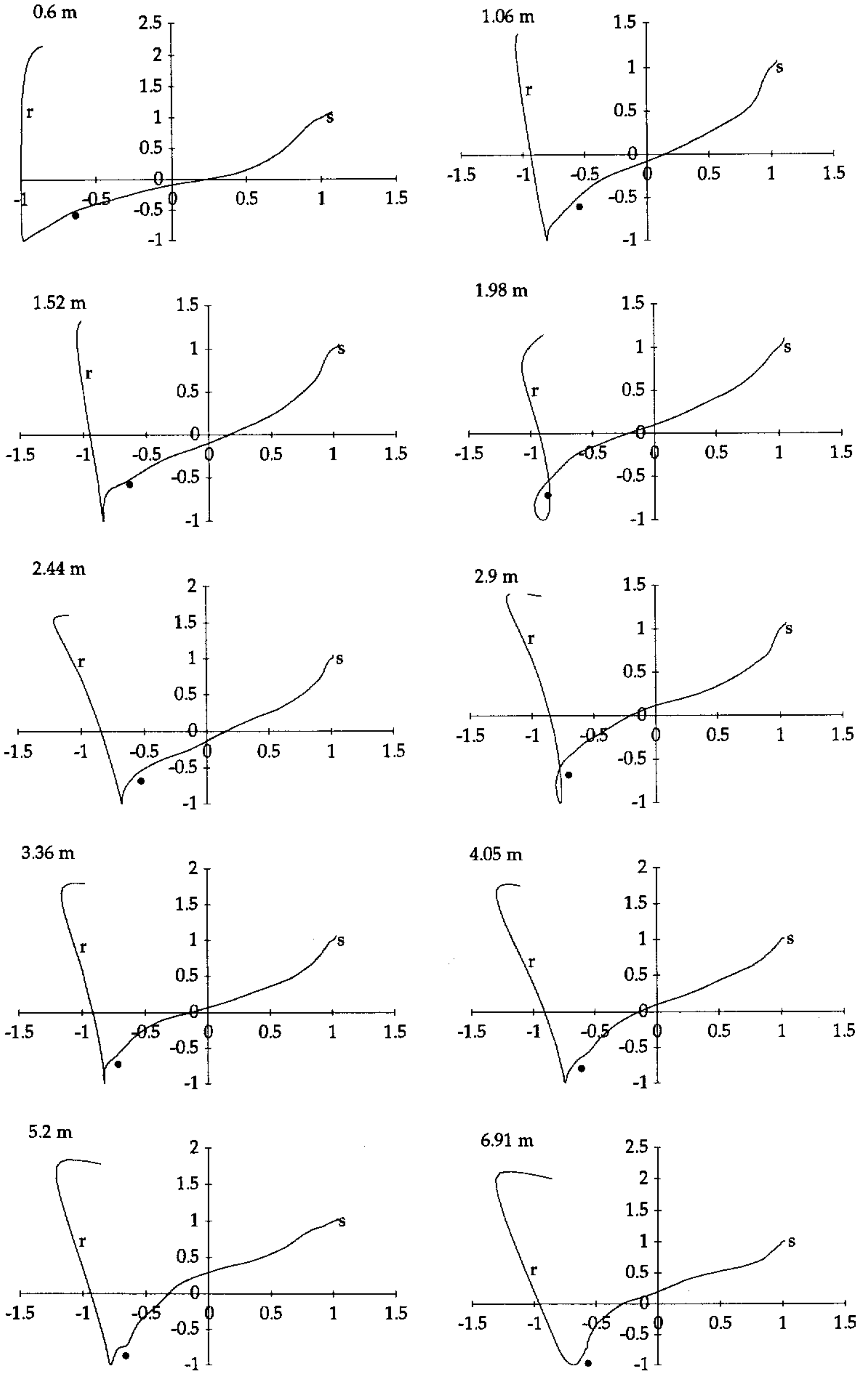


Figure 10 Angle - angle plot between shoulder adduction (x-axis) and wrist flexion(y-axis) of the overarm throw. s = starting point, r = releasing point, •= phase dividing point

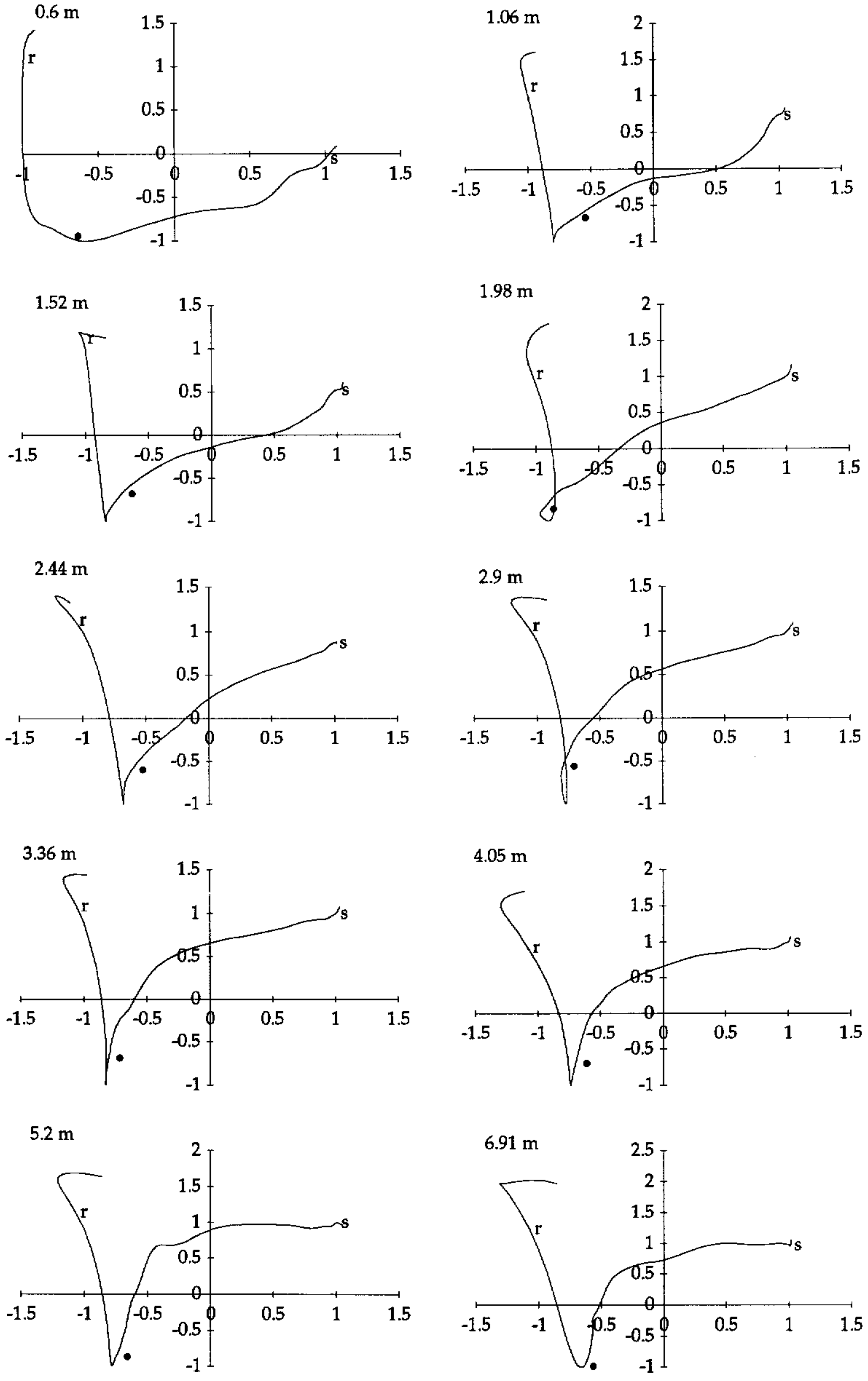


Figure 11 Angle-angle plot between shoulder adduction (x-axis) and wrist deviation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

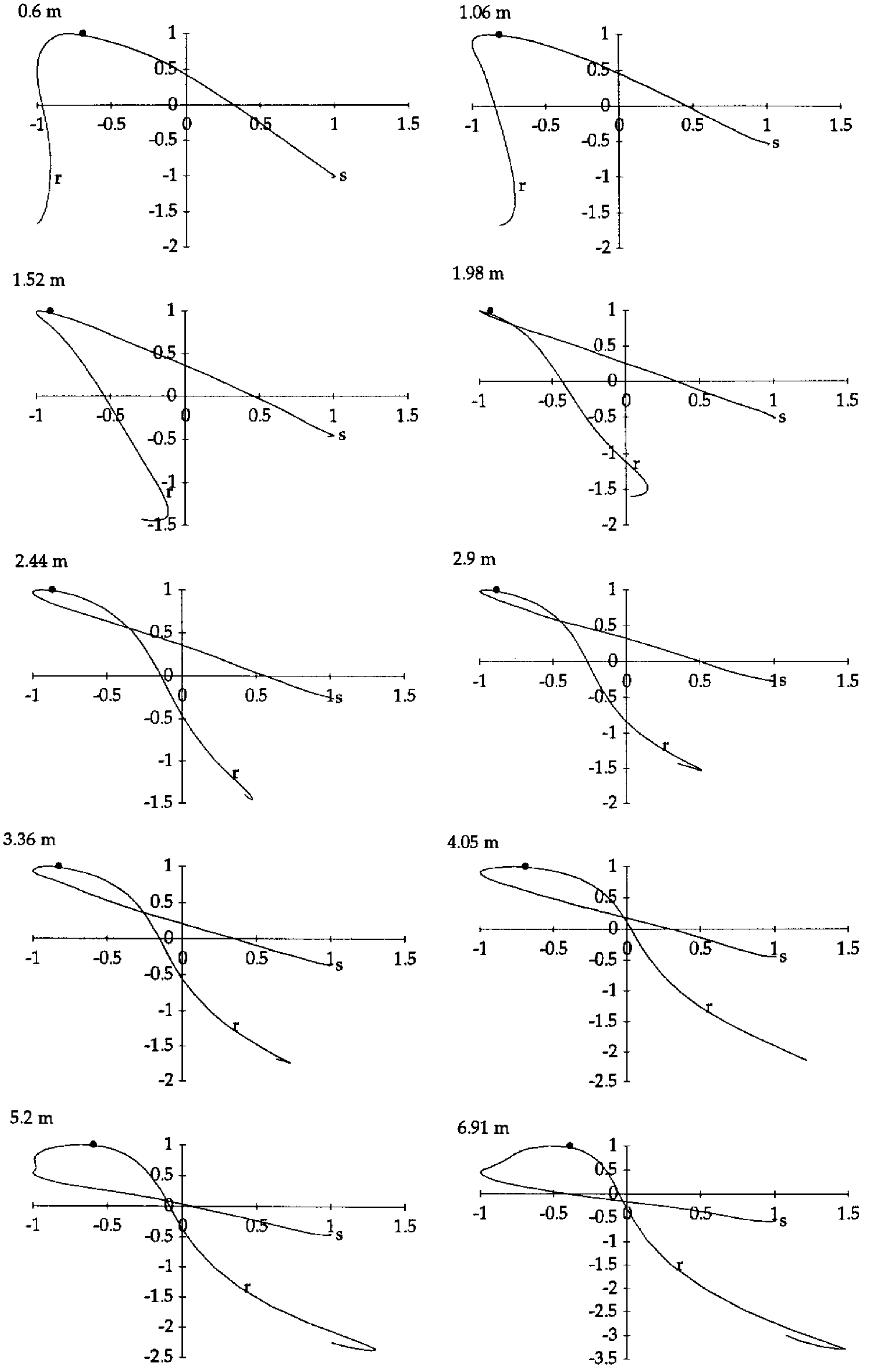


Figure 12 Angle-angle plot between shoulder rotation (x-axis) and elbow flexion (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

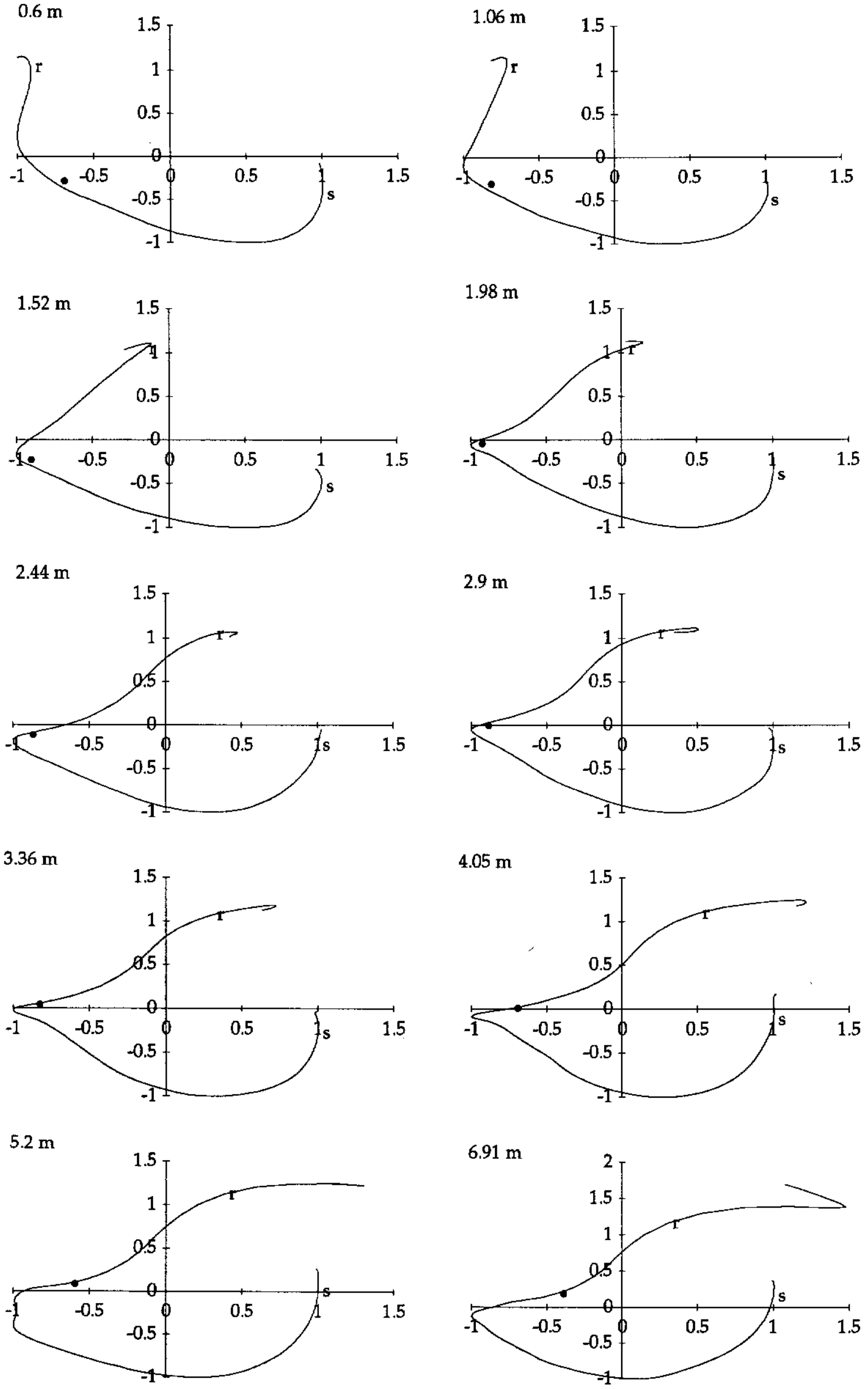


Figure 13 Angle-angle plot between shoulder rotation (x-axis) and forearm rotation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

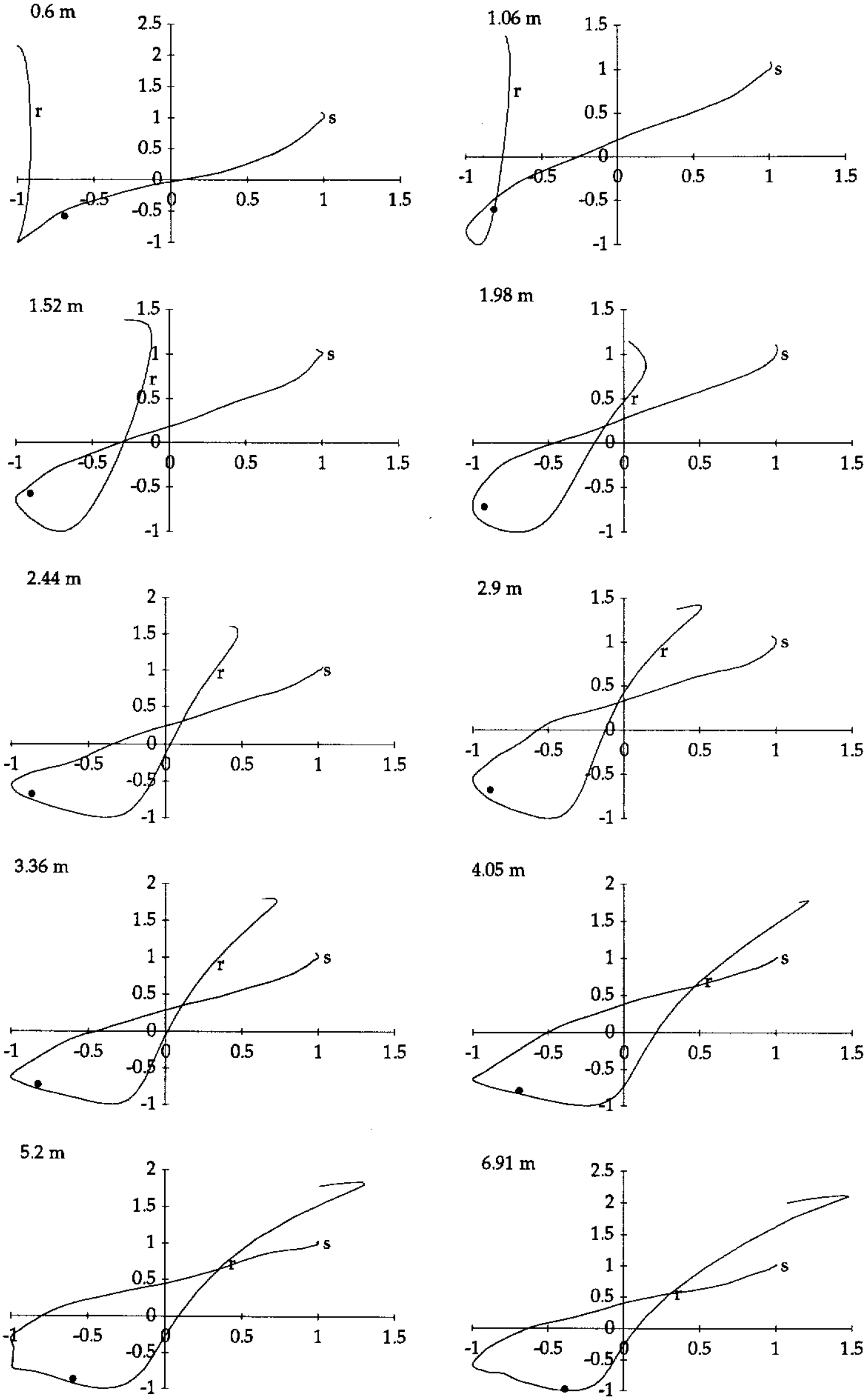


Figure 14 Angle-angle plot between shoulder rotation (x-axis) and wrist flexion (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

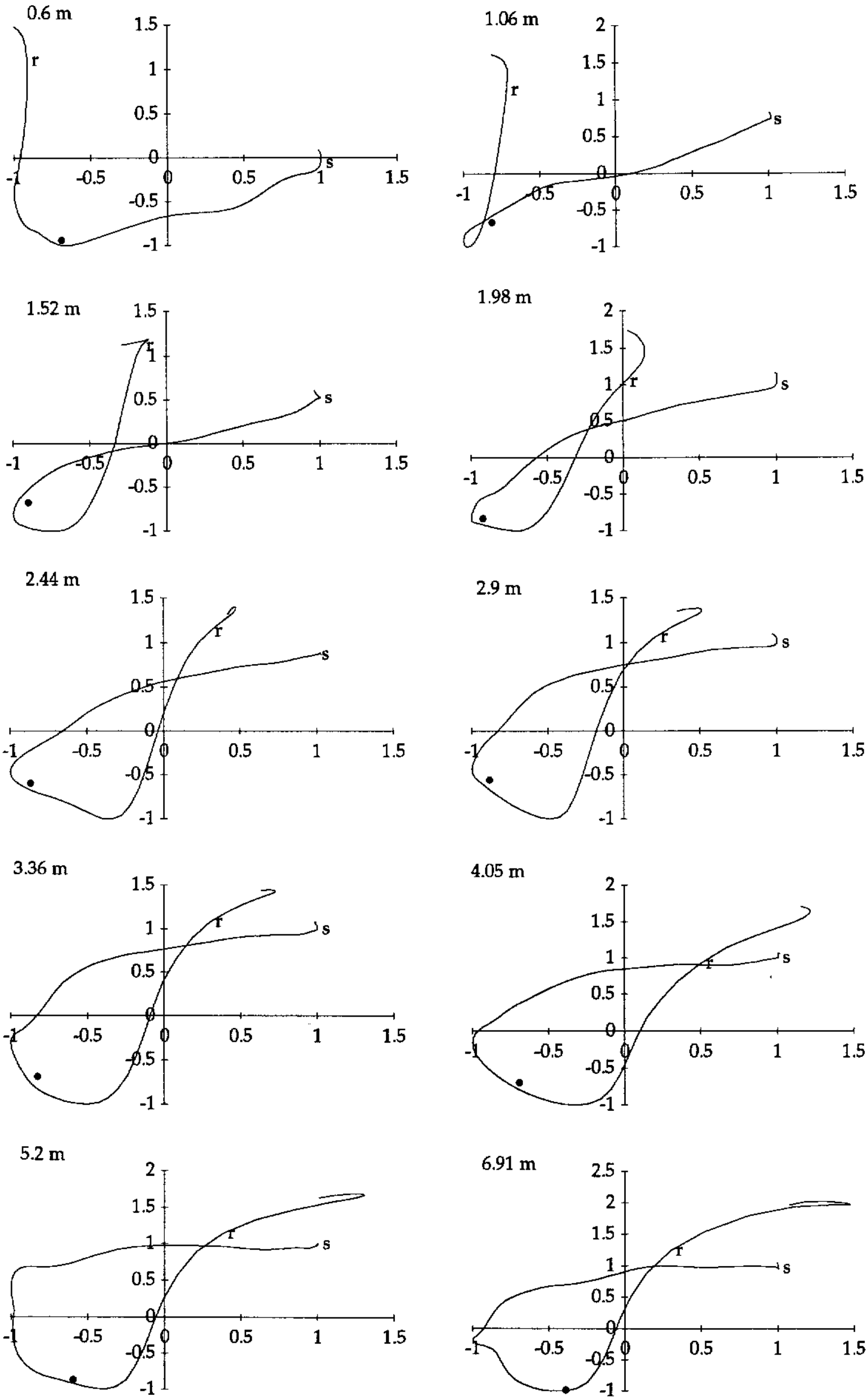


Figure 15 Angle-angle plot between shoulder rotation (x-axis) and wrist deviation (y-axis) of the overarm throw. s = starting point, r = releasing point and • = phase dividing point

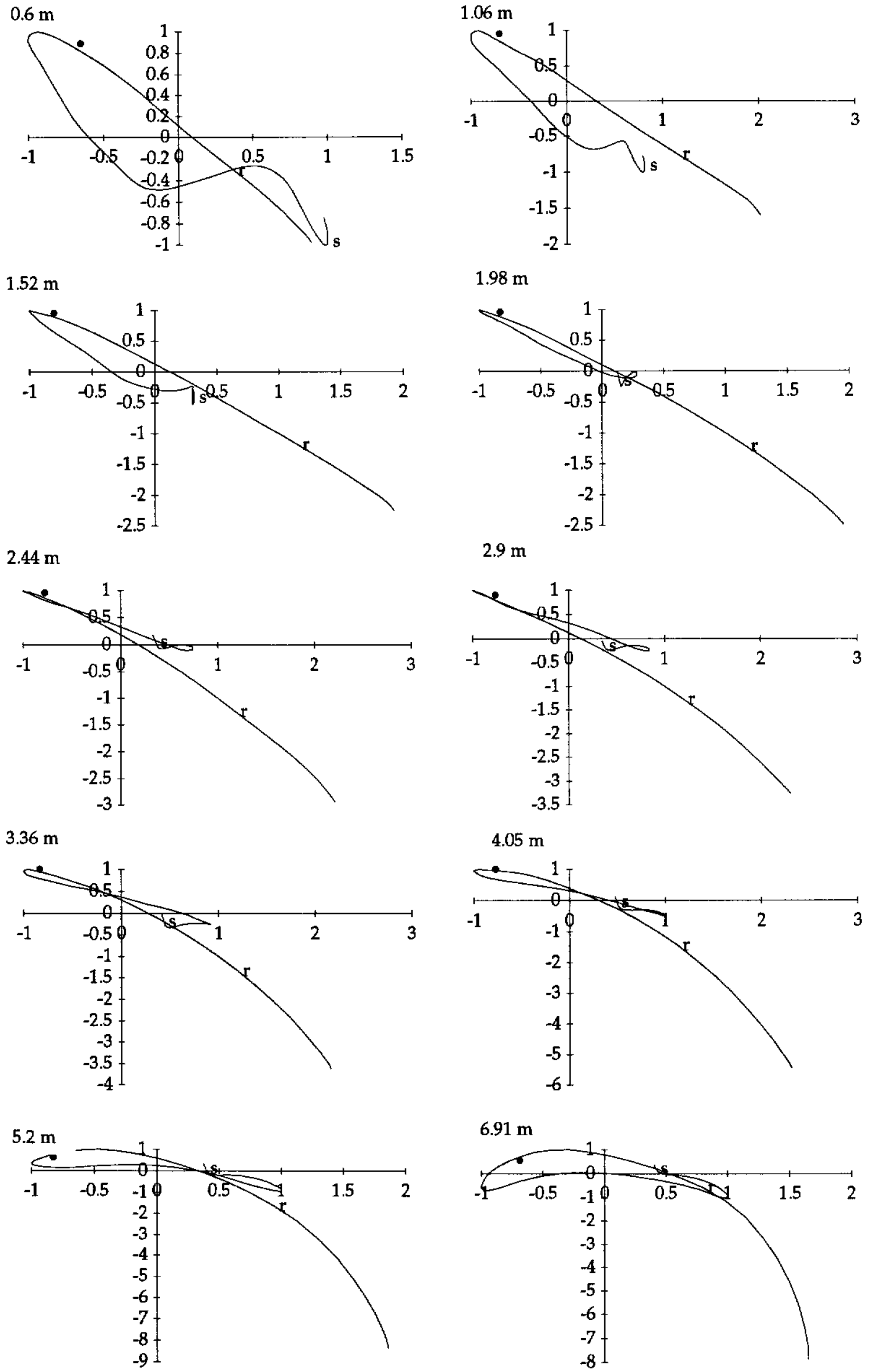


Figure 16 Angle-angle plot between shoulder flexion (x-axis) and shoulder adduction (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

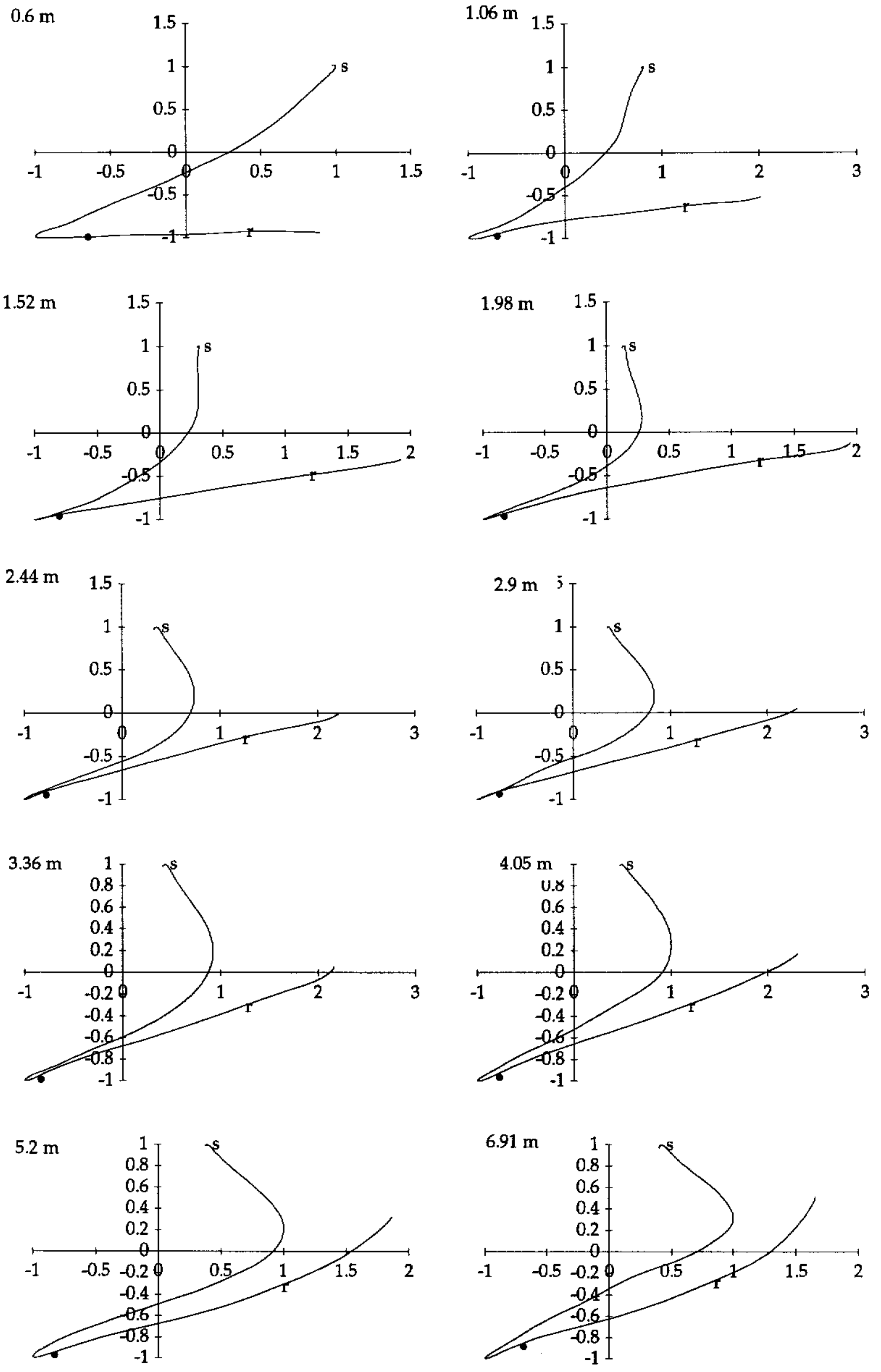


Figure 17 Angle-angle plot between shoulder flexion (x-axis) and shoulder rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

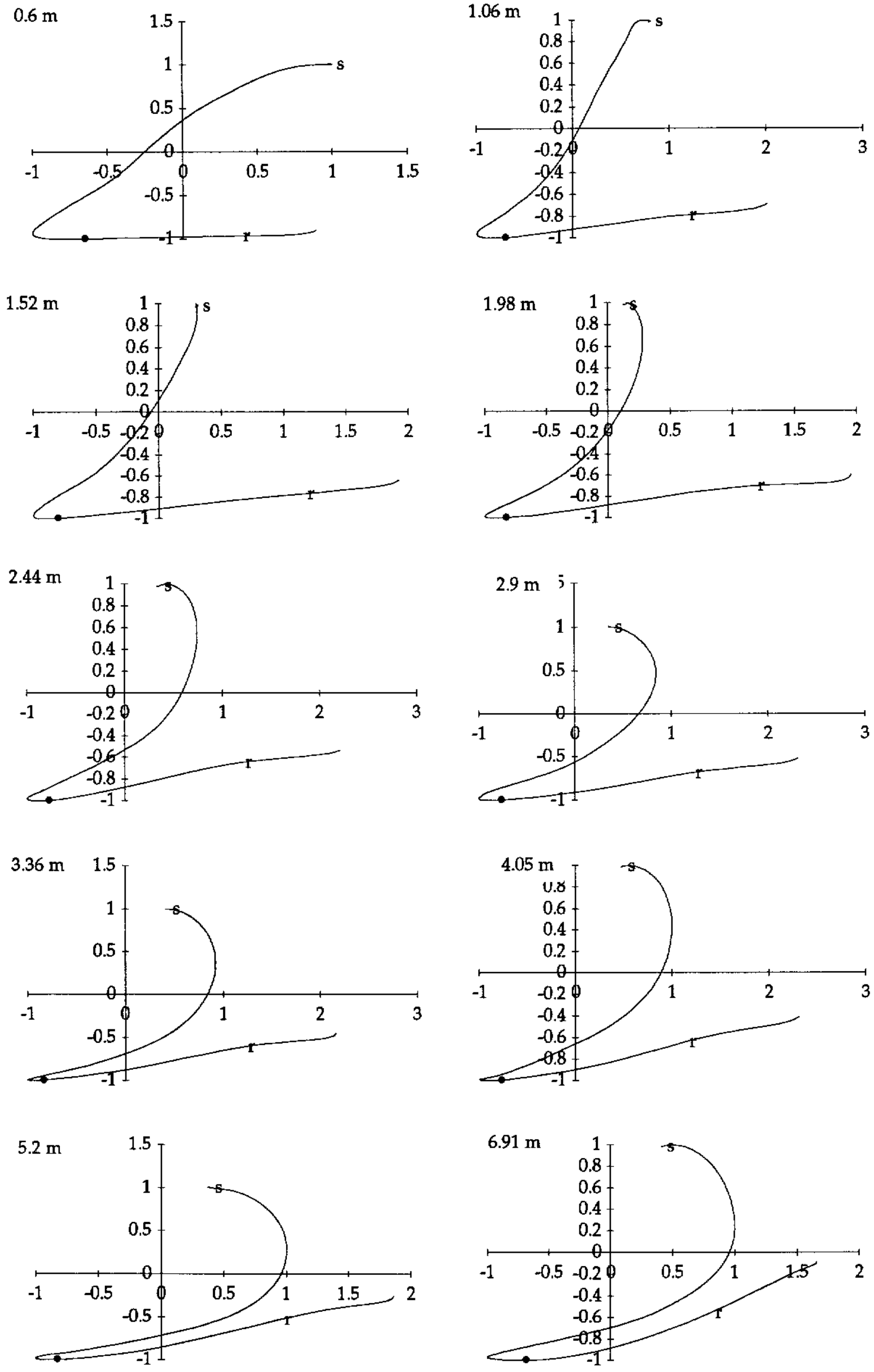


Figure 18 Angle-angle plot between shoulder flexion (x-axis) and elbow flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

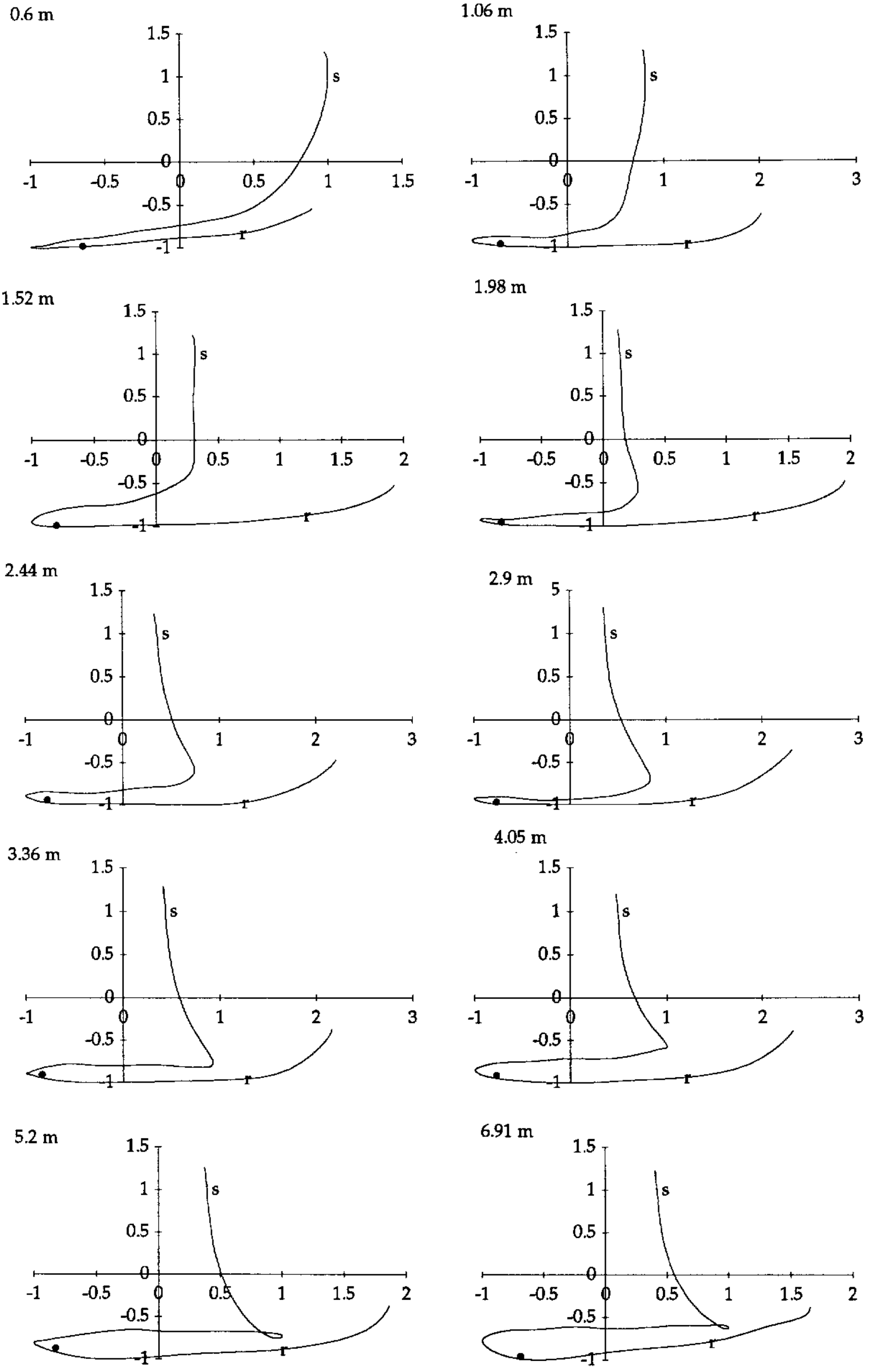
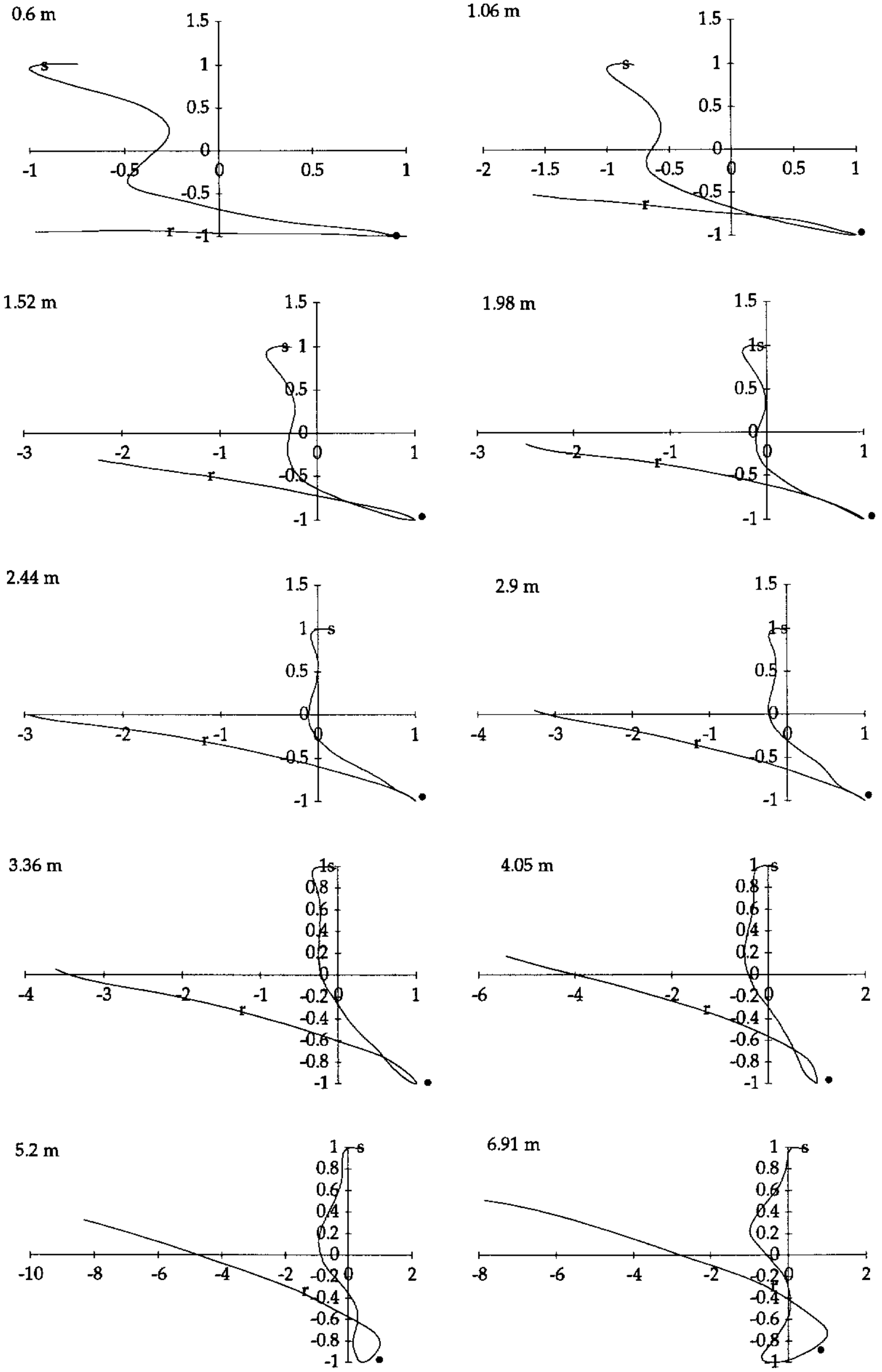


Figure 19 Angle - angle plot between shoulder flexion (x-axis) and forearm rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point


0.6 m

1.06 m

1.52 m

1.98 m

2.44 m

2.9 m

3.36 m

4.05 m

5.2 m

6.91 m

Figure 20 Angle-angle plot between shoulder adduction (x-axis) and shoulder rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

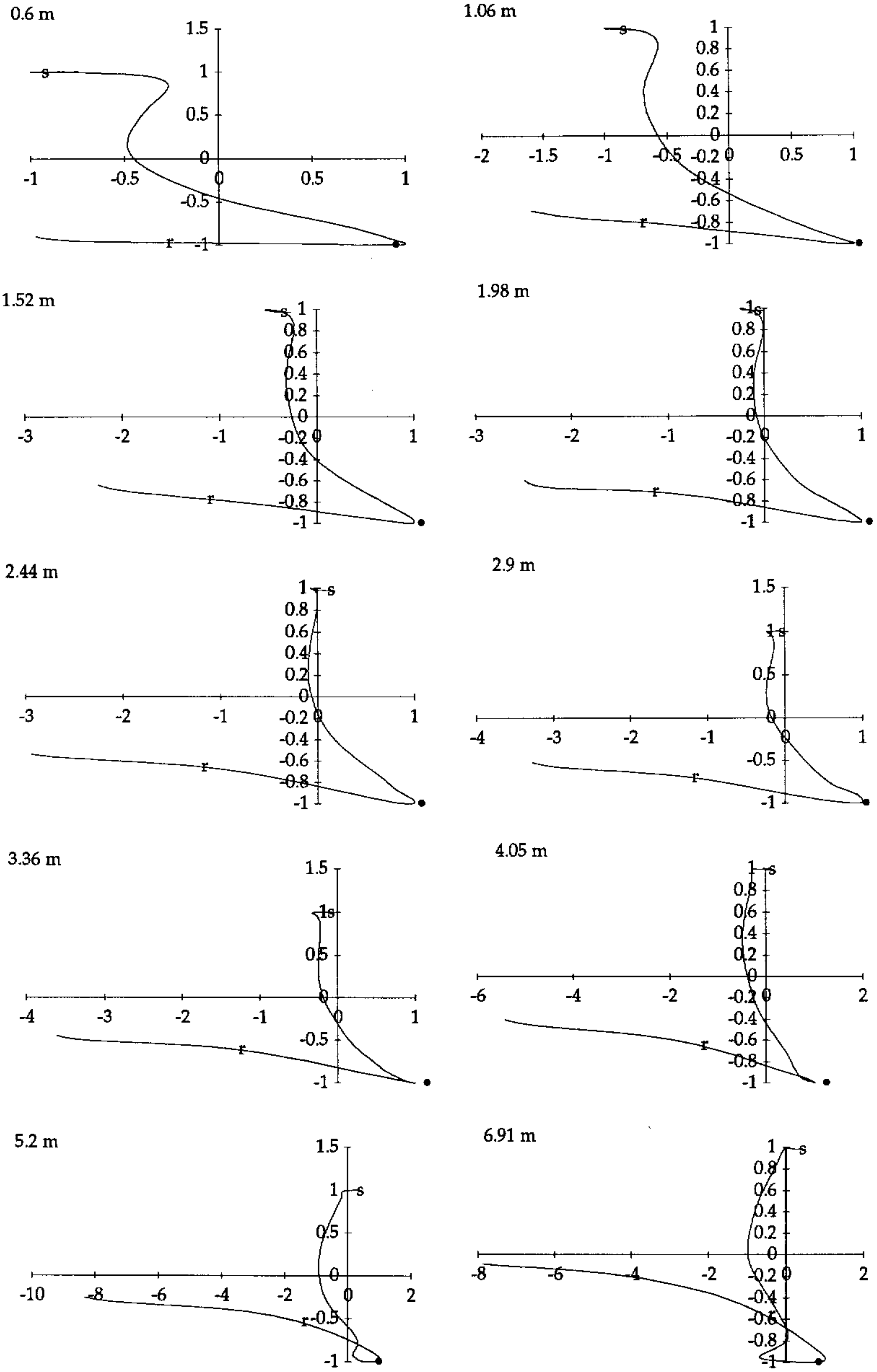


Figure 21 Angle-angle plot between shoulder adduction (x-axis) and elbow flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

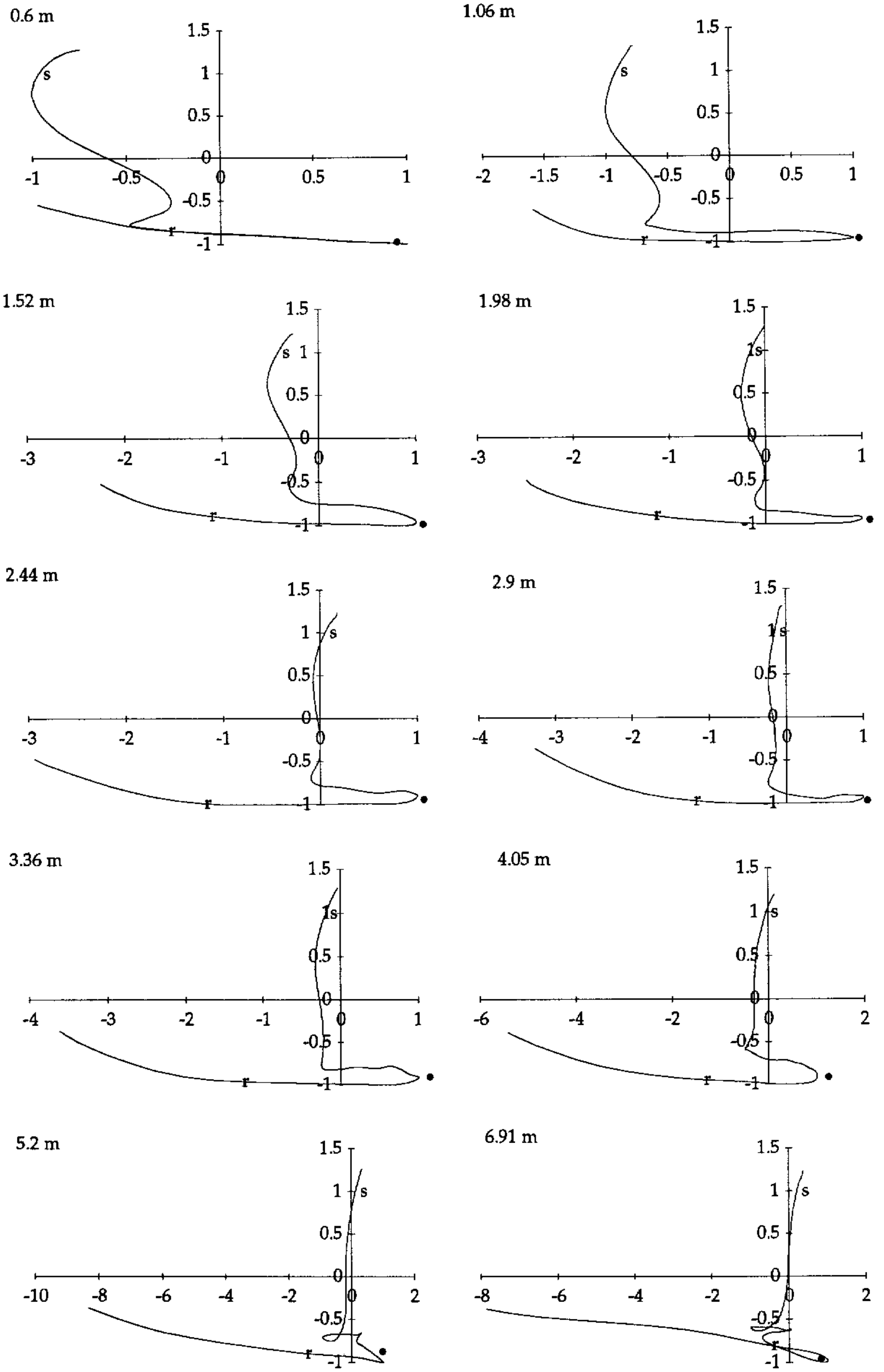


Figure 22 Angle-angle plot between shoulder adduction (x-axis) and forearm rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

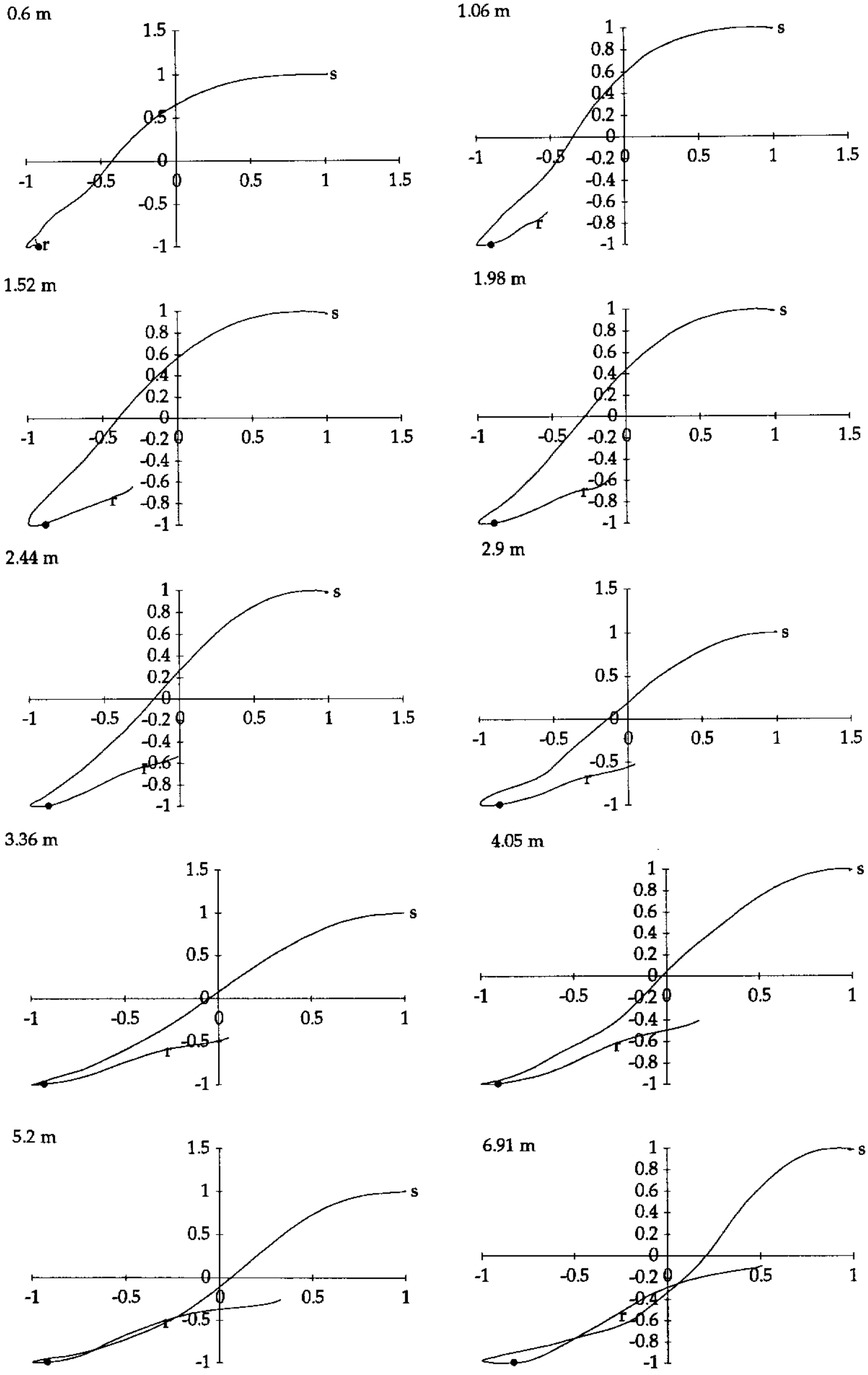


Figure 23 Angle-angle plot between shoulder rotation (x-axis) and elbow flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

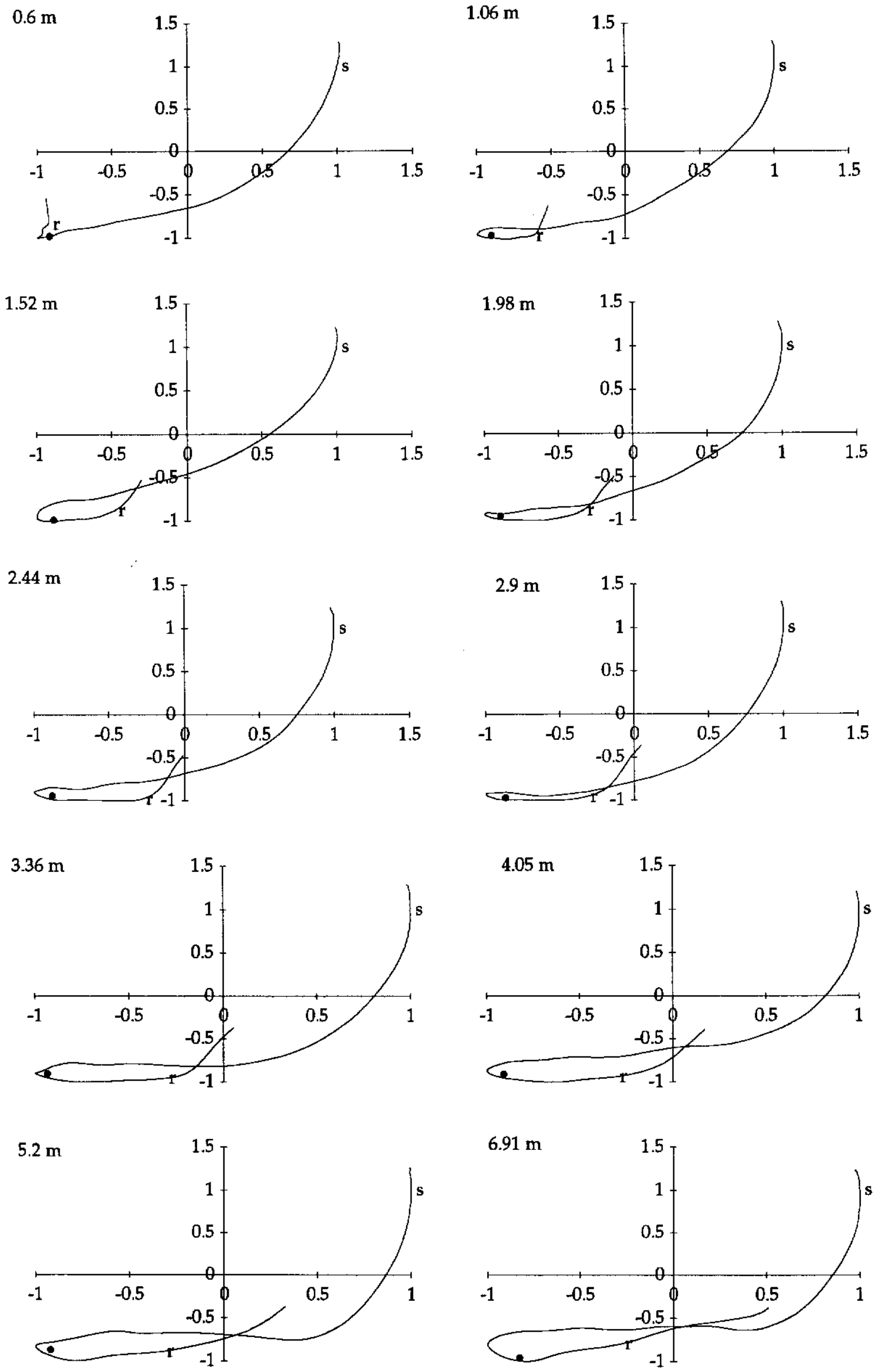


Figure 24 Angle-angle plot between shoulder rotation (x-axis) and forearm rotation (y-axis) of the underarm throw. s = starting point, r = releasing point, •= phase dividing point

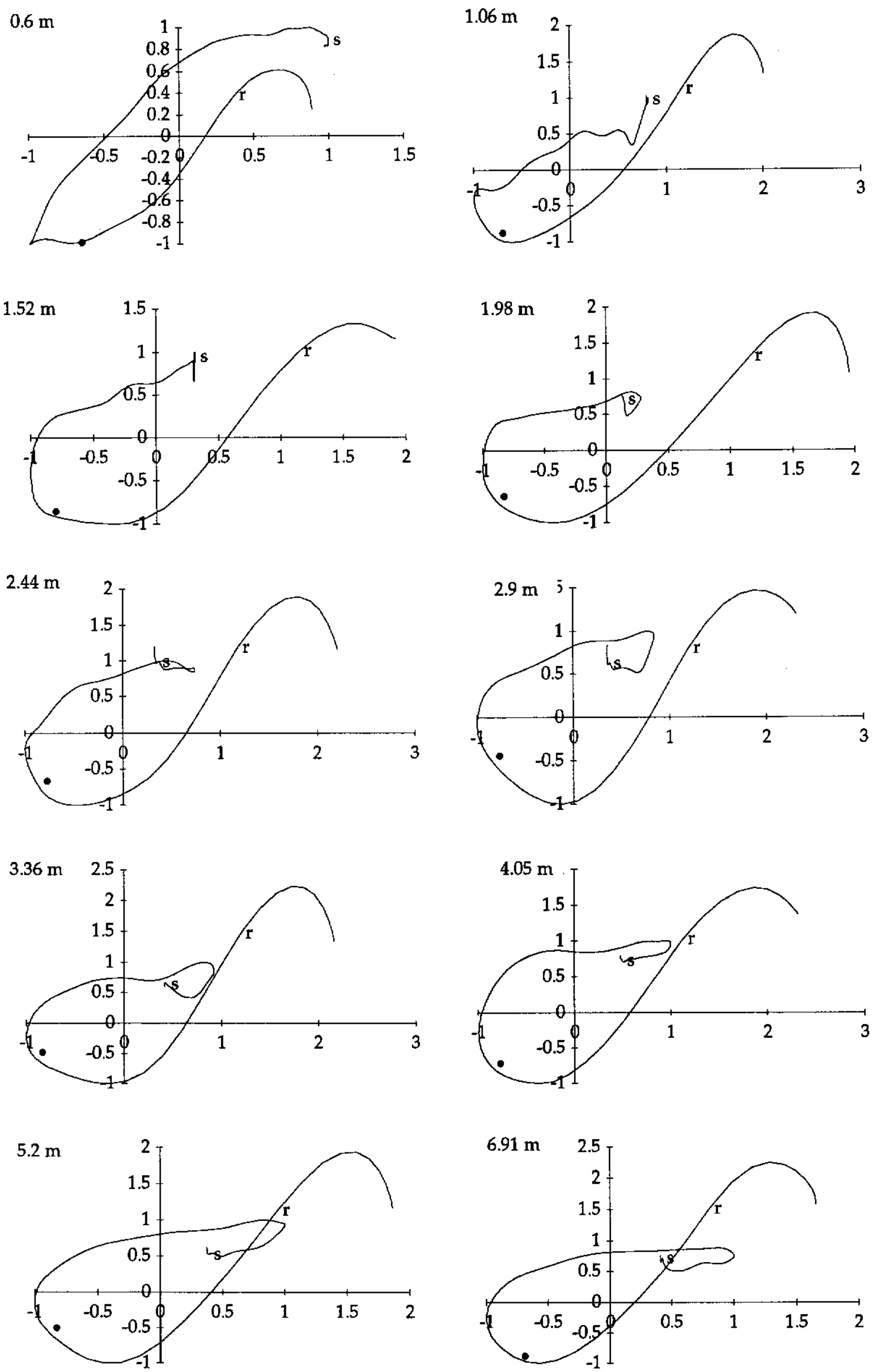


Figure 25 Angle-angle plot between shoulder flexion (x-axis) and wrist flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

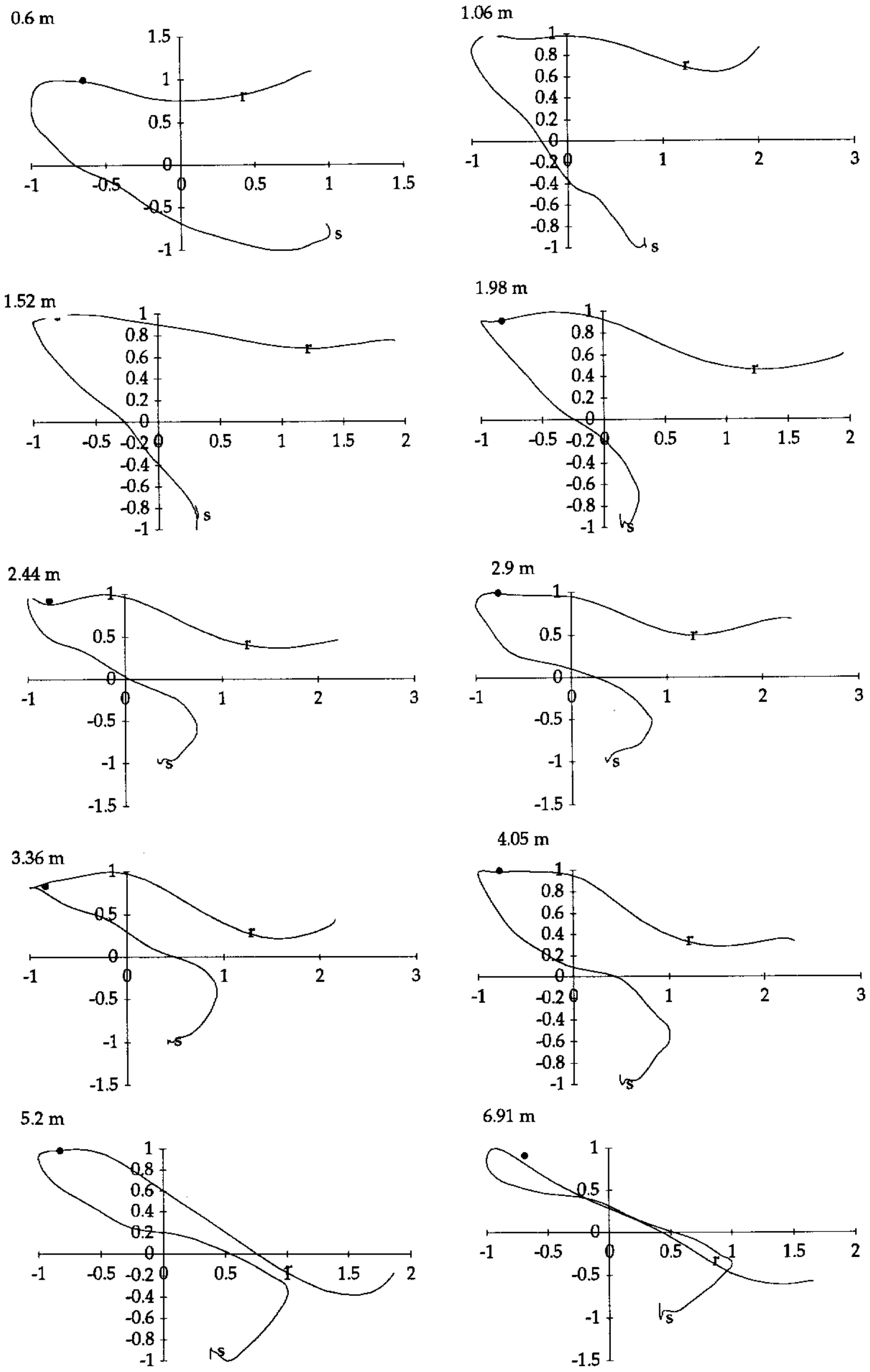


Figure 26 Angle-angle plot between shoulder flexion (x-axis) and wrist deviation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

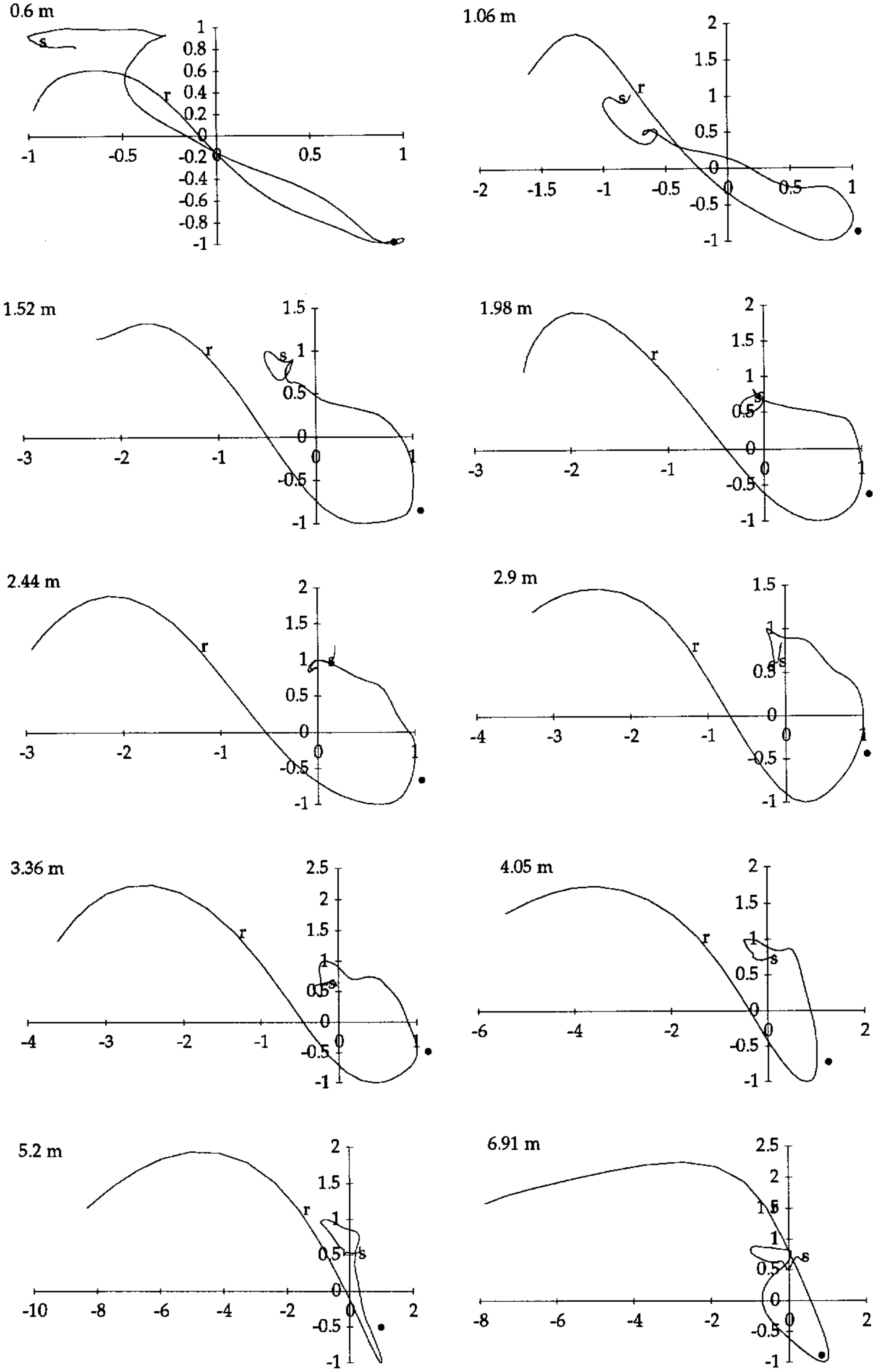


Figure 27 Angle-angle plot between shoulder adduction (x-axis) and wrist flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

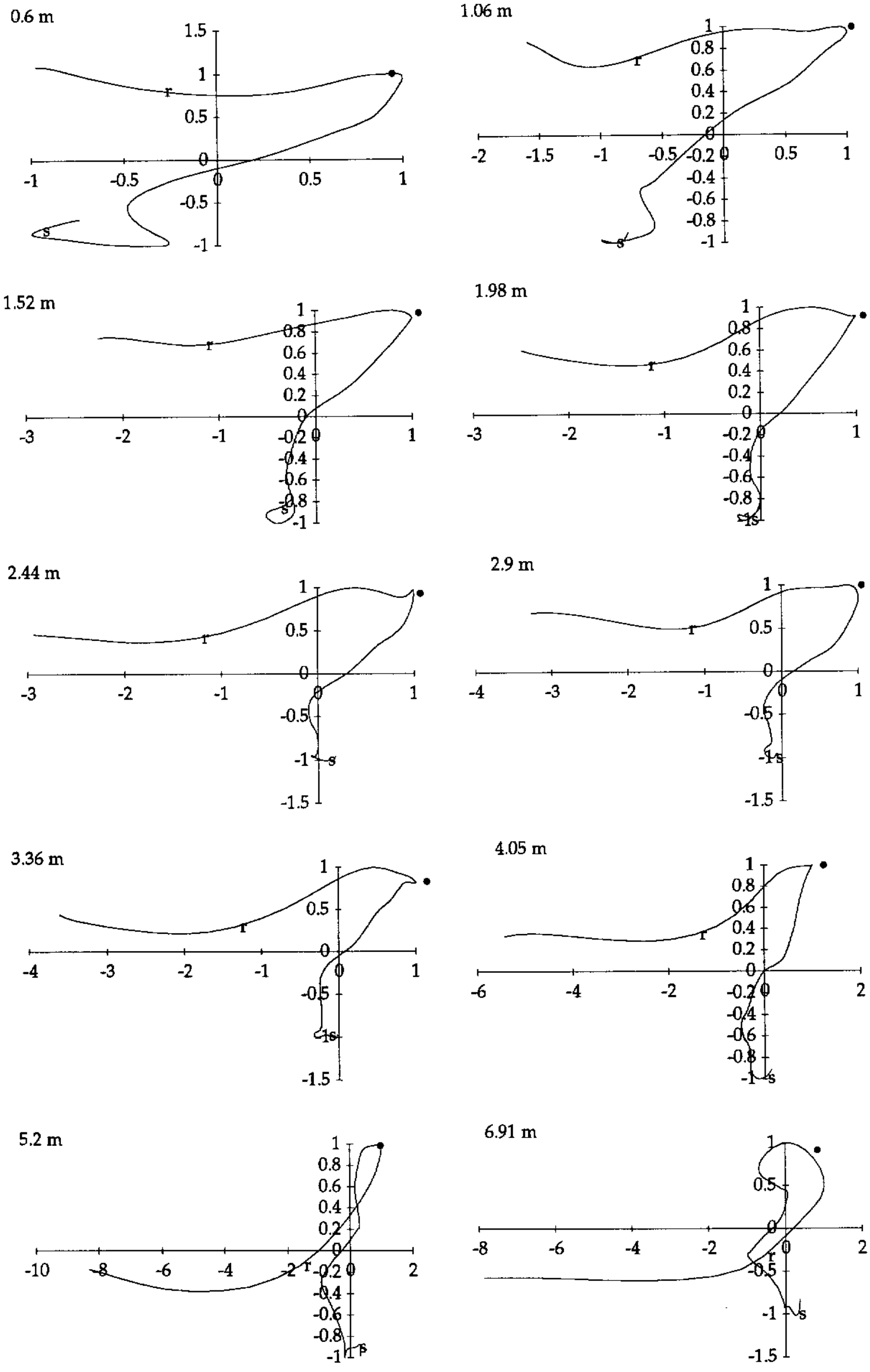


Figure 28 Angle-angle plot between shoulder adduction (x-axis) and wrist deviation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

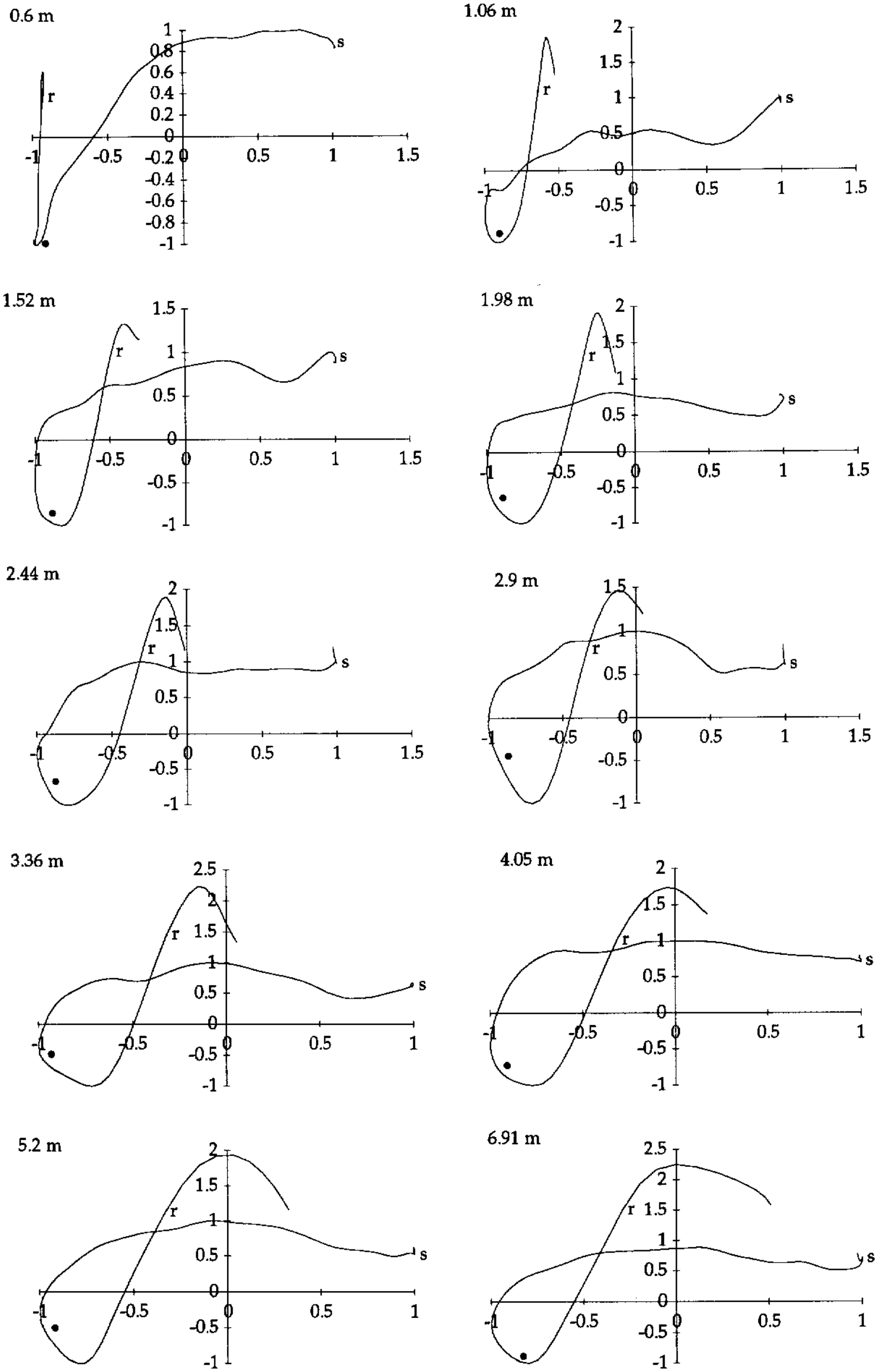


Figure 29 Angle-angle plot between shoulder rotation (x-axis) and wrist flexion (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

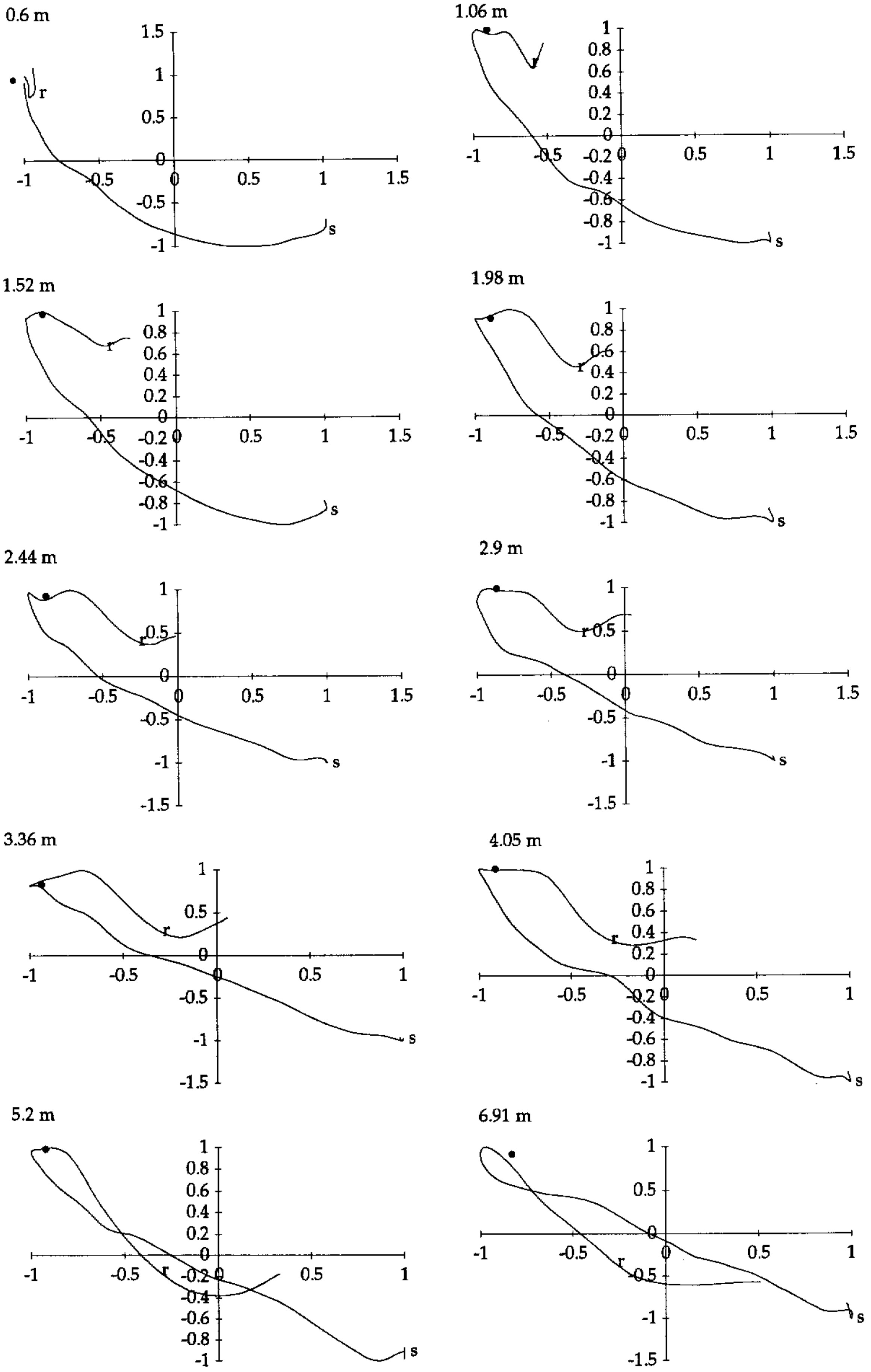


Figure 30 Angle-angle plot between shoulder rotation (x-axis) and wrist deviation (y-axis) of the underarm throw. s = starting point, r = releasing point, • = phase dividing point

Appendix F

Graphs of movement phase and the relative phase for both throwing patterns

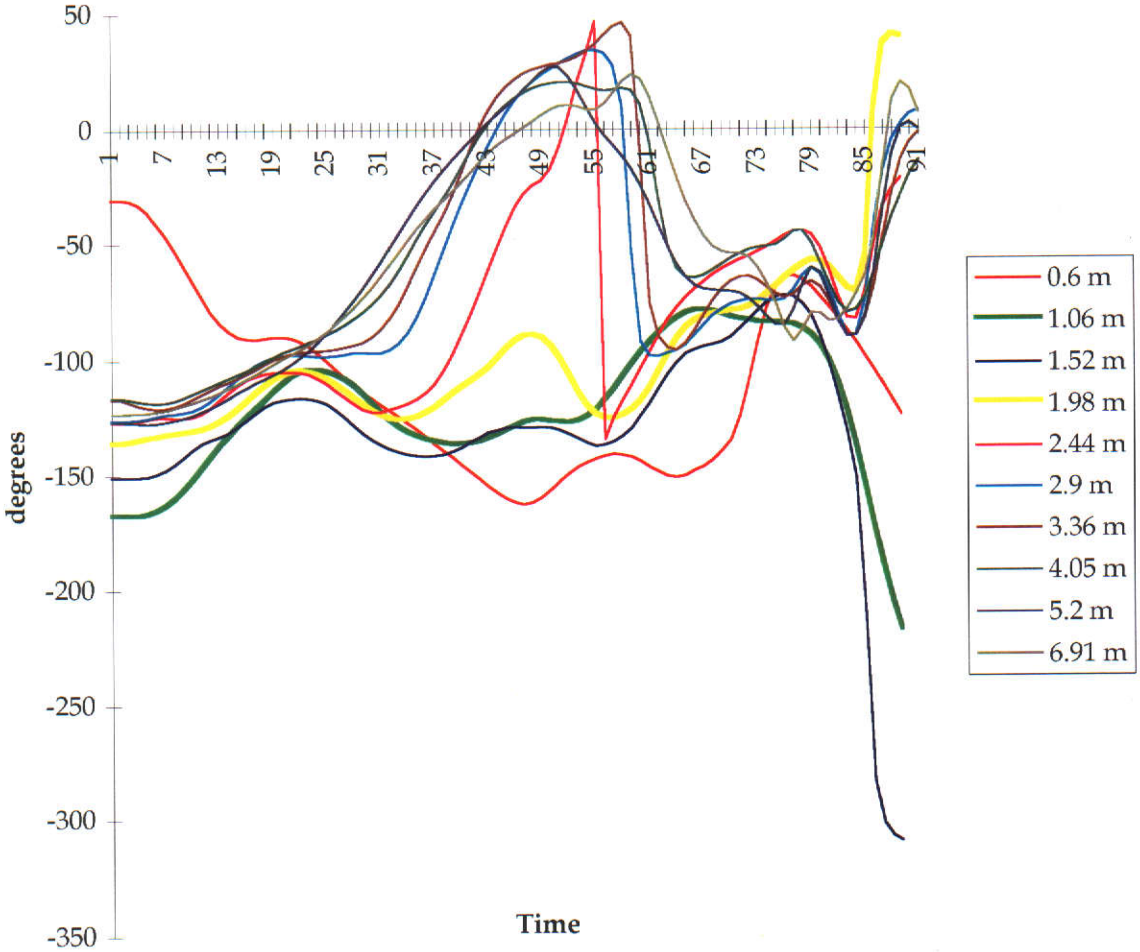


Figure 1 The relative phase between shoulder flexion and shoulder rotation for the overarm throw.

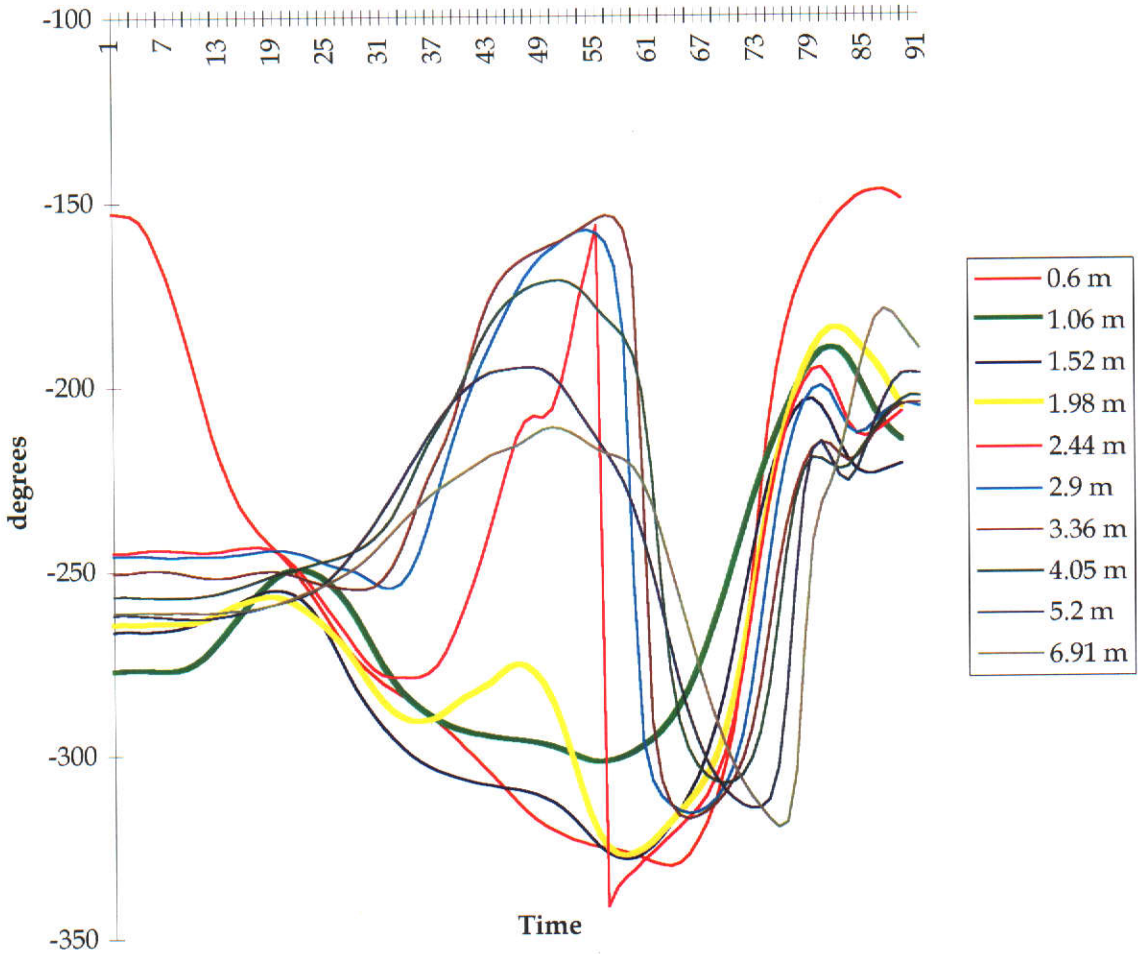


Figure 2 The relative phase between shoulder flexion and elbow flexion for the overarm throw.

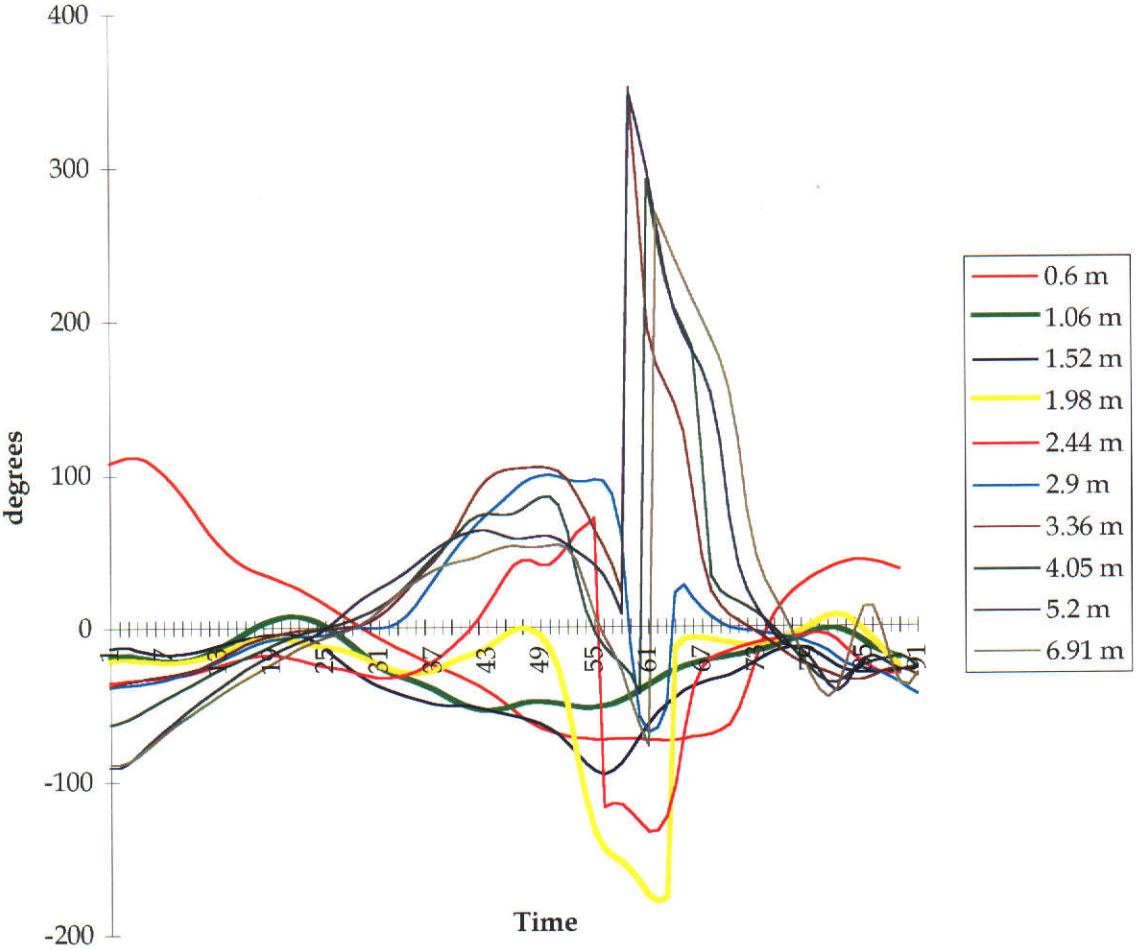


Figure 3 The relative phase between shoulder flexion and forearm rotation for the overarm throw.

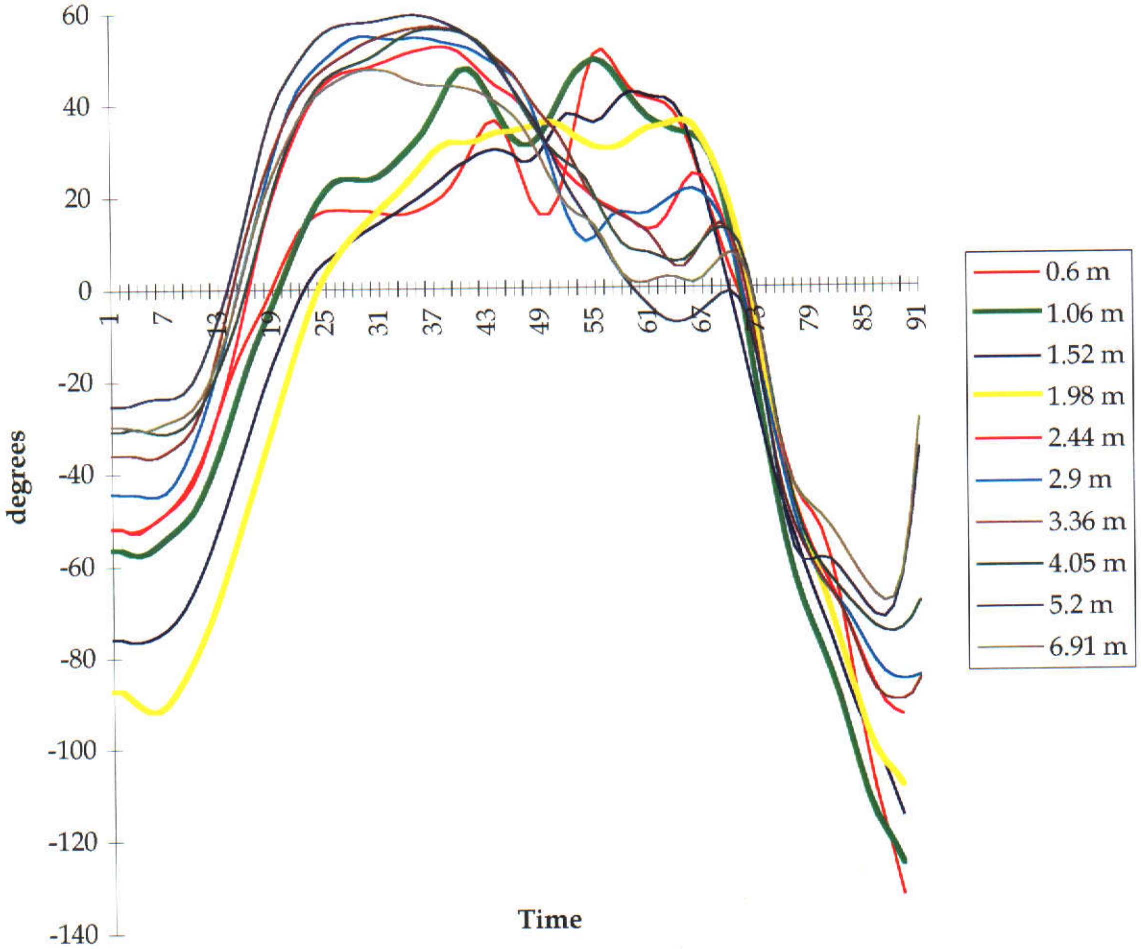


Figure 4 The relative phase between shoulder flexion and shoulder rotation for the underarm throw.

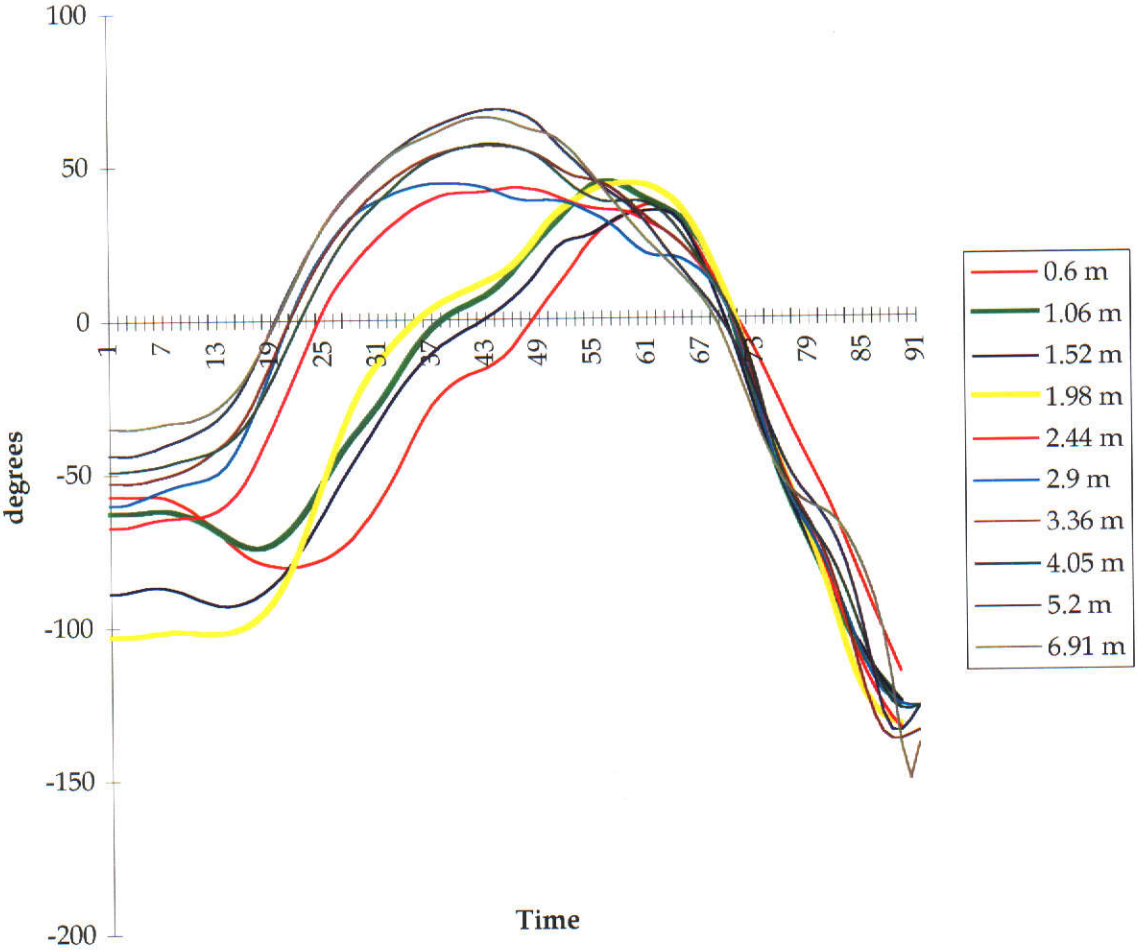


Figure 5 The relative phase between shoulder flexion and elbow flxion for the underarm throw.

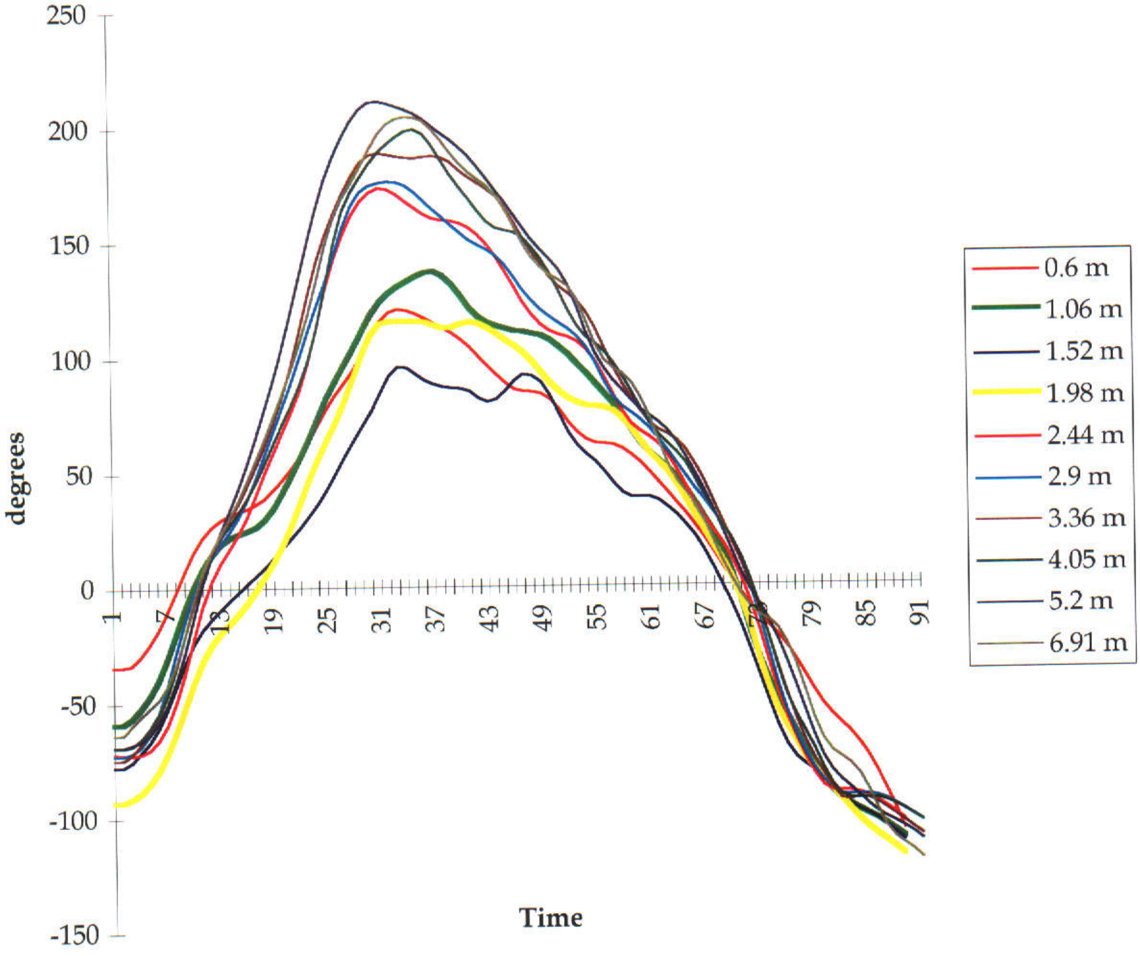


Figure 6 The relative phase between shoulder flexion and forearm rotation for the underarm throw.