ADAPTATION TO CHANGE IN TASK CONSTRAINTS IN FLUTTER KICKING

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification.

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ABSTRACT

PURPOSE: The purpose of this study was to investigate the process of adaptation to change in task constraints, in particular, the presence or absence of flippers in swimming. Human movement systems are 'open' systems which can be influenced by many factors in their environment. The influences that guide the form emerging from the system are considered as constraints on system behavior. Constraints can be manipulated by coaches/teachers to prepare athletes for optimal performance. However little is known about how quickly the human system adapts to changes in task constraints. In particular, little is known about whether the human movement system adapts quickly to constraint environments that are unfamiliar. Dynamical systems theories suggest that, provided the system is familiar with the requirements of the task, it can 'self organise' rapidly to produce a response appropriate for achievement of the task despite change in the constraints of the task.

Swimming kicking with flippers is recognized as an effective practice method for enhancing and optimizing swimming performance. However, whether swimmers can adjust rapidly between kicking with and without flippers is not known. The fundamental requirements of the movement pattern for successful performance in swimming kicking are known through previous research. Also, the movement systems of skilled swimmers have experience of the requirements of the task. Thus, the hypotheses of this study were:

1. The adaptation of skilled swimmers from a familiar task constraint environment (kicking without flippers) to a second familiar task constraint environment (kicking with foot flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

2. The adaptation of skilled swimmers from a familiar task with a familiar constraint environment (kicking without flippers) to the same familiar task with an unfamiliar task constraint environment (kicking with leg flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

METHODS: Nine male competitive age group swimmers with at least one year of training for competition were recruited as subjects. Six of the swimmers were randomly assigned to either a 'leg flipper' group (LF) or 'foot flipper' group (FF). The remaining three swimmers comprised the 'control' group (CO). The LF and FF groups participated in a pre-test

comprising five trials without flippers, 60 trials with flippers and a post-test comprising 10 trials without flippers. The CO group completed the pre-test and post-test only. The kicking performances were videoed and kinematic variables calculated from the digitized data. Fundamental criteria of appropriateness of the movement pattern for performance of the task were the percent power in the fundamental Fourier frequency harmonic of the vertical oscillations of the hip, knee, and ankle and the Fourier phase relationships between them as these are known to be related to successful performance.

RESULTS AND DISCUSSION: The hypotheses were both supported with respect to the movement pattern remaining appropriate for task achievement as indicated by the fundamental criteria. In the case of swimming with leg flippers, the task required a major change in hip and knee joint coupling as indicated by a major change in continuous relative phase across barefoot and leg flipper conditions. Although the system adapted rapidly to changed task constraints in terms of the general movement pattern, continued 'exploration' was required to optimize performance under the new conditions. This involved changing parameters such as frequency of the kicking motion to suit the fluid environment in which the task was being performed, while retaining the predominantly sinusoidal undulations with appropriate phase relationships between the undulations. A quicker optimization by the FF group than the LF group is logically attributable to the fact that the constraint environment was familiar in the case of the foot flipper condition but unfamiliar in the case of the leg flipper condition. Small variability in kicking frequency in the first session with the flippers for the LF group and in amplitude-normalized angle-angle of knee-hip joint and phase planes of knee and hip joints of both groups indicated a tendency for the system to seek stability when first adjusting to a changed constraint environment.

CONCLUSION: Human movement systems can adjust rapidly to unfamiliar task constraints in the task of kicking in swimming when the system is familiar with, from previous learning to a high level of skill, the fundamental movement pattern required for skilled performance. However, rapid adaptation to produce an appropriate movement response does not preclude continued improvement through further 'exploration' to 'fine tune' to the changed environment. Further work is required to establish whether the hypotheses supported in this study for the task of kicking in swimming are supported for other tasks in which the fundamental movement characteristics for skilled performance are known.

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LIST OF ABREVIATIONS

$>$	Greater than
$<$	Less than
$\sqrt{\ }$	Square root
$\sum$	Sum of
BF	Barefoot
C	Energy expended to cover one unit distance
CG	Center of body mass (Center of gravity)
CO	Control (group)
CRP	Continuous relative phase
deg	Degree
E.S.	Effect size
FF	Foot flipper
FTC	Flipper transfiguration coefficient
FTR	Flipper transfiguration rate
Hz	Hertz
KF	Kicking frequency
kg	Kilogram
LF	Leg flipper
LS	Large-stiff flipper
m	Meters
MF	Mono flipper
MSD	Mean standard deviation
P	Flipper performance factor
ROM	Range of motion
s	Seconds
SD	Standard deviation
SF	Small-flexible flipper

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CHAPTER 1

INTRODUCTION

Skill acquisition for performance in competition settings is a common goal in sports. During the process of skill acquisition, performers not only need to understand the environment in which the skill is to be performed but also to practice in a way that enhances the development of skill for performance in competition settings. In particular, performers need to adjust to the requirements of tasks that vary due to constraints such as those associated with the individual, environment and equipment. Thus, it is important to know how individuals can adjust to constraints to maintain optimal performance of the task.

1.1 Constraints in the frame of dynamical systems theory

Dynamical systems approaches have become popular as a way of exploring the systematic coordination of multiple body segments (Newell, 1986; Clark, 1995; Davids et al., 2003). Dynamical systems approaches focus on the processes of coordination of human movement systems. From a dynamical systems perspective, the behavior of a complex system like the human movement system, which involves intricate co-dependent sub-systems and a large number of interacting components, emerges through self-organization of the system (Kelso, 1995; Balasubramanian and Turvey, 2004). It has been proposed that the very many components of the human movement system are combined into functional units called 'coordinative structures' or 'synergies' (Kugler et al., 1980; Mitra et al., 1998). These are temporarily assembled functional units. It is a collective, task-specific organizational state achieved by the system and not restricted in the anatomical sense (Balasubramanian and Turvey, 2004).

One of the advantages of dynamical systems approaches is that it allows for the theoretical expression of the behavior of the human movement system in a low-dimensional form (Kurz and Stergiou, 2004). The application of dynamical systems theory in human movement science has encouraged innovation of analysis techniques to capture the dynamic nature of human movement systems. These include non-linear analysis methods such as angle-angle plots, phase plane, and continuous relative phase to gain a better understanding of how body segments are coordinated (Glazier, Davids and Bartlett, 2003).

The concept of constraints is critical to a dynamical system approach to analysis of human movement (Clark, 1995). Newell (1986) emphasized that skilled performance, as reflected in the optimal pattern of coordination and control, is determined by the interaction of the organismic, environmental and task constraints. From a dynamical systems perspective, movements emerge from a system that is surrounded by constraints. According to Newell (1986), constraints can be categorized into organismic (e.g. height, weight), environmental (e.g. temperature, gravity) and task (e.g. goals of a sport, implements or tools to use during performance) constraints. Task constraints play important roles in human movements. Coaches and teachers can manipulate them to help performers search for functional and individualized coordination solutions (Araújo et al., 2004). The significance of task constraints in human movement (Clark, 1995) is that they 'shape' the performance.

Nourrit et al. (2003) argued that the duration of most studies rarely went beyond the very first adaptation to the task and as such did not allow qualitative modifications of the behavior to appear. The goal of performers practicing under varying task constraints is to enhance the development of skill acquisition. Thus, evaluating the coordination of the human movement system under different task constraints and investigating the learning process would assist in understanding the process of skill acquisition. Furthermore, it could lead to a better understanding of how task constraints can be designed to assist in developing adaptability to changing constraints in competition.

1.2 Developing sport skills under task constraints

Dynamical systems are 'open' systems. Their forms could be influenced by many factors in their environment. It has become clear that the influences that guide the form emerging from the system should be considered as constraints on system behavior (Newell, 1986). Thus, the role of the coach in structuring task constraints and organizing practice environments is important (Schmidt and Lee, 1999; Araújo et al., 2004). One would assume that practicing under a variety of task constraints that one may encounter in a competition setting would improve a performer's ability to adjust rapidly to the task as its constraints change in competition settings. However, the extent to which performers can adjust to unfamiliar task constraints appears to be an area requiring further investigation. Familiar task constraints could be defined as constraints existing frequently during practice. Unfamiliar task constraints are those that are different from any of the conditions under which the task is regularly practiced.

There are different reactions of the human movement systems to unfamiliar task constraints. For example, standing, walking or running on an incline may be a task with constraints unfamiliar to a runner. On an inclined surface, postural, motion and dynamic response are task-specific and the control requirements are different from running on a level surface (Swanson and Caldwell, 2000; Mizrahi, Verbitsky and Isakov, 2001; Watson, 2005; Gottschall and Kram, 2005; Romanov, 2005; Yakozawa, Fujii and Ae, 2005). However, the rate of adjustment to changes in task constraints in these tasks remains unclear.

Studies on snowshoeing showed that there were biomechanical and physiological adaptations of the human movement system when running with snowshoes. This adaptation varied over time (Luk, Fung and Hong, 2005). It is not clear whether or not the same movement pattern was retained or a new movement pattern developed in response to the changed task constraints. It was also not clear how quickly the participants adapted to a change in task constraints.

Nevertheless, a short period of adaptation was required (a few trials) to maintain balance on a moving surface that was sinusoidally translated in the anterior-posterior direction (Ko, Challis and Newell, 2003). The study supported the idea that the nature of the response and the rate of adaptation to changes in the task constraints varies according to the task and the constraints.

Studies of the effect of footwear and running surface on running indicated that there were adaptations (Hardin, van den Bogert and Hamill, 2004) over short periods of time such as changes in hip flexion at contact, plantar-flexion at toe-off, and peak dorsi-flexion and plantar-flexion velocity.

In a drop jumping task, adult performers couldn't accommodate quickly to a change in surface compliance (Sanders and Wilson, 1992). Improvement of jumping height and change in the kinematics and kinetics was still occurring towards the end of 190 trails of jumping from an unfamiliar sprung surface. This indicated that performers couldn't adapt spontaneously to the task with unfamiliar constraints (surface compliance) from the coordination pattern established for the task with familiar task constraints (hard surface).

The slower rate of adjustment to the task of drop jumping than in other tasks where task constraints have been manipulated might be related to whether the system is familiar with (no cognition implied) the optimal movement pattern sought. Sanders and Wilson showed that jumping from a sprung surface was optimized by a movement strategy very different from that required when jumping from a hard surface. Thus, the system had to 'explore' the movement possibilities and gradually 'hone in' on the optimal movement pattern. To assess whether 'knowing' the optimal movement pattern is a prerequisite to rapid adjustment when the task constraints are changed, tasks in which the kinematic or kinetic characteristics associated with optimal performance are known must be studied. Flutter kicking in swimming is such a task.

1.3 Swimming kicking performance and swimming with flippers

Swimming kicking, as a part of whole body movement during swimming, plays an important role in freestyle, backstroke and butterfly swimming. Swimming kicking not only provides a stable 'platform' for the whole stroke by facilitating body position to optimize propulsion and minimize resistance (Maglischo, 1993) but also contributes to propulsion (Watkins and Gordon, 1983; Hollander et al., 1988; Adams, 2000). Specifically, in a learn to swim program, it is common to teach kicking in the prone position in the belief that proper kicking is required as a foundation for development of good coordination in the entire freestyle stroke (Sanders, 2006).

There are a number of practice methods applied in swimming to improve kicking. Swimming flippers (fins) are one of the most widely used in the practice of swimming kicking because they are thought to provide a training effect without corrupting the kicking action. Flippers are worn to increase speed, or to establish the feeling of optimizing performance in a speedy condition (Muckenfuss, 1985; Soloviev, 1993), and to increase loading of muscles responsible for increasing forward swimming speed.

From the view of hydrodynamics, the advantage of swimming with flippers is that the swimmer gains higher propulsive efficiencies. Zamparo et al. (2002) estimated that at comparable speed, the energy cost could be about 40% lower when using flippers than when swimming without flippers. The swimmer obtains forward thrust by undulating/bending the whole or part of the body. Efficient propulsion in swimming with flippers (fins) relies on optimal interaction between the swimmer's body and flippers and the fluid flow environment. Performance depends on the system producing the appropriate vortex distribution, a 'reverse Kármán vortex street' (Lighthill, 1969). In turn, this is related to the harmonic oscillation of the foil (Triantafyllou, Triantafyllou and Yue, 2000; Colgate and Lynch, 2004; Beal et al., 2006). Mathematical optimisation studies of mono fin swimming confirm the sinusoidal nature of the flipper's motion (Luersen et al., 2004). Thus, the underlying movement pattern of the flipper that optimises performance is known to be a simple sinusoidal oscillation.

In flutter kicking, two legs move alternatively and almost symmetrically with respect to the center of mass with some similarities to walking. Like many walking studies (Cavagna and Kaneko, 1977; Winstein and Garfinkel, 1989; Kurz and Stergiou, 2002), the lower extremities could be modeled as a series of 'level' pendulums in which each segment of the lower extremities oscillates about its respective joints (Zamparo et al., 2002). In the case of flutter kicking in swimming the pattern of vertical displacements of each of the lower extremity segments is sinusoidal. It has been found that the body wave in butterfly stroking is similar to the body wave of slender fish (Ungerechts, 1983; Sanders, Cappaert and Delvin, 1995). Similar wave characteristics are features of skilled performance in flutter kicking (Zamparo et al., 2002; Sanders, 2006). Thus, efficient performance in kicking in swimming is known to be associated with sinusoidal vertical motions of the body segments sequenced so that a 'wave' progresses caudally along the body.

The fact that the characteristics of the self optimal movement pattern are known for swimming kicking tasks provides an opportunity to assess whether the movement pattern remains appropriate for task performance following a change in task constraints. Task constraints can be changed readily by adding or removing flippers. The addition of flippers greatly affects the requirement for torque production. That is, the kinetics of the task change and yet the rudiments of the kinematics associated with optimal achievement of the task remain unchanged.

Swimmers practice regularly with foot flippers and so they provide a different but familiar task constraint environment. A new type of flipper, Shinfin™, is worn on the shin and termed a 'leg flipper' provides a different constraint environment that is unfamiliar to most swimmers. This constraint environment differs considerably from either the constraint environment in which there are no flippers used and from the constraint environment offered by standard flippers. The leg flippers differ from the standard flippers by being closer to the knee joint, thereby reducing the lever arm of the hydrodynamic forces relative to the knee joint. Also, leg flippers lie across the shin and the instep of the foot. As a result, the ankle is immobilized and the system is changed from a three segment system to a two segment system. Therefore, the swimmer must adapt not only to a change in the requirements for torque production but also to change from being a system comprising three segments, in which the third segment generates propulsion, to being a system comprising two segments in which the second segment produces propulsion. Araújo et al. (2004) pointed out that the size and mass of a piece of equipment relative to relevant limb segments is one of the most important task constraints during movement. Accordingly, exploring the characteristics of lower limb kinematics with different types of flippers would indicate how readily humans adapt to change in task constraints and to compare the adaptation between familiar and unfamiliar task constraints. Importantly, the effectiveness of adjustment can be assessed in terms of adherence to a movement pattern known to be associated with successful performance of the task.

1.4 Purpose

The purpose of this study was to investigate the process of adaptation to change in task constraints, in particular, the presence or absence of flippers in swimming.

1.5 Hypotheses

Two general hypotheses were addressed:

(i) The adaptation of skilled swimmers from a familiar task constraint environment (kicking without flippers) to a second familiar task constraint environment (kicking with foot flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

The rationale for this hypothesis is that the system is familiar with the movement pattern required for successful performance and that the two constraint environments are familiar and therefore the system can readily adapt between them.

(ii) The adaptation of skilled swimmers from a familiar task with a familiar constraint environment (kicking without flippers) to the same familiar task with an unfamiliar task constraint environment (kicking with leg flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

This hypothesis is in keeping with the idea that if the system is familiar with what the desired movement pattern should be, as it does in swimming kicking, then it can adjust rapidly despite the large change to an unfamiliar task constraint environment. That is, the human movement systems will return readily to stable states or points of equilibrium (Scholz & Kelso 1989; Schmidt et al. 1992). On the other hand, if the adaptation to the leg flippers is not rapid, it indicates that a process of adaptation is required to adapt to unfamiliar task constraints even though the rudiments of the desired movement kinematics remain unchanged.

CHAPTER 2

REVIEW OF LITERATURE

Literature providing appropriate background for addressing the purpose of the thesis, that is, to investigate the process of adaptation to change in task constraints, particularly the presence or absence of flippers in swimming, was reviewed.

The reviewed literature comes from five related areas: 'characteristics of flutter kicking in swimming'; 'kinematics of swimming with flippers'; 'design and optimization of swimming flippers'; 'hydrodynamics of propulsion in swimming with flippers'; and 'coordination development in the perspective of dynamical systems theory'. In the first four parts, the history and the progress of academic studies on kinematics and hydrodynamics of flutter kicking with and without flippers are reviewed. Although there are a number of studies on benefits of swimming with flippers and the optimization pattern of interaction between human movement systems and the environment, this is, water, the process of accommodating to the flippers remains unclear.

In the framework of dynamical systems theory, the problem is related to the general issue of how the human system adapts to changes in task constraints. Unfortunately, there is a lack of studies on both the specific problem of how the human movement system adapts to change in flippers and the general problem of how the human movement system adapts to change in task constraints. Thus, it is expected that the review of literature related to 'coordination development in the perspective of dynamical systems theory' provides the academic base for investigation of the specific problem and its contribution to the body of knowledge relating to the general problem of adaptation to task constraints.

2.1 Characteristics of flutter kicking in swimming

Flutter kicking refers to the style of kicking in which the legs move separately and out of phase (opposite). There are two forms of flutter kicking: freestyle (front crawl) kicking and backstroke kicking. The function of flutter kicking is either as a performance component of competition swimming of freestyle and backstroke (e.g. mid-pool swimming and prior to surfacing in starts and turns) or as an effective practice performance for skilled swimmers and learners. Due to the similar performance structure between freestyle and backstroke flutter kicking, prone flutter kicking (i.e. freestyle flutter kicking), the more commonly performed and researched form, will be discussed predominantly in this section.

There has been relatively scant attention paid to the action of the lower extremities in the flutter kick used in freestyle swimming (Sanders, 2006) due to the main attention being on the body position and arm action (Adams, 2000; Arelleno et al, 1994; Kennedy et al., 1990). This emphasis is natural given that most propulsion is related to the arm action and that body position is important with regard to minimizing resistance. However, Watkins and Gordon (1983), Hollander et al. (1988), and Adams (2000) have indicated that the freestyle kick does contribute to propulsion. Further, the kick plays an important role in providing a stable 'platform' for the whole stroke by facilitating body position to optimize propulsion and minimize resistance, and in assisting an economical body roll (Maglischo, 1993).

There are few studies on flutter kicking (without arm performance) in the literature. The explorations have focused on efficiency of kicking with descriptive kinematics such as kicking amplitude (Alley, 1952), foot frontal area (Fujiwara and Ogita, 1997) as well as comparison with dolphin kicking (Sheeran, 1980; Lyttle, et al., 2000; Clothier, 2004). To date, only Sanders (2006) investigated the coordination development of the movement pattern in flutter kicking.

2.1.1 Kinematics of flutter kicking

2.1.1.1 Amplitude of flutter kicking

The efficiency of different amplitudes and frontal areas of the foot have been investigated in flutter kicking research. Alley (1952) pioneered investigations into the effects of flutter kicking with normal and reduced amplitudes in relation to active drag. One elite male swimmer used typical and reduced amplitude flutter kicking techniques in freestyle swimming. Both kicks were regulated by an audible signal to ensure a consistent six-beat kick frequency. The results showed that the larger amplitude of flutter kicking produced higher velocity and required smaller towing force than the smaller amplitude of flutter kicking.

2.1.1.2 Foot frontal area of flutter kicking

Fujiwara and Ogita (1997) investigated the effect of foot frontal area and lower limb flexibility on maximal effort flutter kicking at the water surface. It was found that the foot frontal area was highly correlated with distance per stroke and velocity of swimming while there were no significant relationships between knee angle and ankle angle with the rate of stroke, distance per stroke and velocity. The authors concluded that larger foot frontal areas would induce a higher propelling efficiency compared to increasing the flexibility of the lower limbs.

2.1.1.3 Kinematics characteristics of flutter kicking in various learning stages

Kinematic characteristics of flutter kicking in various learning stages swimmers were explored by Sanders (2006). Nine novice swimmers (children) divided into three learning level groups (learning level 1, 2 and 3) and ten skilled swimmers (adults) flutter kicking were analysed. It was found that common faults of beginning swimmers include excessive hip flexion and inadequate hip extension, excessive knee flexion, and inadequate plantar flexion of the ankle. From a hydrodynamic perspective, with respect to the hip, a relatively small range of motion with some extension as well as flexion is required. Similarly, small angles of the knee and ankle and large ranges of motion disrupt the flow in both the hydrodynamic sense and in terms of the flow of motion in a 'whip-like' manner. The results implied that teachers might improve teaching effectiveness by guiding swimmers towards appropriate ranges of motion and indicating to the learner the boundaries in the ranges of motion that should be used. Teachers might also assist learning by emphasizing the need to initiate the kick from the hip so that the motion 'flows' to the feet rather than simply moving the feet up and down.

Symmetry of flutter kicking for seven 12 year old children was explored by Li and Sanders (2005). Statistically significant differences were found across right and left sides in variables including timing of peak hip and knee angular displacements and continuous relative phase. The most efficient swimming comes when an athlete's stroke is symmetrical. The results indicated that coaches and teachers shouldn't ignore the asymmetries in the performance of young swimmers.

2.1.2 Flutter kicking and dolphin kicking

Flutter and dolphin kicking have been compared to determine which is more effective and efficient in freestyle turns (Clothier, 2004). In dolphin kicking the leg kick is synchronized. It appears that the better kick might differ according to the characteristics of the individual swimmer. There is cross practice/training of these two types of kicking in swimming specifically by means of different flippers. For example, mono flippers develop a different swimming style (Soloviev, 1993).

Sheeran (1980) examined the range of motion in the knee and ankle articulations of 14 male university level swimmers during performance of the front flutter, back flutter and dolphin kicking with electrogoniometers attached to the knee and ankle to measure the range, maximum flexion, maximum extension and the mean mid-point of the range. For the knee joint, dolphin kicking produced significantly larger range and degree of maximum flexion than during flutter kicking. At the ankle, no significant difference was observed between the kick styles despite the dolphin kicking trials producing a considerably larger range (13%), and greater flexion and extension maxima.

Lyttle et al. (2000) examined the active drag experienced during underwater kicking. Sixteen experienced male swimmers of similar body shape were towed along the length of a 25 m pool at a depth of 0.5 m underwater at five different velocities (1.6; 1.9; 2.2; 2.5 and 3.1 m/s). At each velocity, subjects performed prone and lateral streamlined glides, prone freestyle and dolphin kicking, and lateral dolphin kicking. It was found that when towed at 2.2 m/s, net forces in the prone streamline position were not significantly different from the kicking conditions (flutter kicking and dolphin kicking), suggesting that there is no advantage for the swimmers to kick at this velocity.

Flutter kick and three dolphin kicks (natural, small amplitude and high frequency, large amplitude and low frequency) for seventeen experienced swimmers (11 male and 6 female) were analyzed when performing maximal effort swimming (Clothier, 2004). The natural dolphin kicking technique was found to be significantly faster than that of the flutter and unpracticed modified dolphin kicking techniques. Comparison between the three dolphin kick styles also highlighted that swimmers performed best at their usual technique. Regression analyses showed that to produce faster natural dolphin kick velocity, an optimal combination of greater foot width and greater vertical displacement of the ankle and foot is required.

2.1.3 Coordination of flutter kicking

The function of flutter kicking is not only as a performance component of competition swimming but also as an effective practice performance for skilled swimmers and learners. The object of practice/training is to optimise movement patterns. This process should begin from early in the development of the skill because inappropriate movement patterns may be difficult to change once they have become established by the individual as a preferred movement pattern.

Sanders (2006) explored the characteristics of the movement patterns common to flutter kicking of skilled swimmers to determine how the movement patterns of swimmers at different levels of a ''learn-to-swim'' programme differ from those of skilled swimmers through investigating inter-joint coordination, variability and biological noise. The data suggested that in learning the flutter kick swimmers converged towards appropriate ranges of motion and coordination of joint actions to yield simple sinusoidal movement topologies related to task achievement. Fourier analysis was applied to determine the frequency composition of the vertical undulations of the hip, knee, and ankle and to calculate the velocity of the body wave travelling caudally from hip to ankle as well as to investigate biological noise, as distinct from variability. An index based on the ratio of hip–knee and knee–ankle body wave velocities showed that the inter-joint coordination of most learners was not appropriate for effective flutter kicking. There was strong evidence to suggest that skilled performance in flutter kicking is characterized by sequencing of joint actions to produce a single sinusoidal body wave moving caudally with not decreasing and preferably increasing velocity, low biological noise, and small variability.

2.1.4 Summary

Most studies of flutter kicking have been at a descriptive level and seldom considered the inter joints (segments) coordination. Although comparisons were made across changes such as flutter kicking amplitude (Alley, 1952), and dolphin kicking frequency and amplitude (Clothier, 2004), the rate of adjustment and adaptation of the human movement systems for these changes are not clear.

In addition, the findings of Fujiwara and Ogita (1997) that flutter kicking with larger frontal areas of the foot in swimming generated longer distance per stroke and higher velocity; and Lyttle et al. (2000) that net forces in the prone streamline position at 2.2m/s were not significantly different from the kicking conditions (flutter kicking and dolphin kicking) provided further understanding of the influences on flutter kick performance.

2.2 Kinematics of swimming with flippers (fins)

Studies of the characteristics of swimming with flippers have provided the essential dynamic information of understanding swimming technique and motion of flippers. Furthermore, these characteristics are the bases and preconditions of swimmer-flipper optimization. The main purposes of using flippers are: (1) for competition (e.g. fin swimming; underwater hockey); (2) training tools for swimming; and (3) underwater exploration and aqua-robotics.

Many swimming coaches use flippers as a regular part of their training program (Muchenfuss, 1985). Using flippers to increase speed helps swimmers to 'hide' all the 'sticking out' parts of the body, looking for speed to influence technique through motion dynamics. This is similar to runners running downhill to find out what interferes with their run. Soloviev (1993) pointed out there are two major advantages of competition or training with flippers: (a) if a swimmer could impart this speed by means of flippers and increased the speed by 15-30 percent, it would be enough for a swimmer (freestyle, backstroke, butterfly) to automatically improve all the minor flaws in technique without losing the functional degree of fitness; (b) developing and strengthening the muscle groups in the legs, back and abdominals simultaneously by increasing the load on them. This effect is difficult to duplicate by gym training. The most important is that all these benefits could be obtained simply by the same training methods in regular swimming.

2.2.1 Classification of swimming flippers

Depending on their purpose, flippers vary in size from 0.7 square meters ('mono-flipper') to smaller than the area of the sole of the foot (toe flippers). In general, the flippers can be classified in terms of the number of flippers (stereo flippers /'bi-flippers' and 'mono-flippers') and the position of wearing the flippers (foot flippers and leg flippers). The stereo flippers are the main flippers in the flipper market. All of the mono-flippers and most of stereo flippers are worn on the foot/feet. However, there is a new type of flippers that is worn on the leg: the 'Shinfin™ Leg Flippers'. They are stereo flippers worn on the legs and have a cambered surface to fit the shape of shank (Fig. 2.1.1).

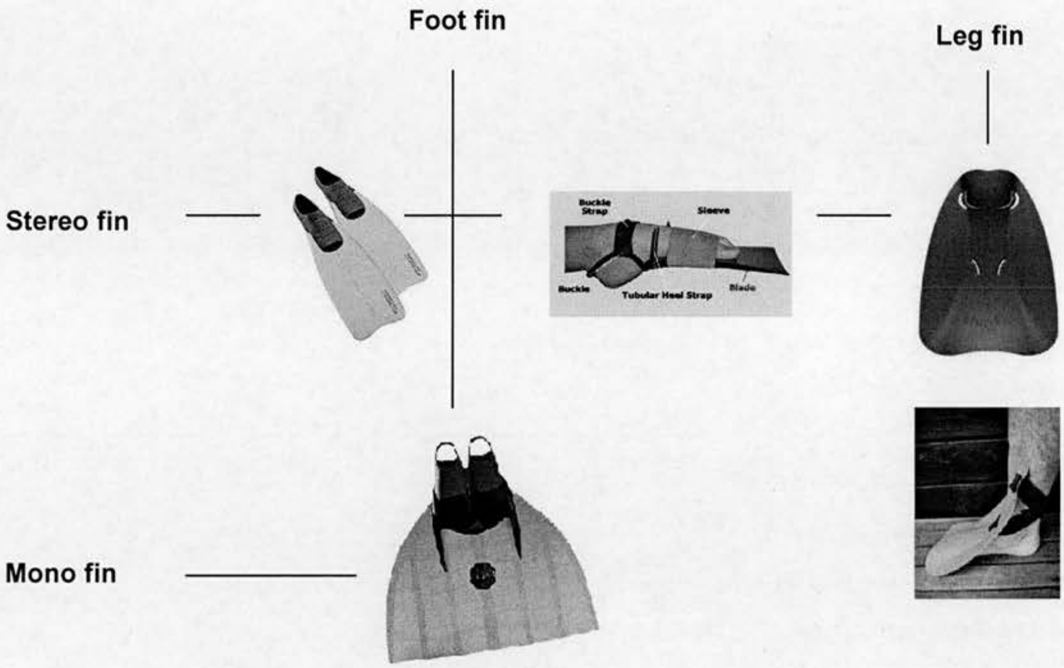


Figure 2.1.1 Classification of flippers in the market

2.2.2 Descriptive kinematics of performance in swimming with flippers

The 'Mono' flipper was created in Russia in 1967 and was widely accepted and dominated in competitive fin swimming since the end of 1970s/early 1980s because the mono flipper is the fastest flipper. Using flippers in swimming could provide much more powerful thrust i.e. higher efficiency of propulsion (Minetti, 2004). Zamparo et al. (2002) estimated that at comparable speed, the energy cost could be about 40% lower with flippers than without flippers. Fin swimming has developed since the mid-20 century (Hoffmann et al., 2002) and has been accepted as an official event of the Olympics in 1986. Fin swimming events in Fin Swimming World Championships are classified into three sub-events: surface (also named fin swimming, using snorkel), apnea (underwater, without underwater breath appliance) and scuba (underwater, using air cylinder) events. The competition items include 50 m, 100 m, 200m, 400 m, 800 m, 1500 m and 4×100 m relay swimming with flippers in a standard swimming pool.

Studies on swimming with flippers are naturally focused on the competition sport – fin swimming. Researchers recorded underwater images of fin swimmers and explored the linear/angular displacement, velocity and acceleration of their represent points (center of extremities' joints) and segments (Li, 1989; Li, 1990; Luk, Hong, Chu and Li, 1999; Szilagyi et al., 1999; Gautier et al., 2004) as well as flippers (Li, 1989; Li, 1990; Luk, Hong, Chu and Li, 1999; Rejman, 1998; Rejman et al., 2002).

Table 2.1.1 Studies of kinematics of fin swimmers and flippers (fins) in standard swimming pools

Studies	Events	Data	Subjects/Skill/ Classify/Gender	Experiment design (record section from start)
Li (1989)	scuba	body+fin	11 experts S/L(M/F)	50m max. speed (25-35m)
Li (1990)	scuba	body+fin	5 experts S/L(F)	50m max. speed (25-35m)
Luk et al. (1999)	apnea	body+fin	8 experts (M/F)	50m max speed (22.5-27.8m)
Szilagyi et al. (1999)	apnea/ scuba	body	2 experts (M)	unclear
Gautier et al. (2004)	surface	body	12 (6 experts/ 6 novices, M/F)	25m per race distance of 100/800m (6m width optical view)

Note: S/L: short/long distance fin swimmer; M/F: male/female fin swimmer

Table 2.1.1 lists studies of fin swimming and flipper kinematics for swimmers in standard swimming pool based on the three sub-events. The results showed the performance of fin swimming is affected by the distance (short or long distance), events (surface or immersion swimming), gender and expertise. As anticipated the average speed of the male fin swimmers were higher than that of females both in scuba (Li, 1989) and surface (Gautier et al., 2004) fin swimming; short distance swimmers higher than that of long distance swimmers (Li, 1989; 1990); experts higher than that of novices and 100 m swimming higher than that of 800 m (Gautier et al., 2004). Both in scuba and surface fin swimming, there were 'whip-like' movements of the lower extremities. The range of vertical displacements increased from hip to knee to ankle joints. In scuba, there was a high correlation between swimming speed and stroke frequency for short distance fin swimmers. This indicated that frequency rather than amplitude of stroke is the key to developing speed. This is supported by the hydrodynamically unstable Woodsward approach (Zheng et al., 1997). Higher upward kicking speed (angular velocity) of the shank for all (male/female, short and long distance) subjects in scuba revealed the effects of asymmetry from anatomical properties of the lower extremity joint and muscle distribution, to the structure of flippers (the two sides of mono flipper are not symmetrical). In surface fin swimming, in contrast to novices, experts have lower amplitude oscillations in upper limbs and smaller bending angles of the ankle joints. These results indicated that experts have more stability in the upper limbs and reduce frontal drag. Luk, Hong, Chu and Li (1999) found that the thigh segment played an important role in fin swimming (apnea). In their test, when the angular velocity of the thigh reached its maximum value, the velocity of the centre of body mass also reached its maximum value. Comparison of the joint vertical displacement and angular displacement of the hip, knee and ankle, revealed that the curves in surface fin swimming differed from those of scuba (Szilagyi et al., 1999). This indicated that there might be different movement patterns between the two events.

Descriptive kinematics can help coaches and fin swimmers to understand their common questions such as whether stroke frequency or stroke amplitude is more important to velocity or body undulation pattern (whole body or part body). The studies discussed above showed there are some different kinematic characteristics of performance in different fin swimming events due to different moving conditions (surface or immersion, with or without snorkel or air cylinder). Naturally, the kinematic characteristics of flippers must also be considered.

2.2.3 Characteristics of flippers during swimming

Underwater video/film is the main way to obtain data regarding the real condition of flippers when fin swimming. It is possible to understand the interrelationship between human performance and flippers. The flipper is an elastic plate. In response to kicking, the flipper is displaced up and down relative to its unloaded position.

2.2.3.1 Flipper's transfiguration during fin swimming

Two variables, flipper transfiguration coefficient (FTC) and flipper transfiguration rate (FTR), were introduced (Li, 1989; Li, Liu and Hong, 1996; Li and Sanders, 2002) to describe the bending of flippers. The flipper transfiguration coefficient indicates the magnitude of a flipper's transfiguration. The distance of the middle point of the line between the foot cover's tips and the middle point of the end edge of the flipper is defined as D. D is a maximum (D_0) when the flipper is not bent and is a minimum when the flipper has the greatest bending. The flipper transfiguration coefficient (FTC) was calculated as:

$$FTC = [1-(D/D_0)] \times 100\%$$

The flipper transfiguration rate (FTR) was defined as the rate of change of D

$$FTR = D/t$$

It was found that the larger the FTC the lower FTR and vice versa. This indicated the elasticity of the flipper is a positive ratio to its transfiguration. It also indicated the importance of the flipper transforming rapidly and the importance of the material mechanical properties of flippers in fin swimming.

2.2.3.2 Flipper's surface strain during fin swimming

Rejman (1998) studied the relationship of the dynamic properties of the mono flipper to fin swimming techniques by measuring the surface strain of mono flippers during swimming. A strain gauge on the middle part of both surfaces of a mono flipper was used to record the forces during fin swimming of 40 male swimmers (four groups, 10 subjects each) in their maximum possible speed for 50 m underwater swimming. The groups were three fin swimmers groups: senior group (mean age: 18.5); junior b (mean age: 16.4); junior d (mean age: 12.2) and one senior swimmer group (mean age; 19.3, crawl and dolphin specialists). The results showed that the time function of force was approximated by a sine harmonic curve. After analyzing the average force amplitudes during downward, upward and whole cycle, according to the laminar flow theory, the authors thought the high constant locomotion speed was decisive for fast swimming. This depended on proportional forces generated by up and downward kicking during the whole kicking cycle.

Rejman et al. (2002) further established the role of flexion of mono flippers. A female swimmer performed 15m fin swimming using an extremely undulating style with a large kick amplitude. It was found that within one kicking cycle, the acceleration periods occurred in the second part of upward kicking and down kicking. The deceleration periods occurred in the first part of upward kicking and during the top part of the forward flipper displacement. It is possible to optimize the kicking performance by using the feedback of the force traces of the flippers.

2.2.3.3 Relationship of flipper's tail velocity to lower extremity performance

The relationship between the lower extremity and mono flipper during short distance apnea was explored by measuring vertical velocity and acceleration of the tail of the flipper, horizontal velocity of whole body center of mass, and angular velocity of the thigh and shank (Luk, Hong, Chu and Li, 1999). It was found that the downward velocity of the flipper tail, the angular velocity of the thigh, and the velocity of whole body center of mass reached their maximum values simultaneously. This indicated that the thigh played an important role in the performance of fin swimming.

2.2.4 Summary

The main focus of scientific research in kicking with flippers is on swimming with mono flippers. The major market of flippers is stereo flippers. Although the lower extremities in mono flipper swimming are moved synchronously and in flutter kicking with stereo flippers are moved alternately, the performance pattern of each lower extremity is similar. Besides giving direct characteristics of swimming with flippers, the real time approaches provided the quantitative evidence of characteristics associated with effective kicking including the 'whip-like' pattern and undulation of the lower half of the body, and established evaluation criteria of skills such as attack angle and stability of upper extremities, and a sine curve pattern of force on the middle part of the flipper. Investigations of flippers regarding the relationships between flipper transfiguration coefficient and flipper transfiguration rate, forces generated by flipper's bending and swimming technique, flipper tail velocity and the kicking performance of lower extremities are helpful in understanding swimming with flippers.

2.3 Design and optimization of swimming flippers

In swimming with flippers, fast swimming depends mainly on the capability of the flippers. It is reported that the physical characteristics of flippers could affect the energy cost and the efficiency of aquatic locomotion (Zamparo et al., 2006).
In the context of this thesis the mechanical characteristics of the flippers are important because the swimmer must adjust their movement pattern to suit the characteristics of the flipper. For example, the optimal kicking frequency and amplitude vary according to flipper characteristics such as flexural stiffness and the natural frequency of the flipper. In other words, the constraint environment, and the movement pattern required to optimize performance in that environment, is influenced by the mechanical characteristics of the flipper.

When comparing ten college swimmers swimming in dolphin kicking with mono flipper, and in prone flutter kicking with a small-flexible flipper (SF), a large-stiff flipper (LS), and without flippers (BF, barefoot), Zamparo et al. (2006) found that the energy expended to cover one unit distance (C) was highest for BF (C=10.6+/-1.8 kJ/m·kg at 0.8 m/s) and decreased by about 50% with LS, 55% with SF and 60% with mono flipper (MF), allowing for an increase in speed (for a given metabolic power) of about 0.4 m/s for MF and of about 0.2 m/s for SF and LS (compared with BF). The comparison of kicking frequency (KF) is: KF=1.6+/-0.22 Hz at 0.8 m/s (for BF) and decreased by about 40% for SF, 50% for LS and 60% for MF. The authors stated that the decrease in KF from BF to SF-LS and MF was essentially due to the increasing surface area of the flipper which, in turn, was associated with a higher Froude efficiency (calculated by computing the speed of the bending waves moving along the body in a caudal direction as proposed for the undulating movements of slender fish).

The study by Zamparo et al. indicated the importance of the surface size of the flippers (e.g. mono flipper (MF) versus stereo flipper (SF and LF)) and the stiffness (small-flexible flipper (SF) versus large-stiff flipper (LS)) with respect to energy cost and the efficiency in swimming. Naturally, optimization of flippers according to the principles of hydrodynamics and materials mechanics has been paid much attention. Although flipper manufacturers advertise the flippers' advantages in terms of its adaptability to the human body and its hydrodynamic efficiency, there are few quantitative analyses of the properties of flippers. In fact, understanding and imitating the function of fish and marine mammals has been the main trend of flipper design and optimization because people believe that these aquatic animals' flippers are excellent solutions that have been optimized over thousands of years of evolution. Thus, it is helpful for coaches/teachers, flipper designers and producers to understand improvements achieved by optimizing shape (include size), stiffness (structure) and hydrodynamics properties on the basis of solid scientific evidence.

It is obvious that the shapes of the stereo foot flipper, mono flipper and leg flipper are different. The material and structure also vary. For example, most stereo flippers are made from direct formation of plastics, while a mono flipper is formed by compressing many layers of fiber-glass. The following review comprises sections relating to the optimization of shape and numerical optimization.

2.3.1 Shape design and optimization based on principles of marine animal locomotion

A number of stereo flippers have emerged to meet the variable requirements of aquatic activities. Stereo flippers vary in size and shape as well as in construction materials and position of wearing. Lewis and Lorch (1979) pointed out that the design of swimming flippers should be based on the principles of marine animal locomotion, that is, keeping movement within the laminar flow condition. The key factors they considered were (a) different swimming speeds need different stiffness flippers, (b) reduction of flipper-tip vortices and (c) minimizing the force transmission from the flippers to the ankle.

2.3.1.1 Design of foot flippers

After analyzing three commercial swimming flippers, Lewis and Lorch (1979) designed two types of V cutout stereo flippers comprising an aluminum fish blade (V cutout) spliced on a base plate (closer to the ankle joint). The V cutout was made to resemble the tail of fish. It was thought that this design could reduce the tip turbulence, to improve the thrust efficiency, and that the splice structure of the flipper could minimize ankle-bending loads due to the decreased moment arm. A flipper performance factor, P

$$P = \text{(distance/kicking cycle)/(change of tank pressure)(time)}$$

was devised to obtain a meaningful comparison of the overall performance of the various flippers. According to Lewis and Lorch, the higher value of the flipper performance factor, the better efficiency (oxygen consumption per unit of velocity) of the flipper. It is interesting that one of the commercial flippers without a V cutout on the edge had the highest value of flipper performance factor and efficiency. The authors argued it might be the size restriction for V cutout stereo flippers: avoiding interference in alternating kicking. It indicated that benefits of this type of flipper could come from increased size. Furthermore, the authors predicted that radically different types of flippers would need to be used if higher speeds and greater ranges are to be attained. This is a good example of why the mono flipper, larger in size and harder in stiffness dominates competitive flipper swimming and a new type of leg flipper has been created since that study. Nevertheless, Lewis and Lorch's concept of evaluating flippers by means of efficiency was applied by several researchers.

2.3.1.2 Design of leg flippers

One interesting flipper is a leg flipper designed by Lewis and Lorch (1979) as shown in figure 2.3.1 (a). The unique characteristic of this type of flipper is that it is worn on the shank by leg straps instead of other flippers that are worn on the feet. The author didn't pay much attention to it because it was thought difficult to use (e.g. aluminum plate too hard) though this type of leg flipper is adjustable and there would be no ankle fatigue.

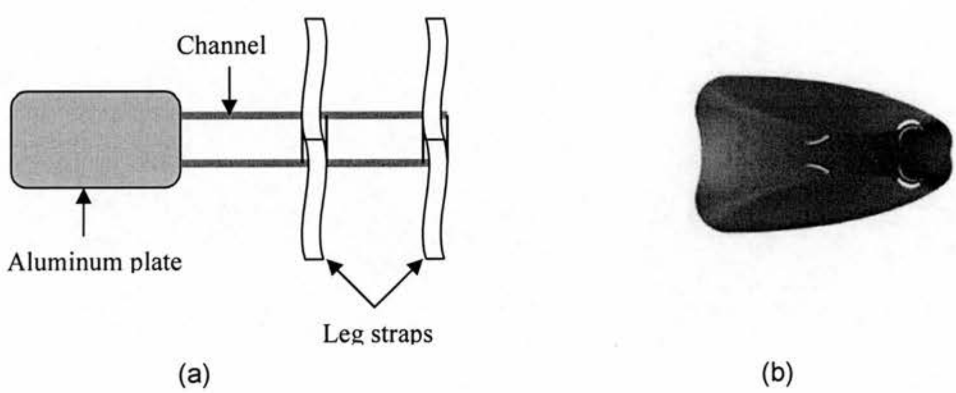


Figure 2.3.1 Leg flipper (a, adapted from Lewis & Lorch 1979) and Shinfin™ Flipper (b, source: www.shinfin.com).

A new type of leg flipper, Shinfin™ Flippers (Figure 2.3.1 (b)) was developed in 2002. Shinfin™ flippers are specially designed to wear comfortably and without ankle fatigue. There is a cambered surface to fit the shape of shank and flexible size to suit different length of leg. It bends along with swimmer's ankle bends. The plate of Shinfin™ flippers are made from high rebound polyurethane and only 300g in weight (around half the weight of conventional foot flipper) which make it strong and light. The philosophy behind the development of the Shinfin™ leg flippers is partly that the advantages of speed and fitness of the lower limbs can be developed without causing disruption to the normal movement pattern. However, whether the movement pattern with the Shinfin™ leg flippers resembles kicking without flippers more closely than foot flippers is yet to be established and will be one outcome of this study.

2.3.2 Numerical design and optimization

Studies investigating how flipper performance can be optimised have yielded important information with respect to the understanding of appropriate movement patterns to maximize performance. In particular, for the purposes of this study, it is important to establish whether the optimal movement pattern of the flipper and the lower extremities is sinusoidal in nature as this underpins the philosophical basis for investigating whether the movement pattern remains appropriate following a change in flipper condition, that is, a change in the task constraint environment.

Luersen et al. (2004) analyzed mono flipper propulsion through coupled fluid-structure simulation and to optimize its flexural stiffness distribution. The optimization was based on three proposed simplification: (a) a two-dimensional unsteady, inviscid and incompressible fluid flow is considered; (b) the swimmer is composed of linear articulated segments, whose kinematics is imposed and identified from experimental data; (c) the mono flipper is represented by rigid bars linked by torsional springs.

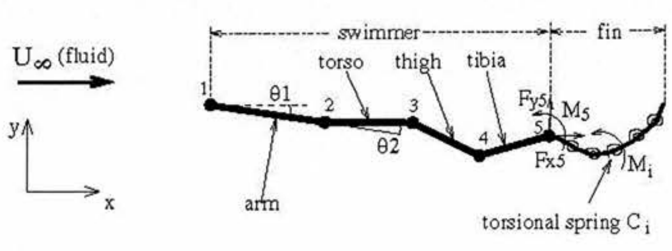


Figure 2.3.2 Swimmer with mono flipper representation (Source: Luersen et al. 2004).

The swimmer was represented by four segments: the arms, the torso, the thighs and the shanks. The mono flipper was modeled by six rigid bars articulated by torsional springs with large rotations allowed (Fig. 2.3.2). All bars had equal and constant linear mass density.

From the analysis of a mono flipper swimmer video, the swimmer movement is approximately segment-wise harmonic. This has important implications for this study in that it supports the approach of analyzing the appropriateness of the movement pattern in terms of sinusoidal undulations of adjoining body segments with phase relationships that ensure a transmission of a body wave caudally.

The modeled equations are:

$$y_1(t) = Y_1^c + Y_1 \sin(2\pi f t), \tag{1}$$

$$\theta_i(t) = \Theta_i^c + \Theta_i \sin(2\pi f t + \varphi_i), \tag{2}$$

where y_1 is the vertical displacement of the hand, θ_1 is the slope between the horizontal and the arms, φ_1 is the phase angle between the vertical hand movement and the arm rotation, θi and φi, i=2, 5 are the angles and the phases between the segments (i-1) and i, respectively. The parameters of Eqs. (1) and (2) (the amplitudes Y_1 and Θi, the mean values Y_1^c and Θ_i^c, the phase angles φ_i, and the frequency f) and the mean swimmer speed (considered to be the free-stream speed) U_∞ are identified from measured vertical displacements of the hand, neck, shoulder, elbow, hip, knee, ankle, and toe of a sprint swimmer. The following values are obtained (Luersen et al. 2003): $U_\infty = 3.0\ m/s$, $Y1 = 0.07\ m$, $Y_1^c = 0.0\ m$, $\Theta1 = 3.4°$, $\Theta_1^c = -1.6°$, $\varphi_1 = -222.6°$, $\Theta_2 = 12.0°$, $\Theta_2^c = 1.6°$, $\varphi2 = -152.8°$, $\Theta_3^c = 20.0°$, $\Theta_3^c = -10°$, $\varphi 3 = 17.2°$, $\Theta_4 = 14.0°$, $\Theta_4^c = 14.0°$, $\varphi_4 = 17.2°$, $\Theta5 = 16.0°$, $\Theta_5^c = -20.0°$ and $\varphi_5 = 107.2°$.

The displacements of the first mono flipper bar ($\theta5(t)$, $x5(t)$ and $y5(t)$) are imposed because they follow the feet. The forces distributed over the flipper are obtained by means of a coupled fluid–structure calculation. The unknowns of the problem are the orientations, the angular velocities and the angular accelerations of the mono flipper's bar joints ($\theta i(t)$, $\dot{\theta} i(t)$, $\ddot{\theta} i(t)$, i = 6, 10), and the efforts at the point 5 (which is approximately the swimmer's ankle), $Fx5(t)$, $Fy5(t)$, $M5(t)$. The mono flipper dynamic equilibrium equations are solved by the Newmark time integration scheme. At each iteration, the system of nonlinear equations is solved using a mixed Newton–Raphson/GBNM scheme. The GBNM algorithm is employed to minimize the residue of the equations when the Newton–Raphson iterations have not decreased the residue.

Figure 2.3.3 shows the vertical positions of the flipper's leading and trailing edges as a function of time for the optimal mono flipper when $P^{min} = -2000W$. Importantly, the traces are sinusoidal curves.

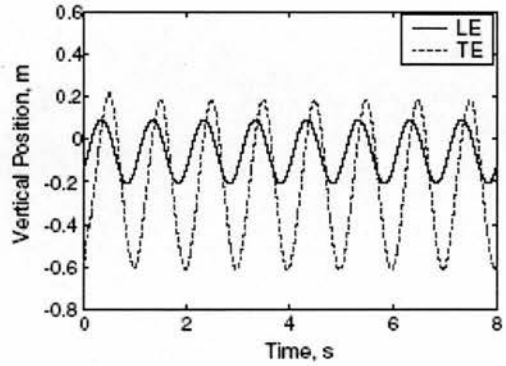


Figure 2.3.3 Evolution of the vertical position of the flipper's leading (—— line) and trailing (…… line) edges for the optimal mono flipper under the constraint $p^{min} = -2000$ *W* (source: Luersen et al. 2004).

2.3.3 Summary

The two parts of the review on design and optimization of flipper represented two typical optimization methods: shape optimization through analogizing aquatic animals, and numeric optimization. The key is to obtain as high as possible efficiency of flippers applied to human swimming. Several characteristics of flippers contribute to the task constraint environment and affect the nature of the movement pattern required to optimize performance. Interestingly, these characteristics are often associated with manufacturer's claims with respect to the advantages afforded to the swimmer, for example, 'strong and light' of Shinfin™ Flippers and distribution of stiffness and thickness.

The optimization of a flipper has to consider the factor of human movement. The numeric optimized motion of the flipper's leading point (equal to ankle joint, tailing point of tibia section) is a perfect sinusoid which is consistent with the findings of Rejman et al. (2002). This result supported the perspective that the vertical displacement-time patterns of the lower extremity segments in skilled flutter kicking are sinusoidal.

2.4 Hydrodynamics of propulsion in swimming with flippers

The mechanisms of propulsion in human swimming kicking have been analogized to the movement of aquatic animals. In recent years, along with the development of numerical methods and the artificial aquatic movement systems, these mechanisms are becoming clearer. The concepts arising from studies of locomotion of aquatic animals are relevant for the study of humans using similar mechanisms to achieve propulsion with and without flippers. In particular, the sequenced oscillations of body parts observed in marine animals has been shown to be used effectively by humans to generate propulsion in both dolphin kicking and flutter kicking (Ungerechts, Daly, and Zhu, 1998; Sanders, Cappaert, and Devlin, 1995; Sanders, 2006).

The key concept of understanding thrust mechanism is reversed Kármán vortex street. Appropriate undulations of swimmer's body parts generate regular vortices from the end of the segmental chain. The reaction of these vortices produces the thrust of swimming (Lighthill, 1969). In studies of the oscillation mode of swimming, as opposed to the undulating mode in which the whole body is involved, the caudal fin is considered to be independent of the rest of the body (Lighthill, 1970; Wu, 1971b). The 'vorticity control mechanism' indicated that an oscillating foil can be used to alter and reposition oncoming vortices and recapture energy contained in those eddies (Triantafyllou, Traintafyllou and Yue, 2000) to generate a reversed Kármán vortex street.

2.4.1 Propulsion in swimming of aquatic animals

2.4.1.1 Swimming modes of propulsion

A good way to recognize properties of propulsion is to understand swimmers' modes in swimming. Classifications of swimming modes based on considerations of the structures employed, their kinematics and mechanics (axial *v.* appendage propulsors), categories based on activity level and duration (continuous cruising *v.* transient swimming) and styles (overall movement patterns, e.g. intermittent *v.* continuous propulsion) are central to the description of the diversity of fish locomotion (Blake, 2004). Breder (1926) classified the propulsive movements (modes) of fish based on 'type' genera employing the suffix 'iform' (*e.g.* anguilliform: based on the eel Anguilla). This classification has been expanded (Lindsey 1978; Webb 1984; Webb and Blake 1985). Webb (1984) classified fishes based on body shape and locomotor mode into three basic categories: body and caudal fin (BCF) periodic, BCF transient (fast starts, turns) and median and paired fin (MPF) swimmers (Figure 2.4.1-

2). Relevant to human swimming, BCF and MPF movement modes provide the concepts of lower and upper extremities respectively.

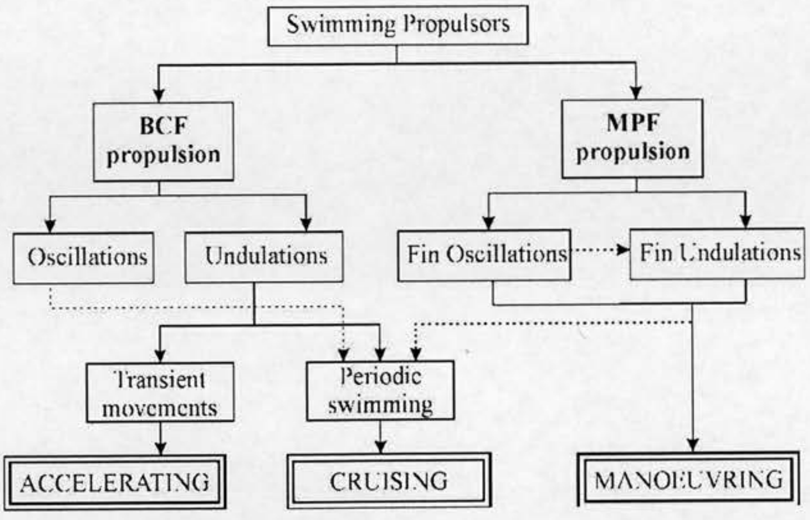


Figure 2.4.1 Diagram showing the relation between swimming propulsors and swimming functions (Source: Webb 1984).

2.4.1.1.1 BCF mode of propulsion

The BCF movement involves a body wave that starts at the front of the body and moves caudally to the tail. Between different animals there exists a continuum of where the body wave starts: at one end of the spectrum is anguilliform, in which a wave travels down the entire body, causing it to undulate. This form has high cost of transport, but fast accelerations and manoeuvrable swimming. At the middle of the spectrum is carangiform, in which the lower half of the body undulates. This form provides fairly fast and efficient, but also manoeuvrable swimming. At the other end of the spectrum is ostraciiform, in which only the tail section oscillates, or pivots relative to the body. This is very fast and efficient form adopted by tunas, dolphins and sharks etc.

Neuhaus et al. (2004) proposed that the use of the legs in underwater swimming can most commonly take on two forms. One form is similar to anguilliform, and is called the dolphin kick (two leg kick synchronized). The other form, which is most like ostraciiform swimming but the legs moving separately and out of phase, is called flutter kicking.

2.4.1.1.2 MPF mode of propulsion

MPF movement also has a spectrum of motions. At one end is rajiform which use an undulation motion. At the other end is labriform mode, in which propulsion is achieved by oscillatory movements of the fin. Within labriform mode, there are two types of movements, drag-based, or rowing, and lift-based or flapping motion. Often, swimmers will use both drag- and lift-based modes, depending on the speed at which they are moving. The drag-based mode is more effective at low speeds and the lift-based mode is more effective at high speeds. The strategy of upper extremities in human swimming is similar to that of labriform mode of underwater animals (Schleihauf, 1979; Toussaint and Truijens, 2005).

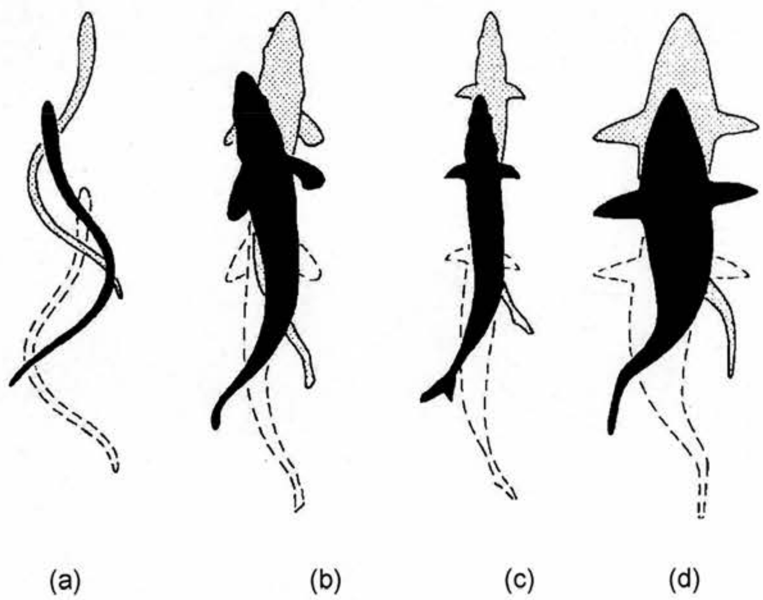


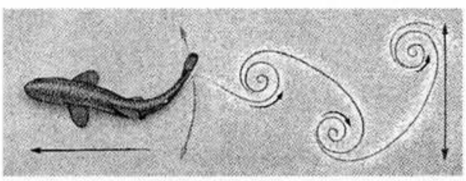
Figure 2.4.2 Gradation of BCF swimming movements from anguilliform(a), through subcarangiform (b) and carangiform (c) to thunniform mode(d). (Source: Lindsey 1978).

2.4.1.2 The approach of propulsion in swimming of aquatic animals

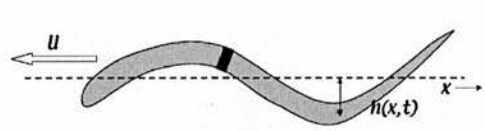
The mathematical/hydrodynamic study on fish and marine mammals started from the foundational works of Lighthill (1960) and Wu (1961). The main attention was focused on the characteristic of vorticity generated by the moving of body or flipper and whether there is a reversed Kármán vortex street as the source of propulsive force. This thought dominates the research of aquatic animals with two movement forms from subcarangiform and carangiform (lower half body undulation) to thunniform and ostraciiform (oscillation mainly by caudal fin) though there are mathematically different treatments of the two movement forms.

2.4.1.2.1 Hydrodynamic approach to undulation mode swimming

Lighthill's slender (elongate) body theory is the most widely applied undulating mode of swimming. In Lighthill's theory, undulating motions pass momentum backwards with each wave - one vortex on each side per full wave is shed into the wake. These reversed Kármán vortex street, first proposed by Lighthill (1969), released regularly from the end of swimmer's undulating part and is thought popularly as the propulsion source of swimming of single or group fishes and marine mammals (Weihs and Webb, 1983; Mŭller et al., 1997; Sfakiotakis, Lane and Davies, 1999) as well as human swimming with flippers (Li, 1998; Li, Hong and Luk, 2000; Li, 2000; Arellano, Pardillo and Gavilán, 2002). Forces produced by undulating motions can be calculated by adding the lateral forces produced by each individual segment according to elongate body theory (Figure 2.4.3).



(a)



(b)

Figure 2.4.3 Reversed Kármán vortex street (a, source: Triantafyllou and Triantafyllou, 1995) and Lighthill's slender body theory (b).

Thrust (*T*) at the edge of tail could be obtained:

$$\overline{T} = m(L)|[(\overline{\partial h/\partial t})w - \overline{w^2}/2]|_{x=L}$$

where $m(x)$ represents the added mass per unit length, L is body length and

$$w = dh/dt = \partial h/\partial t + U(\partial h/\partial x)$$

is the relative fluid velocity at any cross section.

Since the early conceptualization of Lighthill's 'elongate body theory' there has been considerable further development of the model (Lighthill, 1960; 1969; 1970; 1975) to account for large amplitudes of undulation (Lighthill, 1971; Wardle and Reid, 1977); centerline curvature, and the interaction of the caudal fin with the vortex sheets shed from dorsal fins (Wu, 1971a; 1971b; 1971c). Wu (1961) developed a two-dimensional waving plate theory, treating the fish as an elastic plate. Effects of body thickness in relation to thrust and drag have been investigated (Newman and Wu, 1973; Newman, 1973). Katz and Weihs (1978) investigated the effects of body elasticity. Linear and nonlinear extensions of the waving plate theory have also been studied (Cheng, Zhuang and Tong, 1991; Tong, Zhuang and Cheng, 1993; Cheng and Blickhan, 1994; Zhu et al., 2002).

2.4.1.2.2 Hydrodynamic approach to oscillation mode swimming

The studies on oscillation mode swimming (e.g. dolphin, shark) include work on oscillating aerofoils and consider the caudal fin (high aspect ratio, e.g. lunate fin) independent from the rest of the fin body (Lighthill, 1970; Wu, 1971b). The model has been further developed from rigid fin to a three dimensional flexible fin with large or small amplitude in different shape (Sfakiotakis, Lane and Davies, 1999).

A novel form of propulsion based on unsteady flow control has emerged in recent fifteen years (Triantafyllou, Triantafyllou and Yue, 2000; Colgate and Lynch 2004; Beal et al., 2006). Evidence suggests that many fish exploit the natural instability of the flow energetics to assist them in propulsion and maneuvering. By tuning their own kinematics, the fish is able to swim efficiently, to generate large thrust and tuning force, and to move silently through the flow with minimal wasted energy (Beal et al., 2006).

The implication of the above for human swimming with and without flippers is that while the rudiments of the required motion are familiar to the system, that is, a sequencing of sinusoidal oscillations to produce a body wave moving caudally, fine tuning to optimise the interaction of the body with the vortex environment may be required when switching between flipper and no-flipper conditions.

2.4.2 Propulsion in human swimming with flippers

The knowledge arising from studies of locomotion of aquatic animals can now be applied to human swimming. In particular generation of the reversed Kármán vortex street and re-use of the energy to gain propulsion is relevant.

2.4.2.1 Reversed Kármán vortex street

The concept of 'reversed Kármán vortex street' in swimming with flippers and underwater leg kicking has been investigated by several researchers (Li, 1989; Li, 1998; Ugerechts, Daly and Zhu, 1998; Ungerechts, Persyn and Colman, 1999; Li, 2000; Li, Hong and Luk, 2000; Ungerechts, Persyn and Colman, 2000). As showed in Figure 2.4.3 (a), when the flipper is at the highest position and commencing the downbeat, there is an anticlockwise vortex that generates backward impulse to the water. Therefore, the water gives a reaction to the flipper (human body). When the flipper is at the lowest position and commencing the upbeat, there is a clockwise vortex that also generates backward impulse to the water. Thus, the water gives a reaction to the human body again.

Tail vortices must be generated in a controlled way: on the one hand the quantity of vortices are required from which to gain propulsion; on the other hand, one needs to avoid producing vortices which contain great energy that cannot be re-used for propulsion. A balance must be attained. This balance depends in part on the interaction of the vortices with the moving body parts and emphasises the importance of optimization of the movement pattern in flutter kicking.

2.4.3 Summary

The key concept arising from this review is that swimmers must find/produce the appropriate vortex distribution (reversed Kármán vortex street) whether in undulating mode (dolphin kicking) or oscillating mode (flutter kicking) swimming. The balance point is to produce enough 'useful' vortices to overcome resistance and to avoid excessive vortex energy that cannot be re-used. Efficient propulsion relies on optimal interaction between a swimmers' body and flippers and the fluid flow environment.

Considerable progress has been made in recent years towards understanding of generation of propulsion by harmonic oscillation of a foil. The result, together with the results of kinematics of the flipper in section 2.2 and numerical optimization of mono flipper in Section 2.3, indicates that the optimal movement pattern in flutter kicking is one in which there is a sequence of body actions so that a wave travels caudally along the body and culminates in an oscillation of a foil (flipper) in such a way that a reversed Kármán vortex street is generated and utilised appropriately to provide propulsion.

2.5. Coordination development in the perspective of dynamical systems theory

Dynamical systems theory arises from the mathematical study of the behavior of complex systems. Dynamical systems theory of human movement, which focuses on patterns of motor development, is based on two theoretical approaches: the study of complex and nonlinear systems (e.g. thermodynamics) and the work of Bernstein (1967) who looked at the ensemble nature of human movement (Schoner and Kelso, 1988; Clark, 1995; Goodway, 2002).

2.5.1 Dynamical systems vs. dynamical systems theory on human movements

2.5.1.1 Dynamical systems

Dynamical systems are mathematical objects used to model physical phenomena whose state (or instantaneous description) changes over time. These models are used in financial and economic forecasting, environmental modelling, medical diagnosis, industrial equipment diagnosis, and in a host of other applications. The characteristics of a dynamical system are described by 'system state' (an instantaneous description of the system at a given time which is sufficient to predict the future states of the system) and 'evolution of the system state over time' (sequence or continuous trajectory through the space of possible system states).

2.5.1.2 Dynamical systems theory on human movement

Dynamic systems theory has emerged in the human movement science as a viable framework for modelling athletic performance. From a dynamical systems perspective, the human movement system is a highly intricate network of co-dependent sub-systems (e.g. respiratory, circulatory, nervous, musculoskeletal, perceptual) that comprise a large number of interacting components (e.g. blood cells, oxygen molecules, muscle tissue, metabolic enzymes, connective tissue and bone). In dynamical systems theory, movement patterns emerge through a process of self-organization (Glazier, Davids and Bartlett, 2003). That is, movement systems have an autonomous ability to seek stable solutions that may be more complex, efficient and effective.

Bernstein (1967) viewed motor skill learning as the mastery of redundant biomechanical degrees of freedom and he proposed three stages of learning in physical activity. The first stage is characterized by freezing the limb and torso segments in movement execution, thus reducing the number of degrees of freedom at the periphery to a minimum. The second stage is characterized by unfreezing the degrees of freedom so that eventually the performance incorporates all useful degrees of freedom at the periphery. The third stage corresponds to the learner utilizing and exploiting rather than resisting the passive (reactive, inertial) forces that arise from the interaction of the organism with its environment (Ko, Challis and Newell, 2003).

2.5.1.3 Concepts and parameters in terms of dynamical systems theory

In terms of dynamical systems theory, the emergence of a coordination pattern could be simplified by the formation of an 'attractor'. The qualitative changes in patterns that are described by collective variables (such as relative phase) are elicited by relevant control parameters (such as cycling frequency). The dynamics of the system are captured formally by an equation of motion of the collective variables (Schoner, Zanone and Kelso, 1992; Goodway, 2002; Swinnen, 2002). The following sections elaborate the terms: order producing (self-organizing), reducing degrees of freedom, attractors, collective variables, phase shift and control parameters, to outline movement analysis under the framework of dynamical systems theory.

2.5.1.3.1 Order producing

Order producing refers to the system's self-organizing. Dynamical systems are able to seek and find stable solutions that may be more complex, efficient and effective. For example, inconsistent systems may be driven to be consistent and simple and ineffective movement patterns may be stimulated towards more complexity and effectiveness by constraints associated with the environment, the task itself, or the organism.

Based on the characteristics of dynamical systems, new forms of behaviour can arise out of old forms by perturbing the system. The perturbations can disrupt the stability of old forms and push the system to develop new more effective patterns of movement. Constraints such as those associated with the organism, environmental, or task may act as perturbations.

2.5.1.3.2 Reducing degrees of freedom

In a dynamical system, the many parts of a system are free to 'assemble' in many patterns - many degrees of freedom are present in the movement (e.g. a ball can be thrown in many different ways). Under certain conditions these individual degrees of freedom stop acting randomly and begin to cooperate (i.e. the degrees of freedom decrease as the elements of a subsystem cooperate in a given condition). Closed sports skills represent the ultimate in reducing the degrees of freedom (e.g. golf swing, dart throw, running, gymnastics). Consistency is critical in most sports. Skilled performers demonstrate much greater control over the degrees of freedom than novice performers. The reduced dimensionality/complexity of the human system encourages the development of functionally preferred coordination (attractor) states to support goal-directed actions. Thus, it is important to know what variables influence degrees of freedom.

2.5.1.3.3 Attractors

The particular patterns emerging out of the many possible are said to result from 'dynamical attractors'. Attractors are 'softly assembled' and can be both stable and unstable forms of movement. Within each attractor region (the 'neighborhood' of an attractor), system dynamics are highly ordered and stable, leading to consistent movement patterns for special tasks. Variation between multiple attractor regions permits flexible and adaptive movement system behaviour, encouraging free exploration of performance contexts by each individual.

2.5.1.3.4 Collective variables

In a given movement pattern, the movement system with multiple degrees of freedom is 'compressed' under certain conditions to reduce the number of degrees of freedom. The variables which exert this compression are called the collective variables. The collective variable is the dimension of the system that expresses the underlying pattern that emerges from cooperation of the elements. Scientists pay much attention to the collective variables over time because they can reflect the processes underlying coordination development.

It has been proposed that the very many components of the human movement system are combined into functional units called coordinative structures or synergies (Kugler et al., 1982; Mitra et al., 1998). These are temporarily assembled functional units. It is a collective, task-specific organizational state achieved by the system and not restricted in the anatomical sense (Balasubramanian and Turvey, 2004).

2.5.1.3.5 Phase transition

A phase transition is when a movement system shifts between qualitatively different attractor states (i.e. moving from one pattern of movement to another). The phase shift occurs as a result of gradual changes in the subsystems operating on a system and influencing the movement pattern. Using the collective variable we can measure and determine what influences the movement system.

2.5.3.1.6 Control parameters

A control parameter is a specific variable that could influence a system to move from one form of movement to another. Control parameters can be internal (e.g. organic) or external (e.g. environmental) variables. Once the control parameter reaches a critical point a phase shift occurs and a new movement emerges. Understanding what variables influence or 'control' the development of specific skills helps to facilitate learning or to compensate by adapting equipment or the environment for control parameters that may retard the development of motor skills.

2.5.2 Constraints led coordination development

From a dynamical systems perspective, movements emerge from a system that is surrounded by constraints. The concept of constraints was firstly classified systematically by Newell (1986) then refined and extended (Newell, 1996; Araújo et al., 2004). Newell (1986) emphasized that skilled performance, as reflected in the optimal pattern of coordination and control, is determined by the interaction of the organismic, environmental and task constraints (Figure 2.5.1). Motor learning emerges from the interplay of constraints which shape behavior towards an optimal solution.

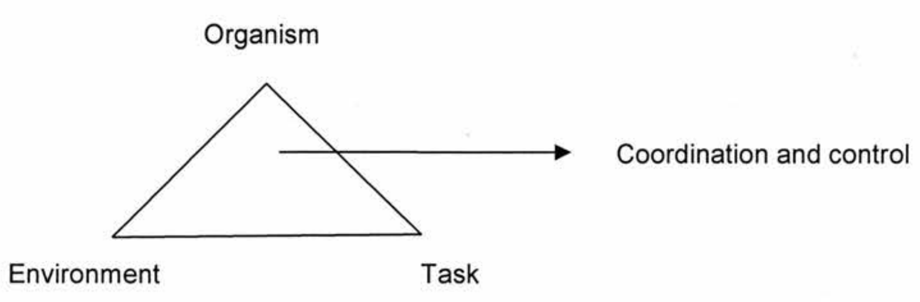


Figure 2.5.1 A schematic diagram of the categories of constraints that specify the optimal pattern of coordination and control (Adapted from Newell, 1986).

In the coordination development for performance in a competition setting, performers not only need to understand the condition in which the skill is to be performed but also to practice in a way that enhances the development of coordination for performance in competition settings. Thus, it is important to know how individuals can adjust to constraints to maintain optimal performance of the task.

2.5.2.1 Organismic constraints

Organismic constraints refer to existing structural and functional characteristics of the individual. Structural constraints are relatively time independent organismic constraints such as height, weight and shape because of their very slow rate of change with development of coordination. Contrast, those relatively time dependent organismic constraints such as connective strength of synapses in the brain, cognitions, motivations and emotions are assumed to be functional constraints. Customary pattern of thought by an athlete, levels of practice or defects in the visual system can act as constraints to channel the way that particular performance goal is approached. Such unique characteristics represent resources that are brought to bear on the task problem or limitations that lead to individual-specific adaptation by the performer.

2.5.2.2 Environmental constraints

Environmental constraints are generally recognized as those constraints that are external to the organism. Any constraint on the organism-environment interaction that is not internal to the organism can be viewed as an environmental constraint. The features of environmental constraints are that they are not manipulated by the experimenter and are relatively time independent. Environmental constraints could be divided into physical constraints, such as gravity, temperature, light and socio-cultural constraints such as peer groups, cultural norms, social expectations and values. Typical examples of physical environmental constraints include different effect between of walking on land and in water due to large difference in density between air and water (e.g. hydrotherapy); shifts in geographical location on earth change the impact of gravity (e.g. altiplano training) on the performer.

2.5.2.3 Task constraints

Task constraints are usually more specific than environmental constraints. The categories of task constraints are: goal of the task, rules of sport, implements or tools to use during performance, pitch and boundary markings, augmented information sources and other instructional aids such as video. In sports, task constraints are significant because coaches and teachers can manipulate them to help learners search for functional and individualized coordination solutions. Adaptive learning allows athletes to cope with novel task constraints as performance conditions change. It needs to be emphasized that the interaction of main classes of constraints on the movement system during goal-directed activity results in the emergence of optimal behaviors. For example, how a basketball dribbler decides to act in a one versus one sub-phase depends on relevant constraints at any one time, including the information available on court, current fitness levels, physiological status, the nature of the practice surface and intensions (e.g. to score points quickly or to maintain possession of the ball, and the interaction with the opponent).

Skilled behavior can be characterized as movement that is adaptable yet resistant to environmental forces which could perturb the stability of the motor system. Movement solutions evolve over time as a consequence of the constraints on system behavior in any given context. Clearly, intra-individual variability in the perceptual-motor landscape reflects the constraints on each individual performer, supporting the need to adopt a constraints-led perspective on skill acquisition. Task constraints play important roles in human movements. Coaches/teachers can manipulate them to help performers search for functional and individualized coordination solutions (Araújo et al., 2004). More specifically, the significance of task constraints in human movement (Clark, 1995) is that they 'shape' the performance.

2.5.3 Adaptation of the human movement systems to changes in task constraints

Dynamical systems are 'open' systems. Their forms could be influenced by many factors in their environment. It has become clear that the influences that guide the form emerging from the system should be considered as constraints on system behavior (Newell, 1986). A key factor in understanding the emergence of skilled behavior in sport is concerning the role of the coach in structuring task constraints and organizing practice environments (Schmidt and Lee, 1999, Araújo et al., 2004). One would assume that practice under a variety of task

constraints that one may encounter in a competition setting would improve a performer's ability to adjust rapidly to the task as it changes due to changing constraints.
Thus, the investigation of the adaptation of human movement systems to changed task constraints can help to understand not only the system's stability in the disturbances (change task constraints) but also the system's evolution (process) of coordination development to a new movement pattern (if any). There are a few studies in the literature on adaptation to changed task constraints.

Nourrit et al. (2003) argued that the duration of most studies rarely went beyond the very first adaptation to the task and as such did not allow qualitative modifications of the behavior to appear. Thus, evaluating the coordination of human movement systems under different task constraints and investigating the learning process, would enable us to deeply understand the skill acquisition of performers. Furthermore, it could lead to better understanding of how task constraints can be designed to assist in developing adaptability to change constraints on task in competition.

2.5.3.1 Changes on soft support surface: snowshoeing

Recently, there has been an increase in popularity and participation in the sport of snowshoeing. Snowshoeing is an event of running on snow course with the snowshoe, a larger slipper to help the athletes enhance their fitness level during the winter months through a full body workout. It also could be applied in grassland or sand conditions. Physiological studies showed fitness benefits that could be obtained by means of snowshoeing. It is interesting that many studies were focused on the comparison of different constraint conditions such as with and without snowshoes (Connolly, Henkin and Tyzbir, 2002), flat and inclined snowshoeing/males and females (Schneider et al., 2001) and snowshoeing with different types of snowshoes (Dalleck, Devoe and Karvitz, 2003). Physiological changes corresponding to the changes of constraint indicated there might be coordination adaptations of the human movement systems. Only one study was found in the literature on the kinematics adaptation to the snowshoeing (Luk, Fung and Hong, 2005).

Kinematic analysis of snowshoeing on sand showed some similar characteristics in changing of running velocity to over-ground running (Luk, Fung and Hong, 2005). In this investigation on the first and fifth lap when snowshoeing on a outdoor beach volleyball court for five laps with maximum speed, they found trends including (a) the stride frequency decreased as the running velocity decrease; (b) both cycling length and stride length were significantly decreased when running from high to slow velocity; (c) the vertical oscillation of center of body mass (CG) increased with decreased running though snowshoeing seems to have large vertical CG oscillations at any given speed. Moreover, the authors assumed that technique employed for snowshoeing at 3.50 m/s is almost equal to over-ground running at 8 m/s due to them having the same maximum thigh angle.

The studies on snowshoeing showed that there were biomechanical and physiological adaptations of the human movement system when running with snowshoes. This adaptation might be varied over time (Luk, Fung and Hong, 2005). It is not clear whether or not the same movement pattern was retained or a new movement pattern developed in response to changed task constraints. It was also not clear how quickly the participants adapted to a change in task constraint.

2.5.3.2 Changes in slope of the surface: inclined running

When inclined running, specifically downhill running, the running technique should be adjusted due to the effect of gravity. It requires much more control of body position: a proper upper body - lower body (feet) interaction, a general reduction of efforts and a much higher cadence (Romanov, 2005). One benefit of inclined (downhill) running is to help to increase the cadence by recruiting fast-twitch muscle fibers (Watson, 2005). Based on gravity analysis, running on a sloping surface (downhill) may induce higher risk of injury on lower extremities. Thus, downhill running is a typical practice of performance improvement and injury prevention.

Compared with level running at the same stride frequency, inclined running provides enhanced muscular loading of key mono- and bi-articular muscles during both swing and stance phases (Swanson and Caldwell, 2000). Larger normal impact force peaks and parallel braking force peaks downhill running substantially increases the probability of overuse running injury (Gottschall and Kram, 2005).

Adjustment of movement systems to the changed constraints in inclined running is very important for preventing injury. Yakozawa, Fujii and Ae (2005) reported the runners on steep downhill conditions would be able to avoid excessive impact load by contacting with the ground in more extended hip position and increasing knee flexion velocity after the foot contact. Further, the muscle fatigue taking place in long distance downhill running and affecting impact shock attenuation is accompanied by an increasing vertical excursion of the hip in the stance phase of running which enables to modulate the vertical stiffness of the body via vertical displacement, somewhat compensating for the reduced muscle ability to attenuate impact (Mizrahi, Verbitsky and Isakov, 2001). However, these studies didn't consider the rate of adjustment of the movement systems to the changes of constraint conditions.

Hardin, van den Bogert and Hamill (2004) reported that there were adaptations in kinematics to changes in stiffness of the surface and footwear for running. It is found that increased midsole hardness resulted in greater peak ankle dorsiflexion velocity. Increased surface stiffness resulted in decreased hip and knee flexion at contact, reduced maximal hip flexion, and increased peak angular velocities of the hip, knee, and ankle. Over time, hip flexion at contact decreased, plantarflexion at toe-off increased, and peak dorsiflexion and plantarflexion velocity increased. It was concluded that lower-extremity kinematics adapted to increased midsole hardness, surface stiffness, and running duration. Changes in limb posture at impact were interpreted as active adaptations that compensate for passive mechanical effects. The adaptations appeared to have the goal of minimizing metabolic cost at the expense of increased exposure to impact shock. It appears that in this study, adaptations to change in task constraints occurred rapidly.

2.5.3.3 Changes in altered support surface: standing and jumping

Clear reports on the adaptation to the changed constraints in standing balance on a moving support surface were presented by Ko, Challis and Newell (2003) and in drop jumping by Sanders and Wilson (1992).

Ko, Challis and Newell (2003) studied standing balance on a moving platform that was sinusoidally translated in the anterior-posterior direction for 30 trials on day 1 and 10 trials on day 2. At the beginning of practice, the motion of the torso and limb segments was less coherent in the attempt to compensate for the movement of the support surface in retaining a balance posture. With practice, the organization of a compensatory posture coordination mode (adaptation) became highly coherent and also progressively utilized the passive, inertial forces generated by the movement of the support surface. With respect to this thesis, the results indicated that the adaptation to the change in task constraints was not immediate and are related to the nature of the task and constraints.

In adapting to a change in surface compliance in a drop jumping task (Sanders and Wilson, 1992), the movement pattern was still changing towards the end of the 190 trials on the unfamiliar surface. With the exception of one subject improvement was still occurring towards the end of the practice period. The authors concluded that there was a gradual shift in the angular kinematics away from the patterns associated with jumps from the hard surface. In particular, there was a reduction in flexion of the ankle, knee, and hip following first contact.

2.5.4 Evaluating coordination of human movement systems

Recent development of dynamical system theory has been accompanied by the application of useful tools to identify changes in movement patterns. These include angle-angle plots, phase plane analysis, and analysis of continuous relative phase (Burgess-Limerick, Abernethy and Neal, 1993; Hamill, Haddad and McDermott, 2000; Robertson and Caldwell, 2004; Kurz and Stergiou, 2004).

2.5.4.1 Angle-angle plots

Angle-angle plots, that is, one angle plotted against another, for example adjoining body segments or adjacent joints, have become popular as a means of showing how the interaction of body parts changes across conditions and testing occasions or varies among individuals or groups (Burgess-Limerick, Abernethy and Neal, 1993; Hamill, Haddad and McDermott, 2000; Robertson and Caldwell, 2004). While these are useful for showing the angular displacement relationships and couplings between segments or joints they do not directly contain temporal information about when particular orientations are achieved.

2.5.4.2 Phase plane

Phase planes (phase plot, phase portrait) describe the behavior of the dynamical system by plotting linear or angular displacement against its rate of change, that is linear or angular velocity. It is very useful for showing differences between movement patterns. When the axes are normalized a phase angle can be calculated that provides quantitative data to discriminate between movement patterns. The phase angle can then be used to determine the temporal relationship, that is, the coupling, between two segments or joints.

2.5.4.3 Continuous relative phase

Continuous relative phase produces the relative phase angle (the spatial and temporal coupling) of a pair of joints throughout the entire movement cycle. This angle is obtained by calculating the four-quadrant phase angle from a phase plane of each joint. The time histories of the displacement and velocity data obtained from each joint must be normalized by subtracting the mean and can also be rescaled to compare movement patterns independent of amplitude of the motion. Then continuous relative phase can be calculated by subtracting the phase angle of one joint from that of the other joint at corresponding time intervals throughout the entire cycle. Continuous relative phase can provide an indication of the type of relationship (in phase or out of phase) between the pair of joints (Burgess-Limerick, Abernethy and Neal, 1993; van Emmerik and Wagenaar, 1996; Hamill et al., 1999; Hamill, Haddad, and McDermott, 2000; Glazier, Davids and Bartlett, 2003; Peters et al., 2003; Kurz and Stergiou, 2004). Continuous relative phase has the advantage over phase plane plots and angle-angle diagrams in that the temporal information is retained in the plot by having the abscissa as either real time or time normalized to percents of the cycle or period of interest.

2.5.4.3 Variability

Measurement of variability is used to explore the various modes of locomotion (Hamill, Haddad, and McDermott, 2000; Heiderscheit, Hamill and van Emmerik, 2002; Kurz and Stergiou, 2004). In the past it has been proposed that the variability in the joint kinematics from one movement cycle to the next (e.g. gait) is the result of biological noise in the movement systems. However, recent investigations have determined that these fluctuations are not random noise superimposed on top of the control system. Rather these fluctuations have a deterministic structure. As such they can provide clues as to the state of the system and its response to perturbations such as change in task constraints. The researchers have noted that points of transition from one mode of locomotion to another are characterized by increased variability in the kinematics. Additionally, these studies have indicated that variability may be related to the health and stability of the movement systems.

In this study quantification of variability is used to indicate whether the system may be constrained to a 'safe' and familiar movement pattern, is struggling to find a stable 'attractor' for a new and more appropriate movement pattern, or is 'exploring' to search for a better solution to the problem of optimising the performance.

2.5.5 Summary

This section outlined human movement coordination from the perspective of dynamical systems theory: from the terms and underlying concepts of dynamical systems theory, through the significant role of constraints in human movement coordination, and the general strategy of searching for optimal movement solutions from a dynamical systems perspective. Common methods of quantifying coordination were briefly described.

The issue central of the present study, that is, how rapidly the human movement system responds to change in task constraints, was addressed in the light of the limited literature. The review revealed that this response varies according to the task and the constraints with rapid adjustment in some cases and slower adjustment in others.

CHAPTER 3

METHOD

3.1 Subjects and Research Design

3.1.1 Subjects' characteristics

Nine male squad swimmers were recruited as subjects. The age, height, and weight of the subjects are shown in Table 3.1.1. Subjects agreed to participate after reading a description of the project (Appendix A). Due to the ages of the swimmers, their parents signed informed consent forms in accordance with the ethics committee protocols established by The University of Edinburgh. Subjects completed a questionnaire about their training history including their previous use of flippers (fins). All subjects were competitive age group swimmers with at least one year of training for competition. All had experience with kicking with foot flippers, having used them many times in training, and no experience with using the leg flippers.

Table 3.1.1 Subjects characteristics

Group	Subjects	Age	Height (cm)	Mass (kg)
Leg flipper (LF)	S1	12.25	150.5	42.15
	S2	13.00	165.0	51.80
	S3	12.33	166.0	49.75
Foot flipper (FF)	S1	12.25	165.5	48.50
	S2	12.17	154.5	37.10
	S3	11.00	160.0	47.25
Control (CO)	S1	13.17	165.0	49.30
	S2	11.00	149.0	35.50
	S3	14.00	167.0	50.35

3.1.2 The skill level of subjects

An indication of the level of skill of the subjects in barefoot kicking prior to the experimental intervention was sought to aid subsequent analytical methods, statistical approaches, and interpretation of results. From the study of Sanders (2006) there are two main variables that are associated with skilled performance. These are a 'velocity index' and the percentage power in the fundamental Fourier frequency of the vertical oscillations of the hip, knee and ankle. The velocity index is the ratio of knee-ankle body wave velocity and hip-knee body wave velocity. Velocity index is close to 1.0 and with small within-subject variability among skilled swimmers. Percentage power in the fundamental Fourier frequency is close to 100% with small variability among skilled swimmers. Therefore, these variables were quantified as described in the 'methods of calculating variables' section.

3.1.3 Research design

Six of the swimmers were randomly assigned to either a 'leg flipper' group (LF) or 'foot flipper' group (FF). The remaining three swimmers comprised the 'control' group (CO). The LF and FF groups participated in a pre-test (pre training) comprising five trials without flippers, sixty trials with their flippers and a post-test comprising 10 trials without flippers. To avoid the possible confounding effect of fatigue, subjects were limited to 10 trials per day of testing. This meant that testing was conducted on eight separate days, one for each of the pre-test and post-test, and six days of 10 trials per day using the flippers. The CO group completed the pre-test and post-test only. The testing was conducted over a period of five weeks as shown in Figure 3.1.1.

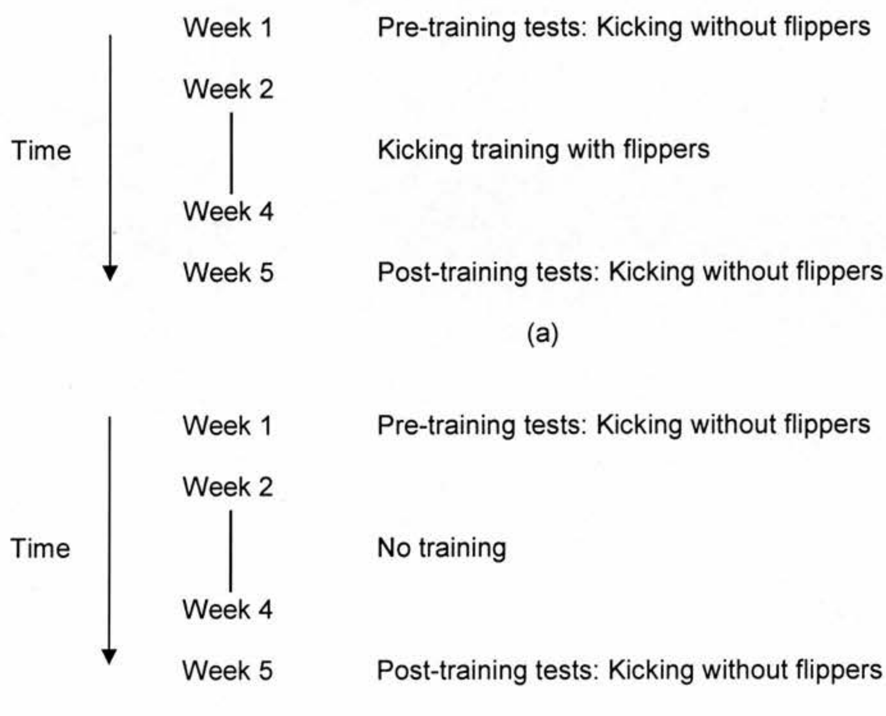


Figure 3.1.1 Measurement setting up: (a) Experimental groups (LF and FF groups) and (b) control group.

3.2 Video Data Collection

3.2.1 Equipment

A video camera (KY32 CCD, JVC Corporation, Japan) in a waterproof housing recorded the underwater motion of the swimmers at 50 fields per second. The camera was positioned perpendicular to the line of the swimmer's motion. The camera capture area was adjusted so that the entire swimmer was recorded for a minimum of three kicking cycles. A kicking cycle was defined as the period from the lowest position of the foot marker following the downbeat to the equivalent position in the next cycle (Figure 3.2.1).

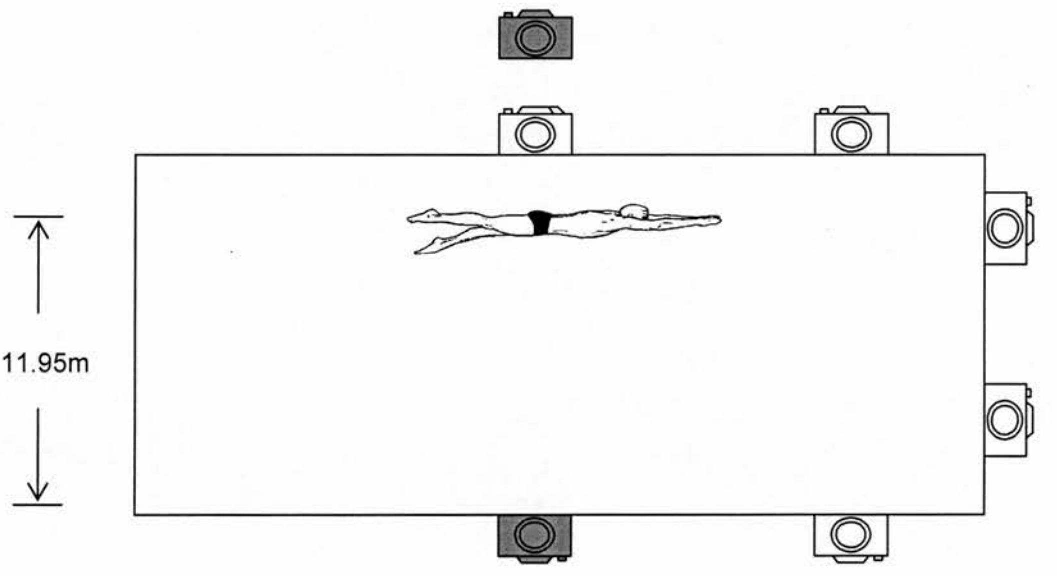


Figure 3.2.1 The locations of the video recording system. Used cameras, not used cameras.

The leg flippers were 'Shinfin™ Leg Flippers' (middle size). All subjects in the LF group wore the same size flippers. All swimmers of FF group wore 'WIN™' foot flipper and all used the same size (6-8). The dimensions of the flippers are showed in Table 3.2.1.

Table 3.2.1 Flipper size parameters

	Trade mark	Size	Max length cm	Max width cm	Surface area cm^2
Leg flipper (LF)	Shinfln™	Middle	38.2	22.8	710.48
Foot flipper (FF)	WIN™	6-8	34.8	19.00	401.57

3.2.2 Preparation of the subjects

Prior to recording, black waterproof markers were placed on anatomical landmarks on the skin surface of the right side of the body such that an imaginary line from the camera through the marker would pass through the joint axis of rotation. Participants were asked to flex and extend the joint to assist in identifying these points while the axis was palpated by the researcher. The process was aided by identifying landmarks known to correspond closely with the joint axes of rotation. These were the greater trochanter of the hips; lateral condyle of the femur for the knees; lateral malleolus for the ankles, and the metatarsal-phalangeal joint. To estimate the camera to joint axis line for the shoulders, the participants emulated the prone swimming position with the arms extended in a streamlined position.

At the beginning of each session, the length of the thigh of each swimmer was measured from the center of the hip joint to the knee joint. This length was used in subsequent scaling in accordance with the method described by Clothier et al. (2004).

For the trials in which leg flippers were worn (LF group) the experimenter fitted the flippers in accordance with the manufacturer's guidelines ensuring consistency with regard to position and tightness of the straps.

3.2.3 Testing Procedure

On each testing session swimmers swam 10 trials perpendicular to the camera axis at a distance of 8m from the camera. Direction was alternated and only the odd trials were recorded for subsequent digitising and analysis. This meant that the right side of the body was recorded five times during each session.

Swimmers were instructed to submerge prior to, and surface after, imaginary lines perpendicular to the wall from markers placed 5m either side of the camera at the water's edge. While submerged, swimmers were required to kick with a flutter kick (no arm front crawl style kicking) to maximise their speed. Swimmers had at least 15 seconds rest between trials with commencement of each trial dependent on swimmers expressing readiness to continue.

3.3 Data analysis

The process of data analysis is illustrated by following flowchart (Figure 3.3.1).

3.3.1 Digitising

The landmarks were digitised manually using an APAS System (Ariel Dynamics Ltd., CA USA) to yield unscaled and unsmoothed two dimensional positional data in pixel units. The period digitised was approximately 15 frames beyond either end of a kicking cycle. These data were then input to a custom designed program (Sanders, 2006) in MATLAB (The MathWorks, MA USA) to calculate the variables of interest.

3.3.2 Scaling

The MATLAB program calculated the thigh length in pixel units using the Pythagorean theorem for each frame and then averaging across the sample of digitised frames. The actual locations of all digitised points were then determined by dividing the pixel locations of the points by the thigh length in pixel units and multiplying by the known thigh length in metres.

3.3.3 Data smoothing, identification of the limits of the kicking cycle, and time normalisation

To identify accurately the limits of the kicking cycle the ankle data were smoothed and interpolated using a Fourier transform and inverse transform. Interpolation expanded the data set so that the highest points of the ankle joint motion, used to identify the limits of the kicking cycle and the duration of the cycle, could be calculated precisely. Once these limits had been identified, the data for all points were smoothed using a Fourier smoothing routine and interpolated to 101 points representing percent of the kicking cycle. The new sampling frequency, used subsequently for calculating timing of events and time derivatives, was determined as 100/cycle duration. To enable comparison of the low frequency waveforms as harmonics independent of actual frequency, four harmonics were retained in the inverse transform of all cycles of all subjects. This ensured that comparisons of movement patterns could be made regardless of the frequency of the kicking cycle. The actual smoothing frequencies corresponded to between 6 and 7 Hz depending on the kick cycle duration.

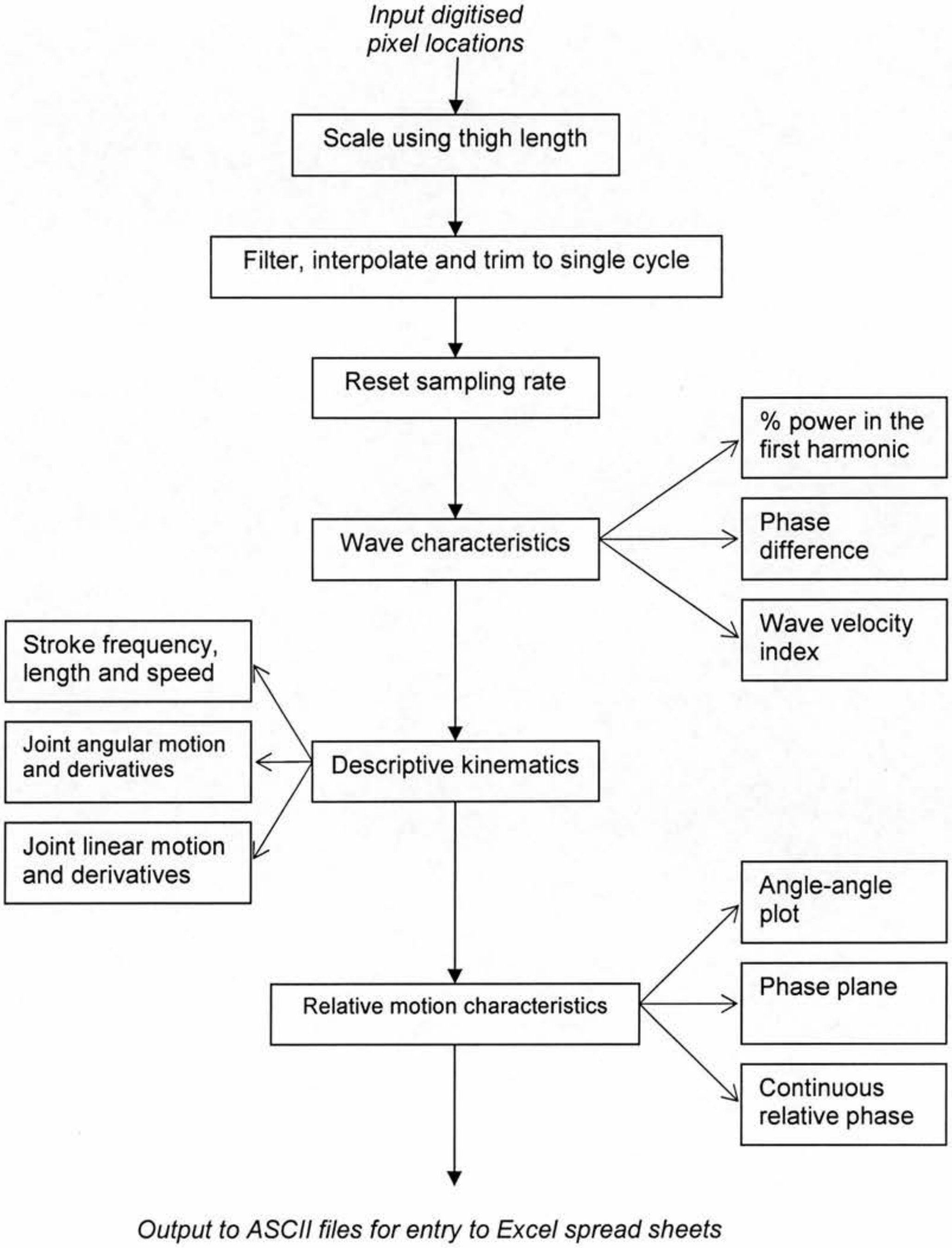


Figure 3.3.1 Flow chart of the procedures for the analysis of kinematics variables.

3.3.4 Reliability of digitizing data in calculation of kinematics variables

The third trial of those recorded on the first day of testing of swimmer '2' of each group (LFS2, FFS2 and COS2) were digitized manually seven times in order to evaluate the reliability of digitized data. The results are presented in the section 4.1.

3.4 Variables analysed

3.4.1 Wave characteristics

The characteristics of the movement pattern in the underwater kick that are known to be associated with skilled performance are the percentage power in the fundamental Fourier frequency of the hip, knee, and ankle vertical motions, the phases of the fundamental Fourier frequency and the associated 'velocity of travel of the body wave' and 'wave velocity index'. Therefore, to address the research questions, it is essential to assess whether these variables and their variability change in response to changing the task constraints, that is, the conditions of swimming flutter kicking with foot flippers, leg flippers and barefoot.

3.4.2 Descriptive kinematics

Descriptive kinematics and their variability provided an indication of how the motion changes in response to change in task constraints. Of particular interest was whether the kinematics variables such as stroke frequency, stroke length, and average speed changed significantly without there necessarily being a significant change in the 'normalised' movement pattern and coordination indicated by variables that were independent of time, for example, percent power in the fundamental frequency and wave velocity index. The variables deemed useful for indicating the characteristics of the movement were the stroke frequency, stroke length, average speed, stroke index, joint vertical displacements, joint angular displacement and velocities. Average speed also provided a measure of performance given that the goal of the task was to maximise speed. Vertical displacements were deemed important because these determined the amplitude of the body wave that propels the swimmer and may require adjustment to maintain effective performance when the task constraints are changed.

3.4.3 Relative motion characteristics

Angle-angle plots, that is, a plot of one joint angle against the temporally correspondent angle of another joint (hip-knee), and phase plane, that is, a plot of angular displacement against its derivative (hip and knee joints), are effective in showing movement patterns and their changes (Robertson and Caldwell, 2004). Further, by amplitude-normalising the angle-angle and phase planes one can detect whether the movement pattern changes its topological shape as well as its magnitude. Differences between phase angles of adjacent joints, that is, continuous relative phase (CRP) provide a sensitive measure of coordination (Hamill, Haddad and McDermott, 2000). Thus, CRP data supplemented the evidence provided by wave velocity index for change in coordination.

3.5 Calculation of variables

3.5.1 Wave characteristics

3.5.1.1 Velocity of wave travel

The velocity of the 'wave' that moved along the body as a result of cephalo-caudal sequencing of the joint vertical undulations was calculated using the approach of Sanders et al. (1995). Fourier phase angles for the fundamental waveform were calculated using the following equation:

$$\Phi = tan^{-1}(B/A)$$

Where A and B are the sine and cosine coefficients for the fundamental Fourier frequency. Average velocity from the hip to the knee joint and knee to the ankle joint was attained by:

$$v = d/t_m$$

Where, d = distance between consecutive joint centres and t = time for the wave to travel from the proximal to distal landmark. Note that the consecutive landmark from the knee is the ankle for the three segment system (bare foot and foot flipper conditions) and is the MP joint for the two segment system (leg flipper condition).

Time for the wave to travel from one joint landmark to the next was calculated as:

$$t_m = (\Phi_m - \Phi_{m+1})\ T/360$$

With Φ_m= phase angle of m^{th} landmark (increasing numbers in the cephalo-caudal direction) and T = period of the cycle (for the fundamental frequency this is equivalent to the period of the kick cycle).

3.5.1.2. Percent power of the fundamental frequency

The amplitude of the Fourier sine and cosine coefficients were calculated with the following equation:

$$C_n = (A_n^2 + B_n^2)^{1/2}$$

Where A_n and B_n = sine and cosine coefficients respectively for the n^{th} Fourier harmonic. The average power of each harmonic was calculated as $2C_n^2$ and then the power in the fundamental frequency was expressed as a percentage of the power contained in all four harmonics comprising the signal.

3.5.2 Descriptive kinematics

3.5.2.1 Stroke characteristics

3.5.2.1.1 Average speed

Average speed of the swimmer was determined as the horizontal displacement of the hip marker during the cycle divided by the cycle time.

3.5.2.1.2 Stroke frequency

The inverse of the cycle time.

3.5.2.1.3 Stroke length

The distance moved by the hip marker during the period of the cycle.

3.5.2.1.4. Stroke index

Stroke index was calculated as the stroke length multiplied by the average speed.

3.5.2.2 Segment and joint angular displacement and velocity

Segment angle was determined by applying the arctangent function to the ratio of the y and x differences in segment endpoint coordinates with the standard corrections for angular quadrant. Joint angular displacements were then determined as the difference between the angles of adjacent segments. The angles were determined such that increasing angle represented extension and decreasing angle represented flexion. Derivatives of segment and joint angles were obtained by applying finite central difference formula. The velocities for the first and last points were obtained by reflecting the difference of the following and preceding two values respectively.

The study focused on key aspects of kicking including hip, knee, and ankle joint angle minimum, maximum, ROM (range of motion). Joint angles were calculated as the difference in angles of the lines from the joint centre to those of adjacent joints. The angles of each line were determined using the arctangent of the ratio of differences in y and x coordinates with the standard corrections for quadrant and with flexion angles being less than 180 degrees.

3.5.2.3 Joint vertical displacement

Joint vertical displacements for the lower extremity joints (hip, knee and ankle) were determined as a function of normalised time from the scaled, smoothed, and interpolated y values reconstructed from the Fourier inverse transform. The vertical velocities were determined using the derivative of the Fourier functions.

3.5.3 Relative motion characteristics

3.5.3.1 Angle-angle plots

Joint angular position was plotted as a function of the joint angular position of the adjoining joint.

3.5.3.2 Phase planes of joint angular motion

Phase planes were produced by plotting angular displacement as abscissa values and angular velocity as the ordinate values. Prior to plotting, the respective means were subtracted from both angular displacement and angular velocity. To enable comparisons of movement pattern normalised for amplitude, values were adjusted by the following formula:

$$Normp(t) = (p(t)-p(mean))*2/(p(max)-p(min))$$

This method of amplitude normalisation was used to retain the possibility for differences in movement pattern between trials to be manifest in separations of the plots at any percent of the cycle. This was deemed more useful and appropriate for this study than methods in which the normalisation constrains the plot to pass through plus or minus 1 on each axis.

3.5.3.3 Continuous relative phase

Phase angle was calculated by:

$$CP(t) = Atan(o(t)/a(t))$$

Where o(t) is the ordinate value for time percent t obtained as described above and a(t) is the abscissa value. Standard corrections were made for quadrant and to ensure continuity.

Continuous relative phase was determined as the difference between the phase angle of adjacent joints or segments.

3.5.3.4 Variability of relative motion

Variability is an important index of coordination in movement. According to dynamical systems theory, variations in movement patterns are attributable to the movement system's response to the global and local perturbations.

The variability in angle-angle plots was determined by multiplying the standard deviations for each percent, then averaging across the 101 percent points. (Georgopoulos, Kalaska and Massey, 1981; Darling, Cole and Abbs, 1988).

$$\text{Variability}_{\text{angle-angle}} = SD_{\text{hip angular displacement}} \times SD_{\text{knee angular displacement}}$$

Similarly, the variability of the phase plane plots was determined by multiplying the standard deviations for each percent, then averaging across the 101 percent points (Darling and Cooke, 1987).

$$\text{Variability}_{\text{phase plane}} = SD_{\text{angular displacement}} \times SD_{\text{angular velocity}}$$

The variability of the continuous relative phase (CRP) was calculated as the mean of the standard deviation for each percent over the complete cycle as suggested by Hamill, Haddad, and McDermott (2000).

3.6 Statistical analysis

A within subject approach was used to investigate changes across blocks (experimental sessions) of trials and conditions. For individual subjects in the experimental groups this involved comparisons among the session for pre training (without flipper) the six sessions of training trials (with flippers), and the post-training session (without flippers). For the control group the post training session was compared with that of the pre training. This was to establish the magnitude of the change that could be expected due to factors other than the experimental factors.

Magnitudes of the changes were quantified statistically using effect sizes (Cohen, 1988). The rationale underpinning the use of effect sizes in this study was that the interest was in determining the magnitude of the effect of changing from one task constraint environment to another rather than attempting to establish whether or not any change was statistically significant. Importantly, conclusions were based on a ‘weight of evidence’ drawn from interpretations of results from a combination of the variables described above.

Effect size is a name given to a family of indices that measure the magnitude of a treatment effect. Unlike significance tests, these indices are independent of sample size. There is a wide array of formulas used to measure effect size. In general, effect size can be measured as the standardized difference between two means. The basic formula applied is:

$$\text{Effect size} = (\text{Mean}_{\text{group1}} - \text{Mean}_{\text{group2}}) / \text{Standard deviation}$$

The key factor in measurement of effect size is the calculation of standard deviation. When the two groups are independent (independent design), a pooled standard deviation should be utilised (see Appendix B). When the two groups are dependent (matched groups or repeated measures design), the pre-treatment standard deviation could be used (Becker, 2000).

In the present study, the dependent design (correlation design) is employed. Thus, the effect size analysis in the present study was based on standard deviations obtained in the pre-test for both individual and group analysis. That is, the pre-treatment standardised mean difference between pre-treatment and the training (test) session or post-training session was used to assess the magnitude of the changes across conditions and training sessions relative to the pre-test. For individual swimmers the effect size for any variable was calculated as:

$$\text{Effect size}_{\text{individual}} = (\text{Mean}_{\text{individual treatment}} - \text{Mean}_{\text{individual pre-treatment}}) / \text{SD}_{\text{individual pre-treatment}}$$

and for the group:

$$\text{Effect size}_{\text{group}} = (\text{Mean}_{\text{group treatment}} - \text{Mean}_{\text{group pre-treatment}}) / \text{SD}_{\text{group pre-treatment}}$$

Cohen's (1988) guidelines were taken into account when interpreting the magnitude of changes. These were small: 0.2, medium: 0.5 and large: 0.8.

Where effect sizes were determined for changes in the time series data rather than for discrete values, means and SDs were calculated for each percent across trials. Then an average of these across the 101 points was used in the formulas above for effect sizes for individuals and groups.

CHAPTER 4

RESULTS AND DISCUSSION

The results and discussion are presented in four parts: (a) kicking skill level identification and digitizing reliability, (b) rhythm and coordination of the vertical motion of the lower extremities, (c) stroking characteristics, and (d) lower extremity coordination pattern.

4.1 Kicking skill level identification and digitizing reliability

This section reports on two factors that might have a considerable effect on the results and the ability to accurately interpret the results, these are, the skill level of the subjects and the magnitude of errors in the variables due to digitizing error.

4.1.1 Kicking skill identification

If a young swimmer's skill level is in a learning stage it is likely that the effect of changing task constraints would be confounded by the effect of skill level and learning during the period of the experiment that is unrelated to the experimental conditions. Therefore, it was necessary to establish that the subjects could be regarded as skilled in flutter kicking prior to the experimental interventions, that is, the changes in task constraints associated with a change from barefoot to leg or foot flippers. Although subjects in this study were competitive age group swimmers with at least one year of training for competition, the possibility that swimmers were not at a high level of skill development prior to testing could not be ignored.

Fortunately, it is known that there are two good indicators of skill in flutter kicking (Sanders, 2006). The first is the percentage of power in the fundamental Fourier harmonic of the vertical displacement-time signal of the hip, knee and ankle. With increasing skill, this percentage increases as the movement becomes 'smoother' and more 'wavelike'. The second is the 'velocity index'. Velocity index is the ratio of knee-ankle (knee-MP for the LF training sessions) wave velocity and hip-knee wave velocity. According to the study on flutter kicking at different stages of learning (Sanders 2006), the skilled swimmers had a velocity index close to or greater than 1.0. An index of this magnitude indicates that the sequential coordination has been developed to progress a body wave caudally to maximize propulsion. Learners typically progress from simultaneous joint vertical displacements characterized by velocity indices much less than 1.0 towards indices close to 1.0 or greater as they become skilled.

4.1.1.1 Percentage power in the first harmonic of lower extremity joint vertical displacements

Table 4.1.1 presents the mean percentage power contained in the first harmonic of hip, knee and ankle joints of swimmers prior to changing the task constraints. The percentage of power in the first harmonic of the undulation of hip, knee and ankle joints for all groups was very high. In Sanders' study, the mean values for skilled swimmers' joints were 97.7 % (hip), 97.2 % (knee) and 99.4 % (ankle). Thus, on the basis of this indicator, the groups in general were all highly skilled. On an individual basis all swimmers displayed a high level of skill based on this indicator. However, it may be that one of the swimmers in the leg flipper group (LFS3) with a 96.24 % for knee joint in the first harmonic may have been slightly less skilled than others in the groups. However, even this swimmer compares favorably with the swimmers at different stages of learning (Sanders, 2006) indicating that he is at the high end of the skill acquisition process.

Table 4.1.1 Mean values, variability (SD) of percentage power in the first harmonic of the hip, knee and ankle joint for LF, FF and CO groups prior to the training intervention.

		LFS1	LFS2	LFS3	FFS1	FFS2	FFS3	COS1	COS2	COS3
Hip										
	Mean	98.88	99.25	97.96	97.74	99.45	99.59	98.83	99.26	99.76
	SD	1.44	0.95	0.48	2.67	0.46	0.29	0.9	0.96	0.13
Knee										
	Mean	99.25	99.22	96.24	98.58	99.11	97.16	99.5	99.28	99.72
	SD	0.74	1.13	0.49	1.29	1.48	0.67	0.4	1.16	0.17
Ankle										
	Mean	99.81	99.8	99.74	99.57	99.88	99.74	99.77	99.81	99.85
	SD	0.14	0.30	0.19	0.65	0.09	0.40	0.23	0.31	0.04

4.1.1.2 Velocity index

Figure 4.1.1 shows the results of individual swimmers for the velocity index in the testing session prior to the training intervention. All the swimmers had an index close to or greater than 1.0 with the lowest score (COS2) of the control group being at the lower extremity of the range of indices of the skilled adult swimmers in the study by Sanders (2006). This indicated that the swimmers were generally skillful in the performance of flutter kicking. However, it also indicated that although all swimmers had attained high levels of skill, there may still be a small difference in skill level among swimmers. Thus, the possibility that differences in responses to the changes in task constraints among individuals should not be dismissed entirely. It is worth noting that the two swimmers (COS1 and CSO2) that had indices that were equivalent to the low end of the range of skilled adult swimmers in the Sanders (2006) study were both in the control group.

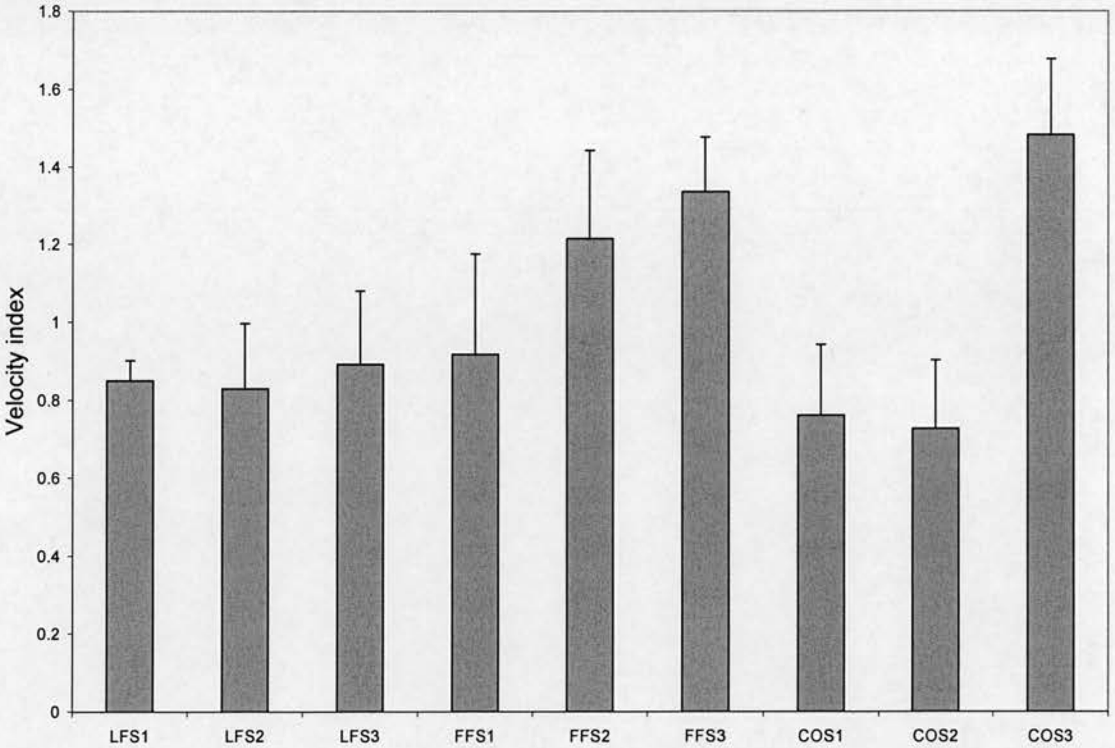


Figure 4.1.1 Kicking skill identification by velocity index of knee-ankle/hip-knee for the leg flipper swimmers (LFS1, LFS2, LFS3), foot flipper swimmers (FFS1, FFS2, FFS3) and control group swimmers (COS1, COS2, COS3)

4.1.2 Digitizing reliability

The digitizing reliability was tested in subjects of each group. The 'middle' trial of the pre-training session (the 3rd trial) and second subject of each group (LFS2. FFS2 and COS2) were digitized manually seven times to assess the error associated with the digitizing process. The whole kicking cycle of the selected trials was digitized. The kicking cycle was defined as the period between and including the instants of the highest vertical displacement of the ankle. The variables quantified included the angular displacement and velocity of hip and knee joints, and continuous relative phase (CRP, normalized) of hip-knee joint (Table 4.1.2, Figure 4.1.2-4). These three variables were selected because they are critical to interpretation of changes in movement patterns and coordination required to address the purpose of the thesis. To indicate the magnitude of the errors relative to other sources of variability, in particular, within subject variability, typical within subject variability is shown in Figures 4.1.2-4.using the results for the pre-training session of LFS2.

For all of the variables, the mean standard deviation of the mean (MSD) was used across each of the seven repeat digitized trials and selected pre-training trials by the following formula:

$$\text{MSD} = \frac{1}{n}\sum_{i=1}^{n} SDi$$

where SDi is the standard deviation among trials within the test session at time point i (percent), n is the number of data points (=101).

Table 4.1.2 Mean standard derivation for the joint angular displacement (deg) and angular velocity (deg/s), continuous relative phase (CRP, hip-knee, deg) calculated across seven repeat digitized on one pre-training session trial and all trials of pre training session.

Subject		Hip joint		Knee joint		CRP
		Displacement	Velocity	Displacement	Velocity	
LFS2						
	Repeat digitizing	0.69	10.32	0.85	14.05	3.24
	Pre-training	4.83	24.74	3.41	48.87	8.78
FFS2						
	Repeat digitizing	1.37	15.05	1.88	17.26	4.35
	Pre-training	5.34	39.27	6.20	71.80	8.81
COS2						
	Repeat digitizing	1.05	21.09	1.47	28.03	7.57
	Pre-training	3.70	28.81	4.14	61.43	8.96

Table 4.1.2 presents the digitizing errors in the calculated kinematics variables for representing subjects, hip and knee joint angular displacement and velocity, hip-knee CRP, and typical within subject variability. From these results it is clear that variability arising from digitizing errors was small relative to the typical within subject variability. This was reinforced by the magnitude of the SD envelopes of the curves of these variables below

(Figure 4.1.2-4). The results indicated that the digitizing error could be rejected as a factor causing substantial differences among the pre training, training and post training data or in preventing differences reaching statistical significance. Therefore digitizing error can be ignored as a factor that is likely to affect the ability to interpret results.

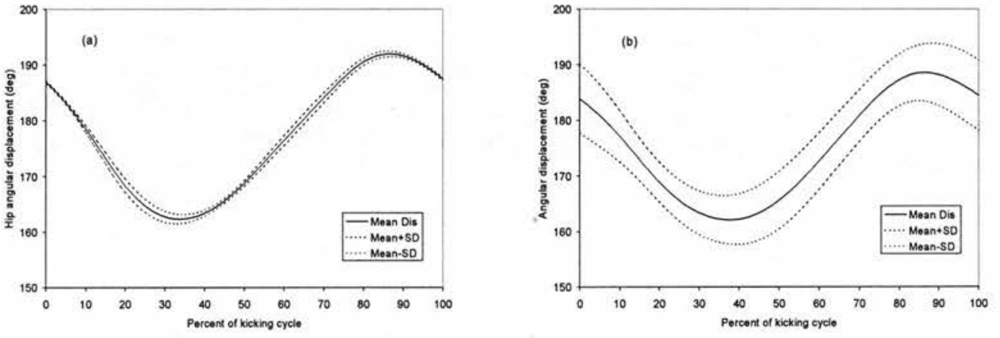


Figure 4.1.2 The hip angular displacement from seven repeated-digitizing (a) and pre training (b) of LFS2. Dashed lines present mean values and dotted lines represent variability (standard deviation).

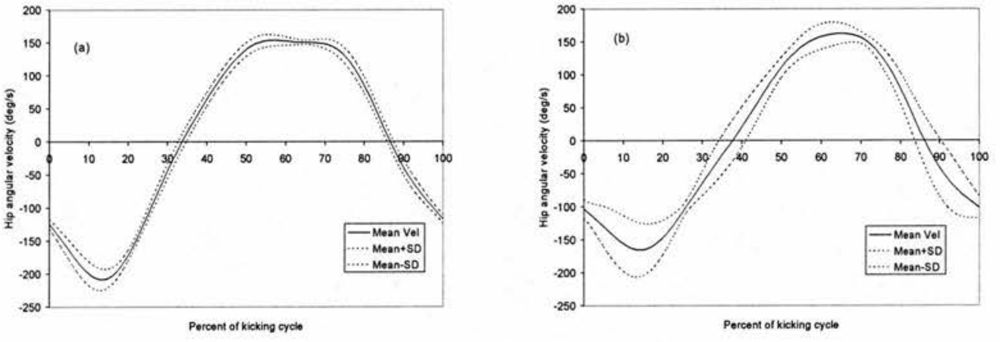
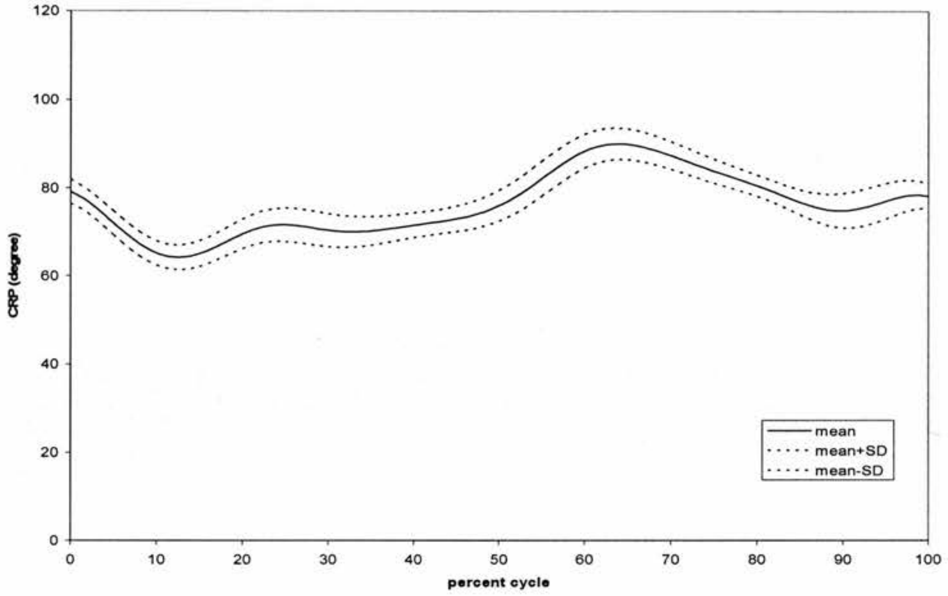
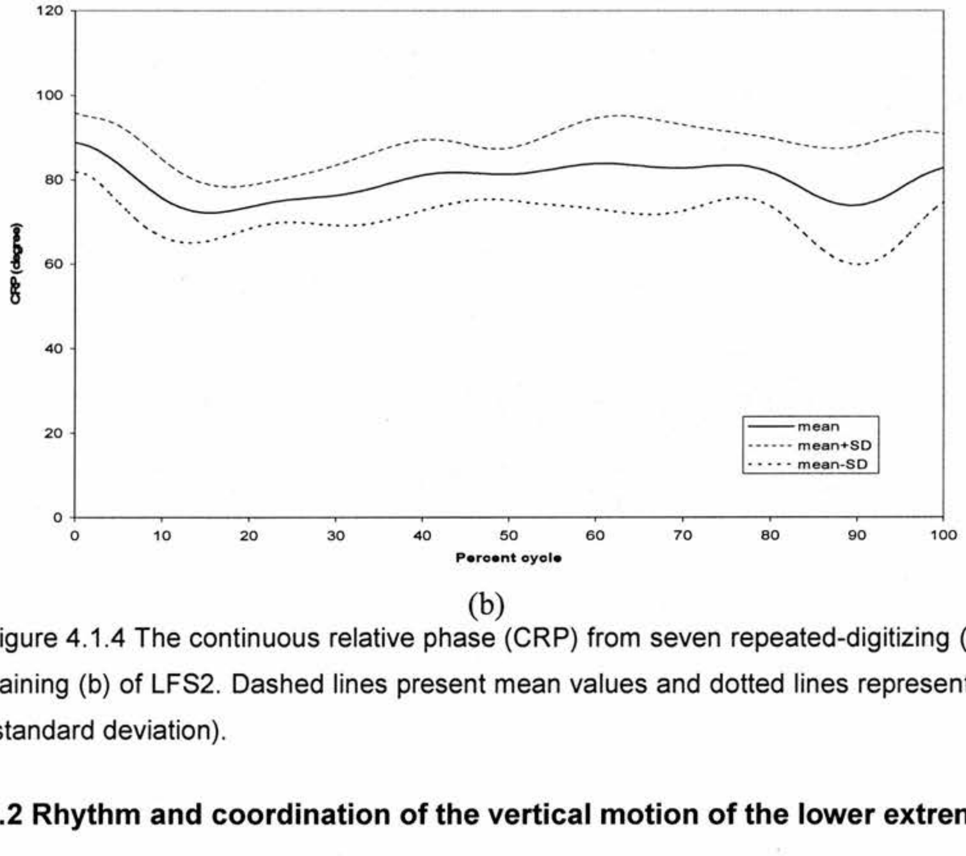


Figure 4.1.3 The hip angular velocity from seven repeated-digitizing (a) and pre training (b) of LFS2. Dashed lines present mean values and dotted lines represent variability (standard deviation).



(a)



(b)

Figure 4.1.4 The continuous relative phase (CRP) from seven repeated-digitizing (a) and pre training (b) of LFS2. Dashed lines present mean values and dotted lines represent variability (standard deviation).

4.2 Rhythm and coordination of the vertical motion of the lower extremities

In this section the results of the investigation into the changes in the key performance criteria for skilled performance in flutter kicking when the task constraints are altered by adding or removing foot flipper or leg flippers are presented. The key indicators of whether the movement pattern is appropriate for performance are the percentage of power in the fundamental Fourier frequency and the velocity index relating to the velocity of progression of the body wave from hip to knee and knee to the ankle joint.

4.2.1 Percentage power in the first harmonic of the lower extremities

Table 4.2.1 presents the mean percentage power contained in the first harmonic, variability (SD) across trials and subjects within the conditions, and mean effect size (E.S.) of hip, knee and ankle joints for each condition. Although decreases during training sessions and the post training session were reflected in substantial effect sizes, the percentage of power in the first harmonic of the undulation of hip, knee and ankle joints for all groups remained very high. Even though there were some effects as indicated by the effect sizes, neither the LF group nor the FF group fell substantially below the mean values for skilled swimmers' in Sanders (2006) study 97.7 % (hip), 97.2 % (knee) and 99.4 % (ankle). Thus, any effect on this indicator of suitability of movement pattern for the task was very small.

It is interesting that in the post-test, the swimmers did not return to as high values as in the pre-test. This may indicate that there was a 'residual effect' of the constraint intervention that affected the smoothness of the movement pattern when the constraint environment was returned to that of the pre-test. However, given that a similar effect occurred in the control group which did not have any change in the task constraints, and that the percentage of power in the first harmonic of all swimmers remained high, it can be concluded that any effects of change in task constraints on the sinusoidal nature of the task were very small.

Table 4.2.1 Mean values, variability (SD) and effect size (E.S.) of percentage power in the first harmonic of the hip, knee and ankle joint in pre training, training (mean pooled) and post training sessions for LF, FF and CO groups.

		LF			FF			CO	
		Pre training	Pooled training	Post training	Pre training	Pooled training	Post training	Pre training	Post training
Hip									
	Mean	98.76	98.32	96.33	98.87	97.79	95.51	99.32	97.30
	SD	1.11	1.65	2.33	1.74	2.02	2.90	0.77	1.95
	E.S.		-0.40	-2.20		-0.62	-1.93		-2.62
Knee									
	Mean	98.41	97.03	97.10	98.38	98.73	97.92	99.50	97.79
	SD	1.60	1.93	2.84	1.39	1.07	1.15	0.68	1.48
	E.S.		-0.87	-0.82		0.25	-0.34		-2.53
Ankle									
	Mean	99.79	99.64	99.50	99.73	99.51	99.16	99.81	99.47
	SD	0.20	0.37	0.45	0.42	0.53	0.71	0.21	0.44
	E.S.		-0.72	-1.41		-0.51	-1.35		-1.64

Table 4.2.2 Mean values, variability (SD) and effect size (E.S.) of percentage power in the first harmonic hip, knee and ankle joint over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Hip									
LF	Mean	98.76	98.82	99.17	98.11	98.01	97.62	97.99	96.33
	SD	1.11	1.09	0.72	1.58	2.15	2.20	1.54	2.33
	E.S.		0.06	0.37	-0.59	-0.68	-1.03	-0.69	-2.20
FF	Mean	98.87	98.06	97.62	97.92	97.78	98.13	97.28	95.51
	SD	1.74	2.38	2.13	2.17	2.11	1.44	1.98	2.90
	E.S.		-0.47	-0.72	-0.54	-0.62	-0.43	-0.91	-1.93
Knee									
LF	Mean	98.41	96.83	96.48	97.25	97.34	97.31	97.06	97.10
	SD	1.60	1.43	1.59	1.63	2.32	2.10	2.53	2.84
	E.S.		-0.99	-1.21	-0.73	-0.67	-0.69	-0.85	-0.82
FF	Mean	98.38	98.62	98.88	98.36	98.42	99.17	98.89	97.92
	SD	1.39	1.03	0.71	1.09	1.86	0.47	0.65	1.15
	E.S.		0.17	0.36	-0.02	0.02	0.57	0.37	-0.34
Ankle									
LF	Mean	99.79	99.71	99.74	99.30	99.80	99.69	99.59	99.50
	SD	0.20	0.35	0.21	0.61	0.20	0.20	0.29	0.45
	E.S.		-0.37	-0.25	-2.39	0.04	-0.48	-0.98	-1.41
FF	Mean	99.73	99.46	99.49	99.48	99.44	99.74	99.50	99.16
	SD	0.42	0.62	0.48	0.49	0.74	0.31	0.47	0.71
	E.S.		-0.64	-0.56	-0.59	-0.67	0.02	-0.55	-1.35

Like the data of Sanders (2006), the ankle joint had the highest percentage of power in the first harmonic among the lower extremity joints in all groups in all conditions. On the basis that the mean percentage was more than 99% under all conditions and that variability was very small it may be concluded that the movement at the end of the segmental chain remained extremely smooth and rhythmical regardless of the changes in task constraints and regardless of whether the task constraints were familiar or unfamiliar (Figure 4.2.1-6).

Table 4.2.2 shows the results for the individual testing sessions during the training intervention period. No trends were apparent across the training sessions in either the percentage contained in the first harmonic of the joint vertical motions or in the variability. In particular, T1 appears similar to all of T2 to T6 indicating that adjustment to the change in constraints was rapid for both the unfamiliar constraints (leg flipper) and the familiar constraints (foot flipper).

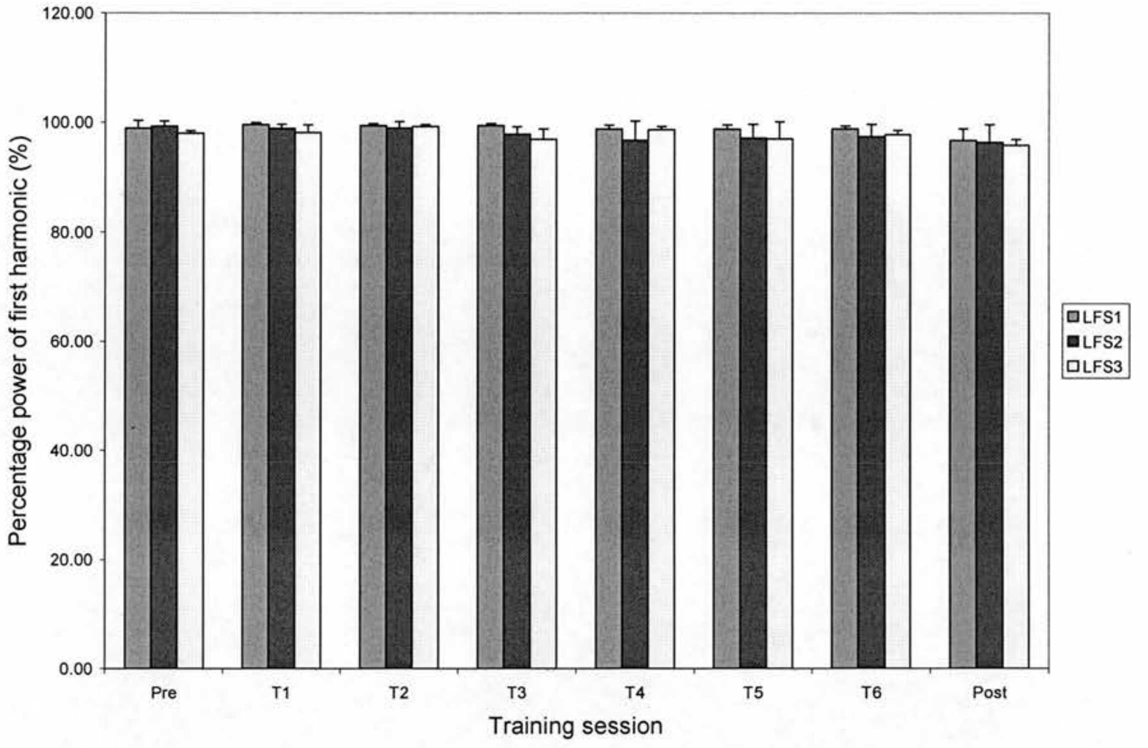


Figure 4.2.1 Percentage power of the first harmonic of the hip joint over all sessions for the LF group.

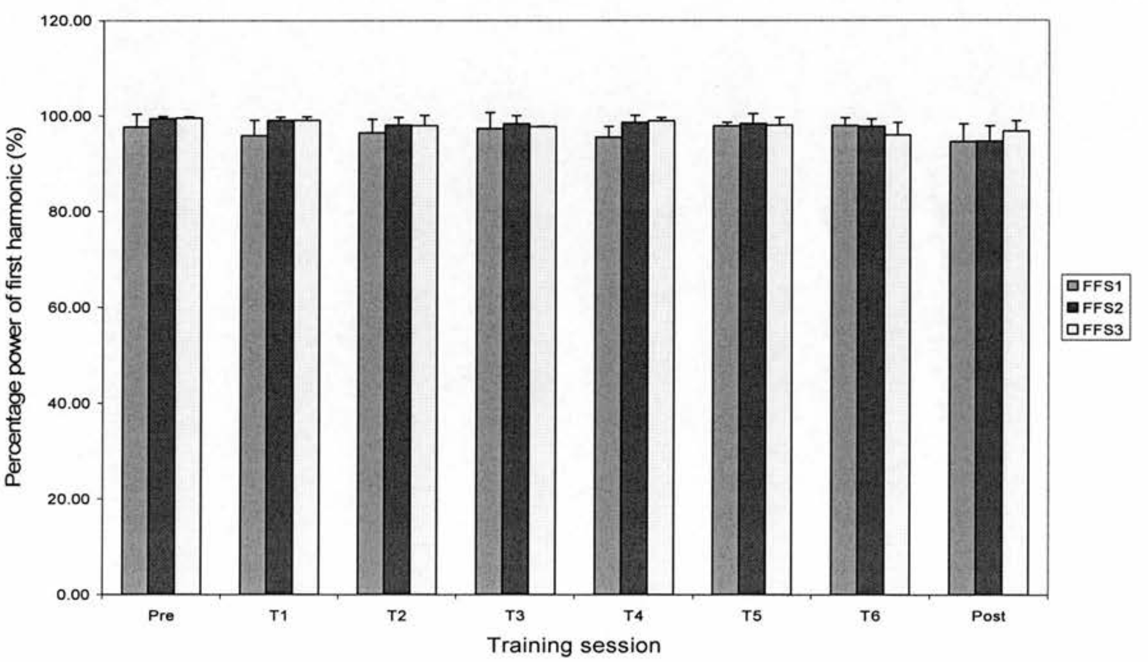


Figure 4.2.2 Percentage power of the first harmonic of the hip joint over all sessions for the FF group.

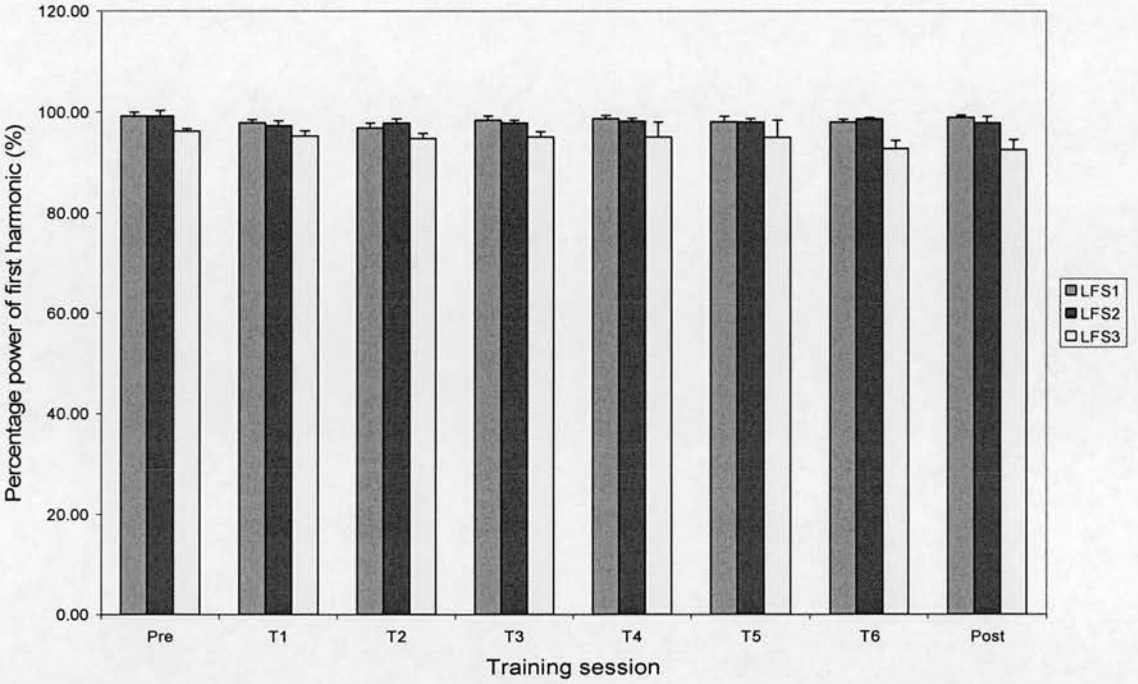


Figure 4.2.3 Percentage power of the first harmonic of the knee joint over all sessions for the LF group.

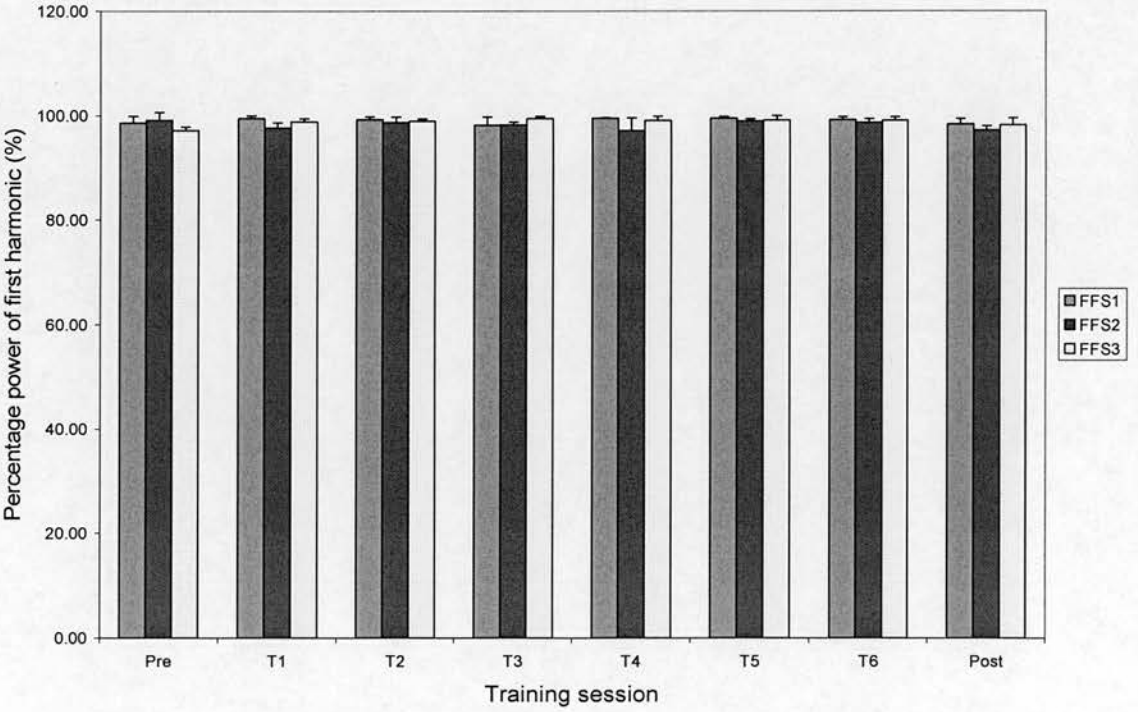


Figure 4.2.4 Percentage power of the first harmonic of the knee joint over all sessions for the FF group.

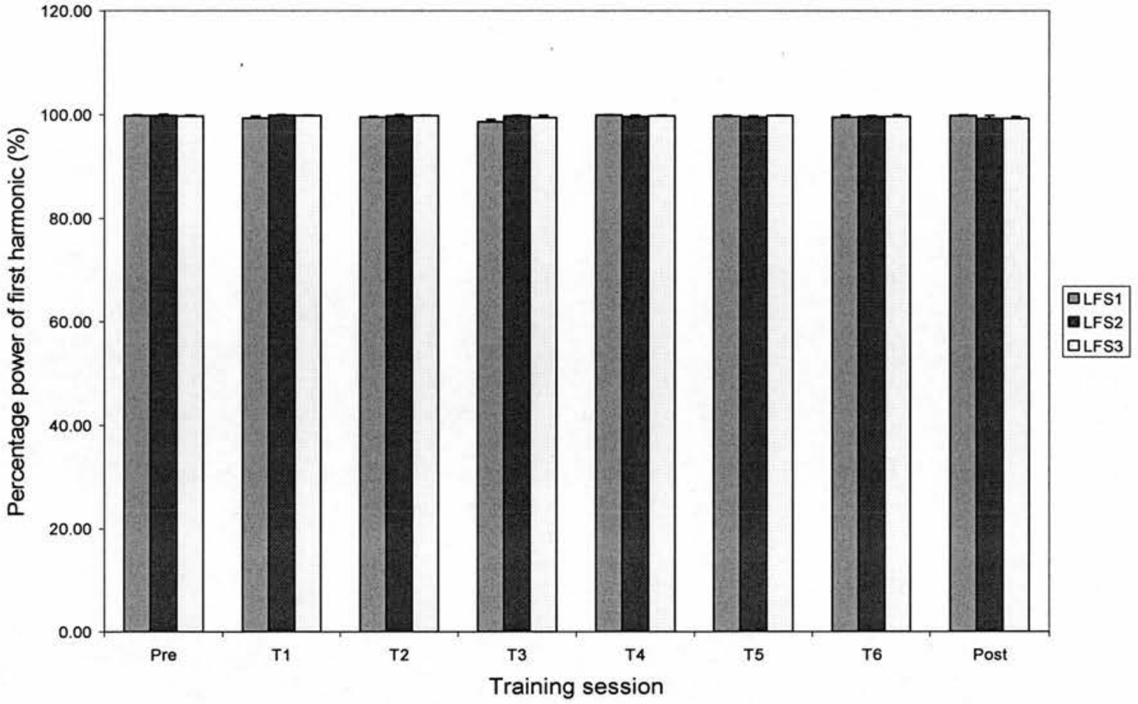


Figure 4.2.5 Percentage power of the first harmonic of the ankle joint over all sessions for the LF group.

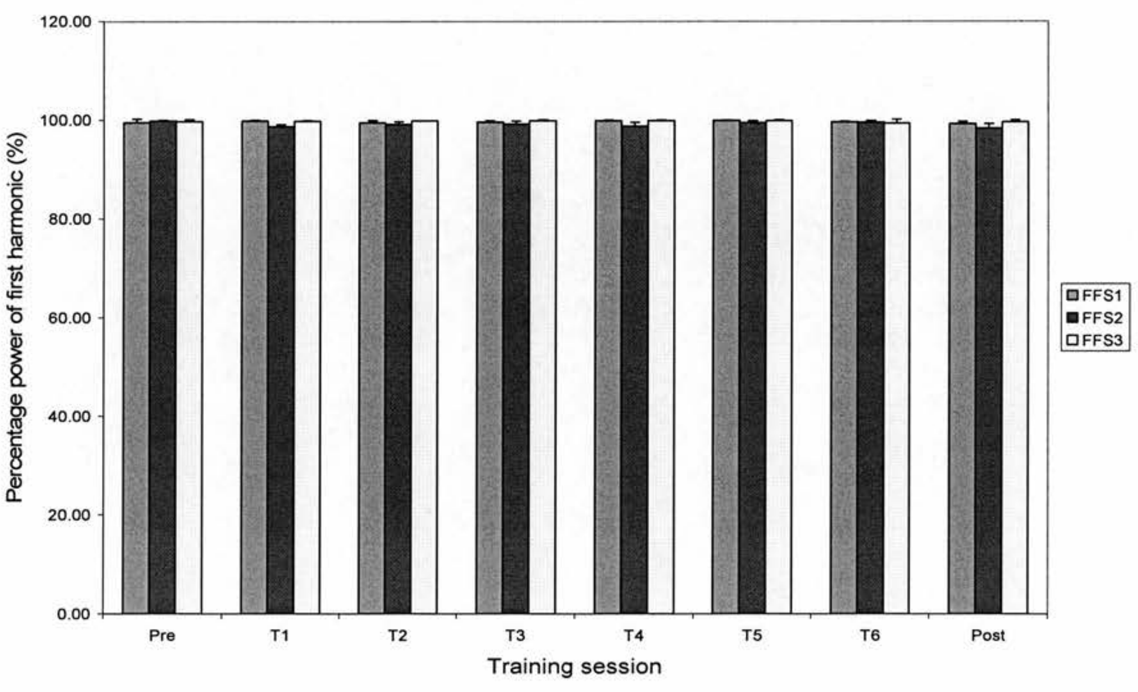


Figure 4.2.6 Percentage power of the first harmonic of the ankle joint over all sessions for the FF group.

4.2.2 Body wave velocity across hip-knee and knee-ankle

Table 4.2.3-4 presents the results for the wave velocity of the fundamental Fourier frequency from hip to knee and from knee to ankle (knee to MP for LF training sessions) and the velocity index (knee-ankle/hip-knee). When using flippers, the LF group had a larger hip-knee velocity (absolute value 3.35-4.53 $m.s^{-1}$) and knee-MP velocity (absolute value 2.82-4.30 $m.s^{-1}$) than the hip-knee and knee-ankle velocity of barefoot kicking. The FF group reduced the hip-knee velocity (absolute value 3.68-3.25) and increased the knee-ankle velocity (absolute value 3.96-4.28 $m.s^{-1}$) of the wave in response to using the foot flipper.

The velocity index of both the LF and FF group increased when using the flippers due to an increase in knee-MP wave velocity for LF (knee-ankle for barefoot condition) and knee-ankle for FF (higher knee-MP wave velocity) from that in the barefoot condition. The increase in velocity index for the FF group was due to reducing the hip-knee wave velocity and increasing knee-ankle wave velocity. The LF group increased body wave velocity both from hip-knee and from knee-MP. However, the increase from knee-MP was relatively greater than that of hip-knee and accounted for the overall increase in velocity index.

Table 4.2.3 Mean body wave velocity ($m.s^{-1}$), variability (SD) and effect size (E.S.) of the hip-knee, knee-ankle (MP joint for LF training sessions) and velocity index in pre training, training (mean pooled) and post training sessions for LF, FF and CO groups.

		LF			FF			CO	
		Pre training	Pooled training	Post training	Pre training	Pooled training	Post training	Pre training	Post training
Hip-knee									
	Mean	-3.35	-4.53	-3.34	-3.68	-3.25	-3.51	-4.46	-3.79
	SD	0.70	1.17	0.96	1.23	0.77	1.33	1.45	0.75
	E.S.		-1.70	0.02		0.34	0.13		0.46
Knee-ankle/MP									
	Mean	-2.82	-4.30	-2.98	-3.96	-4.28	-3.86	-3.97	-3.84
	SD	0.50	0.98	0.31	0.81	0.86	0.84	0.60	0.69
	E.S.		-2.96	-0.33		-0.40	0.12		0.21
Velocity index									
	Mean	0.85	0.94	0.97	1.14	1.33	1.17	0.99	1.07
	SD	0.13	0.20	0.30	0.27	0.38	0.32	0.40	0.39
	E.S.		0.68	0.86		0.70	0.12		0.21

When the task constraints from flipper kicking returned to barefoot kicking, the FF group returned to similar values as in the pre-training session. However, the body wave velocity index increased for the LF group. Inspection of results for the individual swimmers revealed that the increase in wave velocity index of the LF group was due mainly to changes in body wave velocities of LFS1 (Figure 4.2.11).

Table 4.2.4 Mean body wave velocity ($m.s^{-1}$), variability (SD) and effect size (E.S.) of the hip-knee, knee-ankle (knee-MP for leg flipper condition) and velocity index over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Hip-knee									
LF	Mean	-3.35	-4.24	-4.82	-4.88	-4.22	-4.42	-4.59	-3.34
	SD	0.70	1.06	1.30	0.92	1.19	1.08	1.42	0.96
	E.S.		-1.28	-2.11	-2.20	-1.25	-1.54	-1.78	0.02
FF	Mean	-3.68	-3.28	-2.72	-3.23	-3.53	-3.44	-3.44	-3.51
	SD	1.23	0.77	0.49	0.63	0.89	0.89	0.75	1.33
	E.S.		0.32	0.78	0.36	0.12	0.19	0.19	0.13
Knee-ankle									
LF	Mean	-2.82	-4.11	-4.20	-4.38	-4.21	-4.52	-4.39	-2.98
	SD	0.50	1.22	1.18	1.70	1.14	1.64	1.46	0.31
	E.S.		-2.58	-2.76	-3.12	-2.78	-3.41	-3.13	-0.33
FF	Mean	-3.96	-4.09	-4.09	-4.51	-4.04	-4.22	-4.70	-3.86
	SD	0.81	0.61	1.13	1.09	0.68	0.47	0.94	0.84
	E.S.		-0.17	-0.17	-0.68	-0.10	-0.33	-0.92	0.12
Velocity index									
LF	Mean	0.85	0.98	0.87	0.86	1.01	0.97	0.98	0.97
	SD	0.13	0.18	0.16	0.16	0.24	0.17	0.23	0.30
	E.S.		0.96	0.11	0.02	1.19	0.87	0.94	0.86
FF	Mean	1.14	1.30	1.40	1.38	1.19	1.28	1.41	1.17
	SD	0.27	0.32	0.56	0.38	0.25	0.35	0.30	0.32
	E.S.		0.58	0.97	0.91	0.19	0.53	0.99	0.12

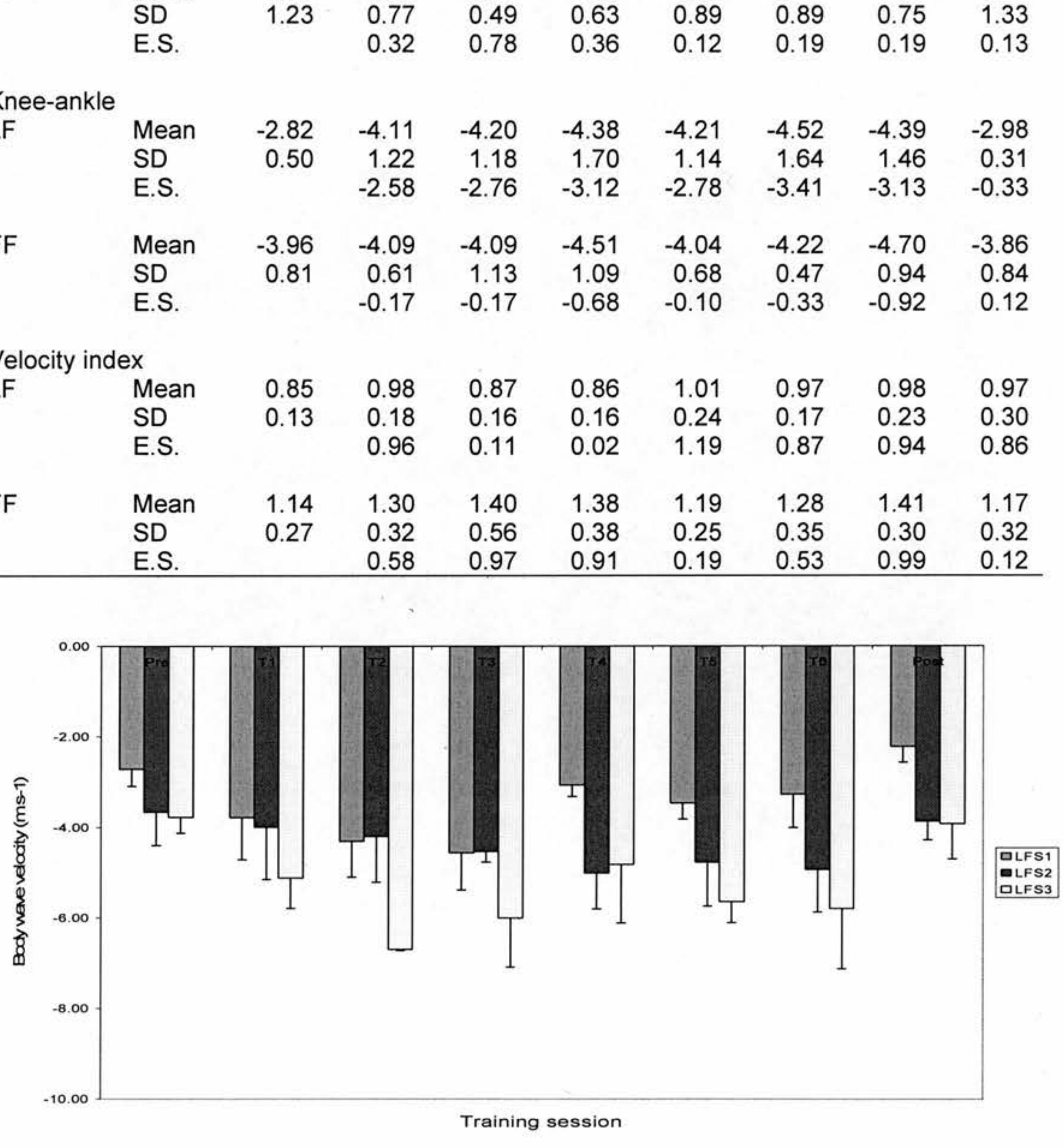


Figure 4.2.7 Hip-knee body wave velocity over all sessions for the LF group.

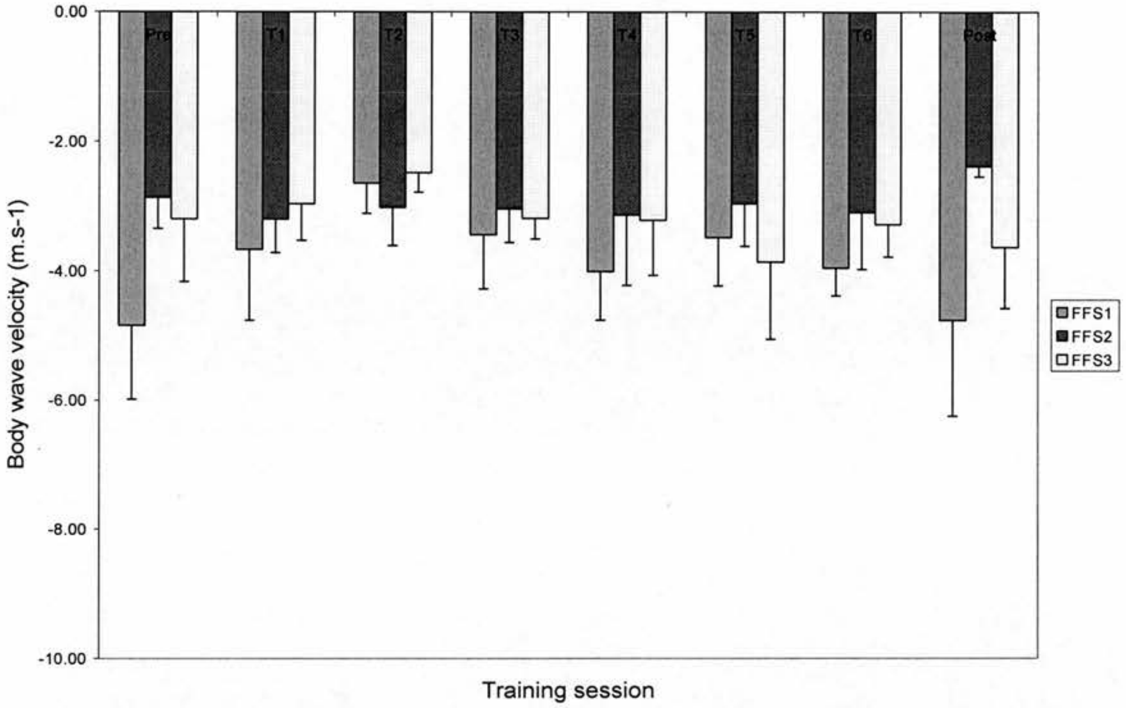


Figure 4.2.8 Hip-knee body wave velocity over all sessions for the FF group.

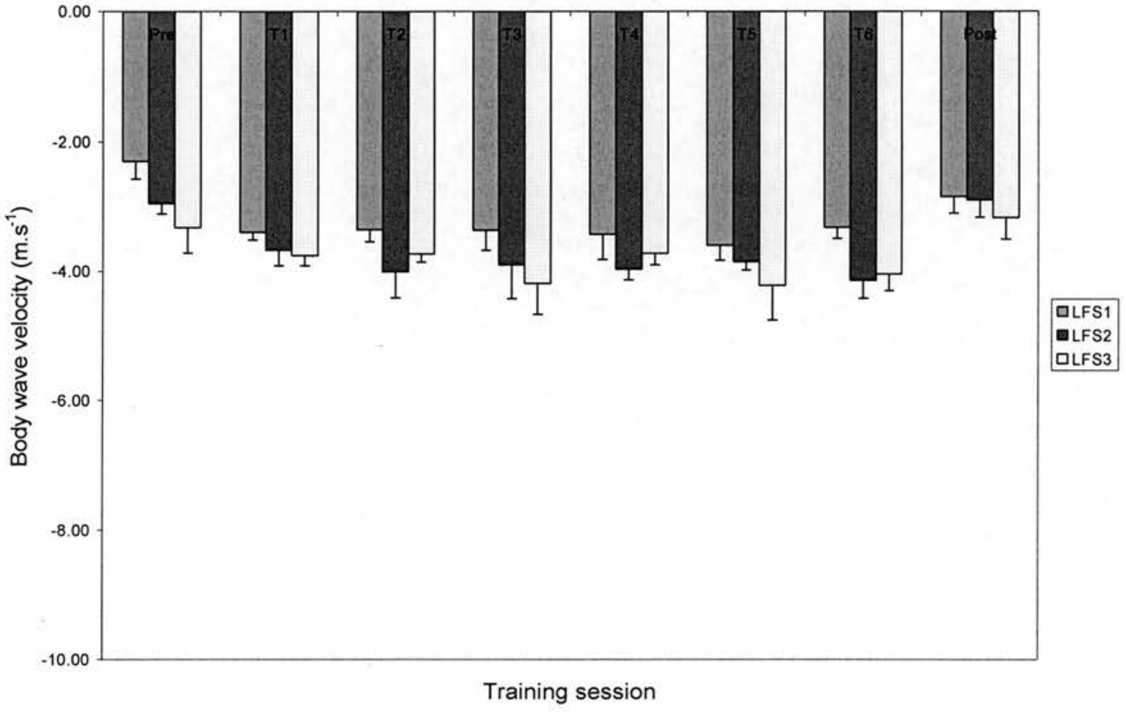


Figure 4.2.9 Knee-ankle body wave velocity over all sessions for the LF group.

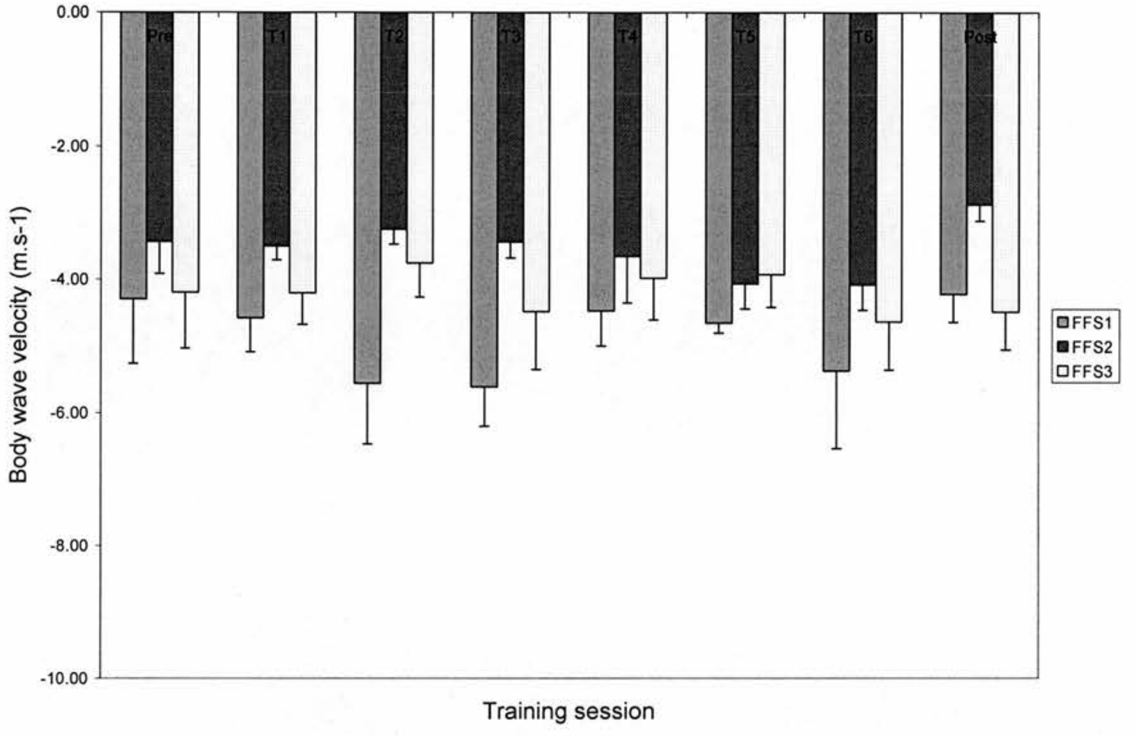


Figure 4.2.10 Knee-ankle body wave velocity over all sessions for the FF group.

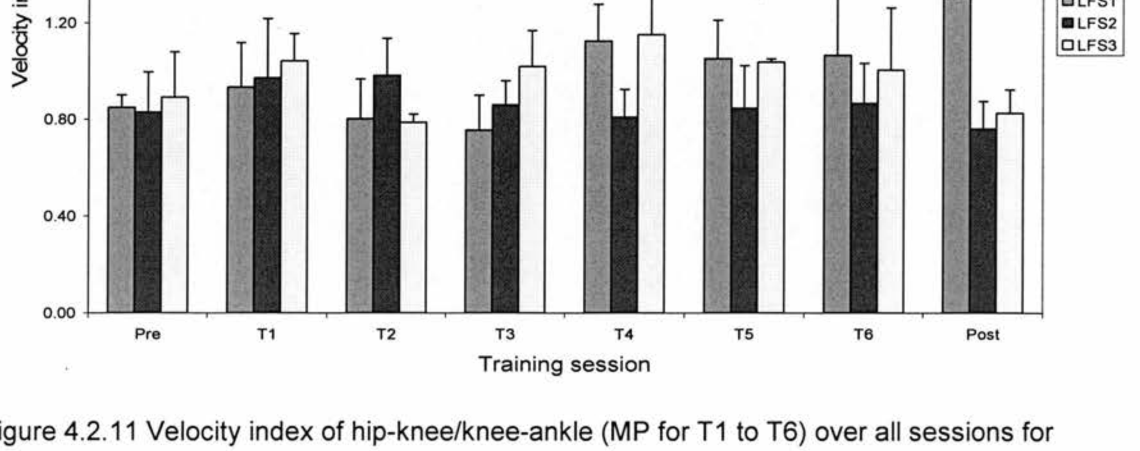


Figure 4.2.11 Velocity index of hip-knee/knee-ankle (MP for T1 to T6) over all sessions for the LF group.

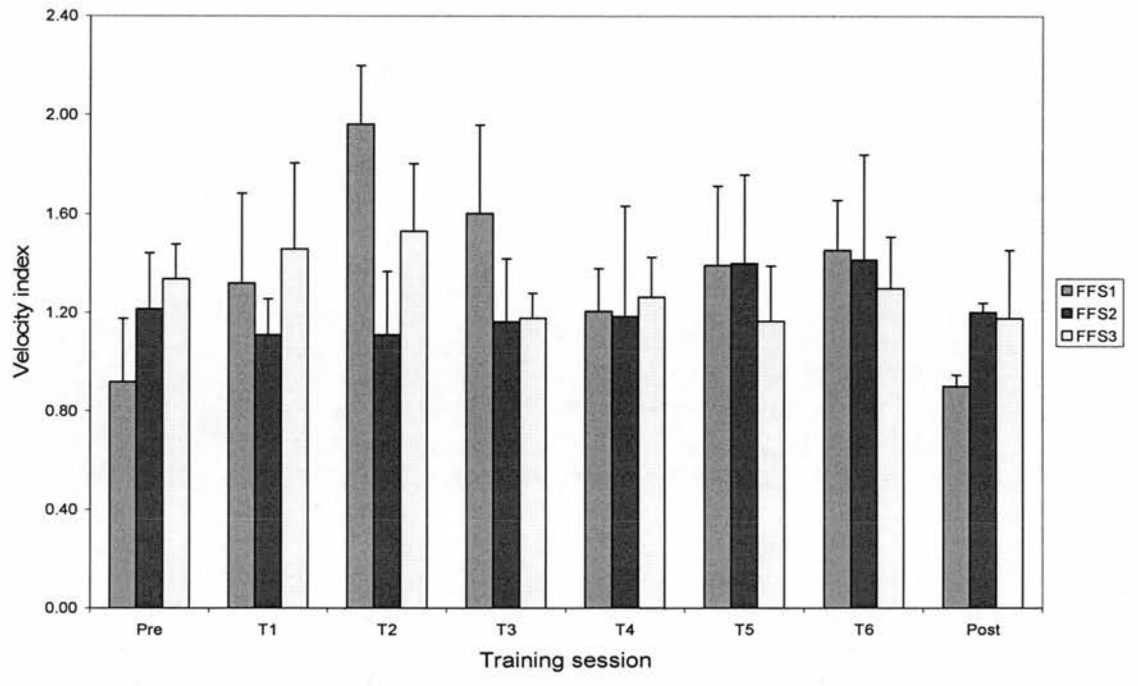


Figure 4.2.12 Velocity index of hip-knee/knee-ankle over all sessions for the FF group.

4.2.3 Summary

There was a very high percentage of power contained in the first harmonic for both the LF and FF groups for all of hip, knee and ankle joints throughout all sessions. This indicated that when changing to a different task constraint environment the system was able to retain the desirable rhythmical and smooth sinusoidal wave form as in skilled barefoot kicking.

Appropriate Fourier phase characteristics of the vertical oscillations of the joints were indicated by the hip-knee and knee-ankle (knee-MP for LF group flipper condition) body wave velocities and body wave velocity index. The velocity index increased when using both leg and foot flippers. When the swimmers returned to barefoot kicking the body wave velocities and velocity indices for the FF group returned rapidly to values similar to those in the pre-training session.

The results indicate that the systems of swimmers adapted in the first 10 trials to changes in task constraints by retaining the smoothness and phase characteristics of the vertical undulations known to be associated with efficient propulsion.

4.3 Kinematics characteristics of flutter kicking with and without flippers

In this section, descriptive kinematics characteristics of flutter kicking with and without flippers such as stroke parameters - stroke (kicking) frequency, stroke length, swimming speed, and stroke index as well as linear and angular kinematics of the lower limb joints are presented. The comparison of most interest is the comparison between conditions. Thus, the effect sizes were employed in these comparisons.

4.3.1 Stroke parameters

Table 4.3.1 presents the mean and SD for the stroke parameters for the leg flipper, foot flipper and control groups for pre training, pooled training, and post training sessions. Effect sizes are indicated relative to the pre training (barefoot) condition.

Table 4.3.1 Mean values, variability (SD) and effect size (E.S., mean values relative to pre training session) of stroke parameters in pre training, training (mean pooled) and post training session for leg flipper (LF), foot flipper (FF) and control (CO) groups.

		LF			FF			CO	
		Pre training	Pooled Training	Post training	Pre training	Pooled Training	Post training	Pre training	Post training
Stroke frequency (1/s)									
	Mean	1.92	1.68	1.94	1.96	1.63	1.84	2.21	2.12
	SD	0.24	0.24	0.33	0.19	0.29	0.35	0.21	0.35
	E.S.		-0.99	0.06		-1.70	-0.60		-0.43
Stroke length (m)									
	Mean	0.39	0.52	0.37	0.52	0.75	0.47	0.48	0.48
	SD	0.11	0.10	0.08	0.07	0.10	0.07	0.05	0.06
	E.S.		1.24	-0.12		3.38	-0.81		-0.13
Swimming speed (m/s)									
	Mean	0.72	0.86	0.70	1.01	1.20	0.85	1.06	0.99
	SD	0.16	0.10	0.07	0.07	0.14	0.12	0.05	0.06
	E.S.		0.86	-0.14		2.88	-2.50		-1.47
Stroke index (m^2/s)									
	Mean	0.29	0.45	0.27	0.53	0.90	0.40	0.51	0.47
	SD	0.12	0.12	0.08	0.09	0.15	0.08	0.07	0.06
	E.S.		1.33	-0.24		3.98	-1.45		-0.58

4.3.1.1 Stroke (kicking) frequency

Stroke frequencies decreased greatly when using flippers in flutter kicking. The effect sizes were larger than 0.8. The average decrease of the stroke frequency during training for the FF group was 16.8% of the pre training value and 12.5% for the LF group. A decrease in kicking frequency was expected due to the increase in resistance to movement through the water due to the increased surface area pushing against the water. To continue kicking at the same frequency as in the barefoot condition would require a very large increase in torque at the joints. Table 4.3.2 presents the mean and SD variables of stroke frequency for the leg and foot flipper groups for pre training, training, and post training sessions. Effect sizes are indicated relative to the pre training (barefoot) condition.

Table 4.3.2 Mean values, variability (SD) and effect size (E.S., mean values relative to the pre training session) of stroke frequency over all sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	1.92	1.60	1.64	1.70	1.70	1.77	1.71	1.94
	SD	0.24	0.13	0.21	0.30	0.22	0.18	0.36	0.33
	E.S.		-1.34	-1.18	-0.91	-0.91	-0.61	-0.88	0.06
FF	Mean	1.96	1.57	1.61	1.71	1.71	1.58	1.63	1.84
	SD	0.19	0.22	0.22	0.30	0.26	0.25	0.46	0.35
	E.S.		-2.01	-1.81	-1.30	-1.29	-1.96	-1.71	-0.60

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

Although all swimmers' stroke frequencies decreased when kicking with flippers, the responses over the period of training varied among the three swimmers in the leg flipper group (Figure 4.3.1). The variability of the individuals in the LF group varied considerably across the training sessions. Interestingly, the variability of all three subjects in T1 was small relative to many of the other sessions.

When the constraint environment was returned to the barefoot condition in the post training session all three swimmers of the LF group increased frequency to values that were similar to the pre training session (E.S. 0.06).

The response of FFS2 and FFS3 is as one would expect, that is, a decrease in frequency in the training sessions compared to the pre training due to the increased surface area pushing against the water, and, given that they were familiar with training with the foot flippers, very little change across the training sessions. However, the response of FFS1 differed because a higher frequency than that of the pre training was recorded in T6 while wearing the flippers (Figure 4.3.2).

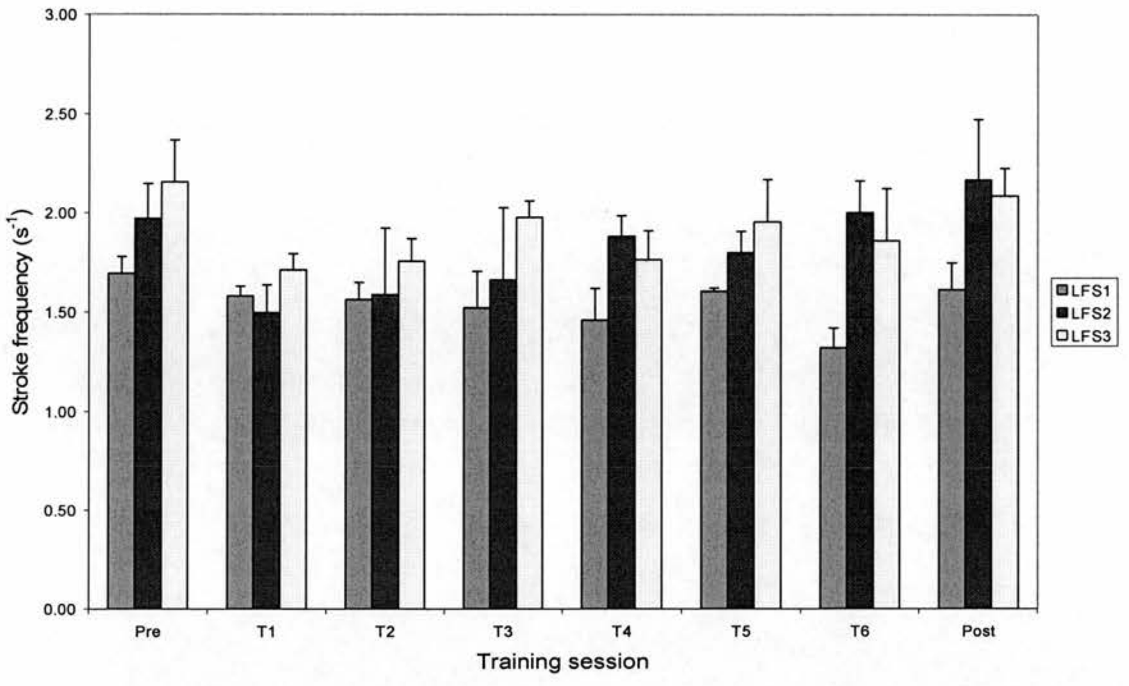


Figure 4.3.1 Stroke frequencies over all sessions for the LF group.

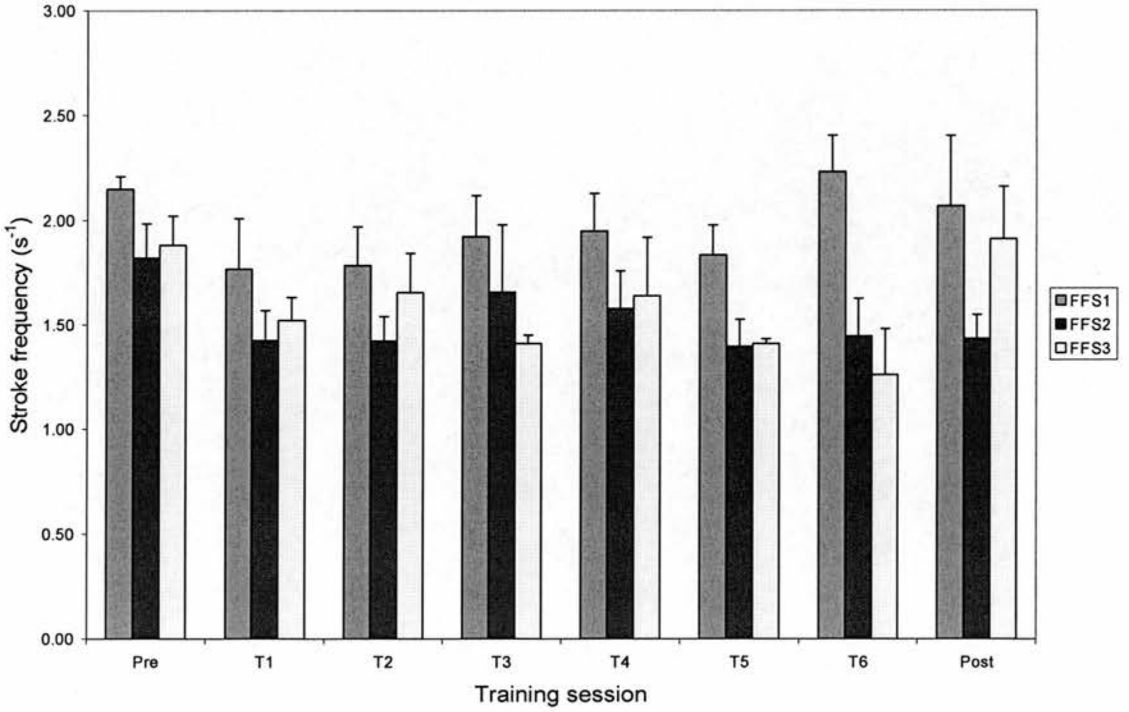


Figure 4.3.2 Stroke frequencies over all sessions for the FF group.

FFS1 and FFS3 returned to similar frequencies in the post training to that of the pre training. However, FFS2 did not. Given FFS2 was the only participant that did not return to kicking frequencies in the post training session similar to those in the pre training session it would seem that the effect of the change in constraints during the training sessions did not have a persistent effect on kicking frequencies when the swimmers returned to the barefoot condition. Therefore, it is likely that the continued reduction of kicking frequency of FFS2 in the post training session was related to other factors, for example, fatigue from other activity, or a loss of motivation.

There were no obvious differences in variability across sessions for the FF group.

These results indicated that although there were some slight variations in individual responses, swimmers adjusted their stroke frequencies immediately to a change in constraint conditions, both with the introduction of flippers, and when returning to barefoot kicking. There appeared to be a natural tendency to vary the kicking frequency within and between the training sessions. This may indicate the system 'exploring the movement possibilities'. There were no obvious trends with respect to the within participant variability across the sessions except that all three LF participants had small variability in T1 relative to many other sessions.

4.3.1.2 Stroke length

Table 4.3.1 and 4.3.3 indicate that stroke lengths increased greatly when using flippers with increases of 33% for the LF group and 44% for FF group with very large effect sizes of 1.24 for LF group and 3.38 for the FF group. Similar to stroke frequency, the change in stroke length in response to change from the barefoot to flippers and from flippers to barefoot was rapid. As a group, the LF group displayed very little change in stroke length from pre training to post training. However, there was a slight decrement in stroke length (0.05m) from pre to post of the FF group (E.S. -0.81). Inspection of Figure 4.3.4 reveals that this was due primarily to the decrement in stroke length of FFS3. Considering that there was little change in stroke frequency for FFS3 this result is hard to explain. Given that the swimmer was accustomed to changing from barefoot to flipper swimming in training, the decrement is probably related to factors such as fatigue or lack of motivation rather than effects of the training intervention on movement pattern.

Table 4.3.3 Mean values, variability (SD) and effect size (E.S., mean values relative to the one in pre training session) of stroke length over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	0.39	0.52	0.57	0.52	0.51	0.49	0.50	0.37
	SD	0.11	0.09	0.13	0.11	0.08	0.06	0.08	0.08
	E.S.		1.23	1.73	1.24	1.15	0.95	1.07	-0.12
FF	Mean	0.52	0.80	0.73	0.73	0.71	0.76	0.76	0.47
	SD	0.07	0.09	0.09	0.06	0.10	0.09	0.13	0.07
	E.S.		4.16	3.06	3.11	2.75	3.58	3.51	-0.81

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

Figure 4.3.3 and 4.3.4 indicate that, similar to the results for stroke frequency, there were some slight variations in individual responses. However, swimmers adjusted their stroke lengths immediately to a change in constraint conditions, both with the introduction of flippers, and when returning to barefoot kicking.

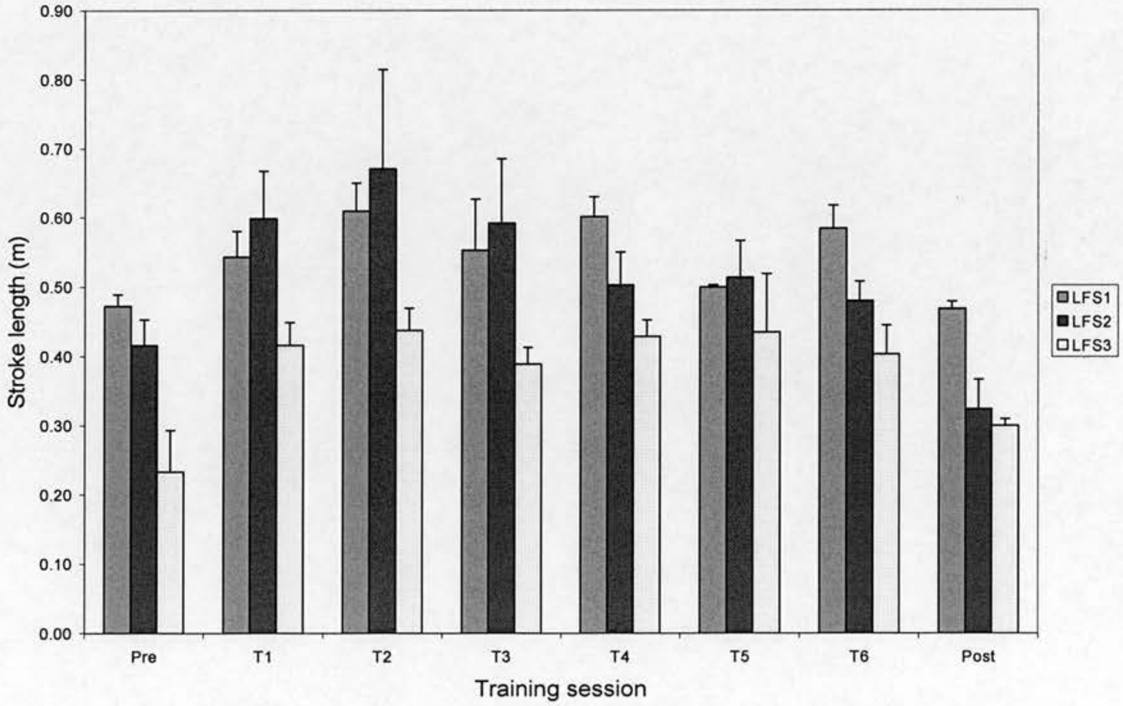


Figure 4.3.3 Stroke length over all sessions for the LF group.

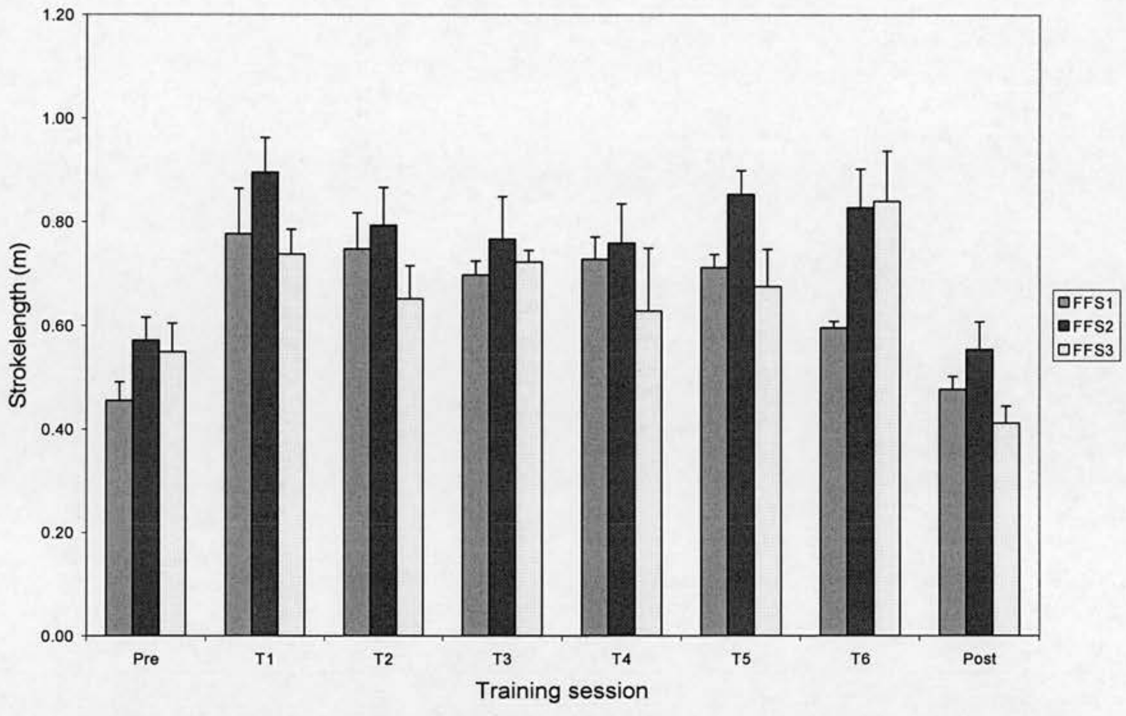


Figure 4.3.4 Stroke length over all sessions for the FF group.

There were no obvious trends with respect to within participant variability of swimmers in both LF and FF groups. When returning to barefoot kicking, swimmers of both LF and FF groups had smaller or similar variability to that in pre training. Similar to there being a natural tendency to vary the kicking frequency there was a tendency to vary stroke length. This is a further indication of the system 'exploring the movement possibilities'.

4.3.1.3 Swimming speed

Speed is the product of stroke frequency and stroke length and so is directly dependent on the results for stroke frequency and stroke length presented above. Stroke speeds increased greatly when using both foot flippers and leg flippers. The LF group increased speed by $0.14 m.s^{-1}$ (19.4 %) and the FF group by $0.19 m.s^{-1}$ (18.8 %) in the training sessions compared with the barefoot pre training session. This represented an effect size of 0.86 and 2.88 respectively. For the LF group the post training speed was $0.2 m.s^{-1}$ less than the pre training speed and the effect size was small (-0.14). However, for the FF group there was a considerable reduction in stroke speed ($0.16 m.s^{-1}$) and the effect size (-2.50) was considerable. The fact that the decrement in performance was much larger for the FF group is surprising given that the FF group was accustomed to changing between the foot flipper and barefoot constraints. In view of the fact that there was no decrement in the indicators of skilled movement pattern, that is, percent power in the fundamental harmonic and velocity index, and that there were decrements in stroke frequency, the evidence suggests that the decrement in speed from pre to post training was due to factors other than deterioration in the movement pattern such as fatigue or loss of motivation. Figure 4.3.6 indicates that the decrement was due to a decrease in speed of FFS2 and FFS3. FFS2's decrease in speed appears to be linked to his decrease in stroke frequency (Figure 4.3.2) while the decrease by FFS3 was linked to a decrease in stroke length (Figure 4.3.4).

Table 4.3.4 Mean values, variability (SD) and effect size (E.S., mean values relative to the one in pre training session) of swimming speed over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	0.72	0.82	0.91	0.86	0.86	0.86	0.84	0.70
	SD	0.16	0.09	0.12	0.10	0.10	0.07	0.11	0.07
	E.S.		0.62	1.22	0.86	0.85	0.87	0.71	-0.14
FF	Mean	1.01	1.25	1.16	1.24	1.20	1.20	1.18	0.85
	SD	0.07	0.13	0.11	0.15	0.17	0.15	0.13	0.12
	E.S.		3.56	2.21	3.40	2.81	2.75	2.57	-2.50

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

The maximum speeds during the training sessions for the LF group were attained during T2 session (Table 4.3.4). T1 had the lowest speeds. Thus, it appears that there may have been a brief process of finding the most appropriate stroke frequency to optimize performance in the changed and unfamiliar constraint environment. The best speeds for the FF group were achieved in the first training session with the foot flipper indicating rapid adjustment to the changed but familiar constraint environment.

When the task constraints returned to the barefoot condition, all swimmers except swimmer LFS3 and FF1 had lower speeds than that of pre training session. It is interesting that even the control group subjects had a decrement in performance. The evidence suggests that the results for the post training session were affected by factors such as fatigue or loss of motivation and differences between the pre and post training tests were unrelated to the quality of the movement pattern (Figure 4.3.5-6).

There were no obvious trends with respect to within participant variability across sessions.

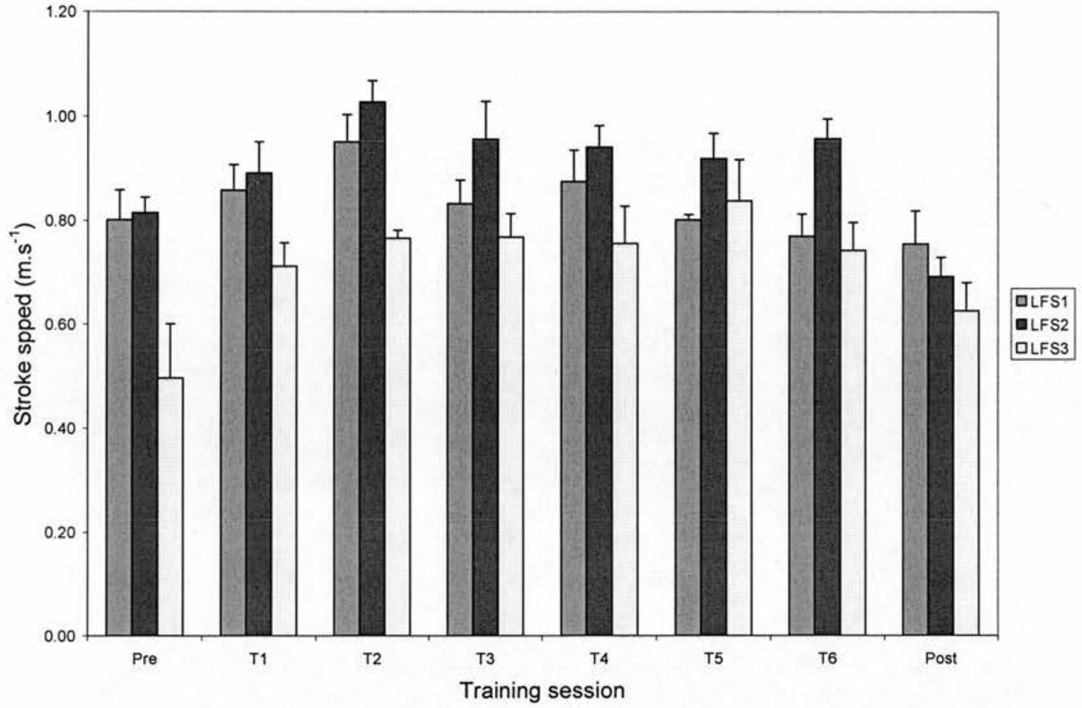


Figure 4.3.5 Stroke speed over all sessions for the LF group.

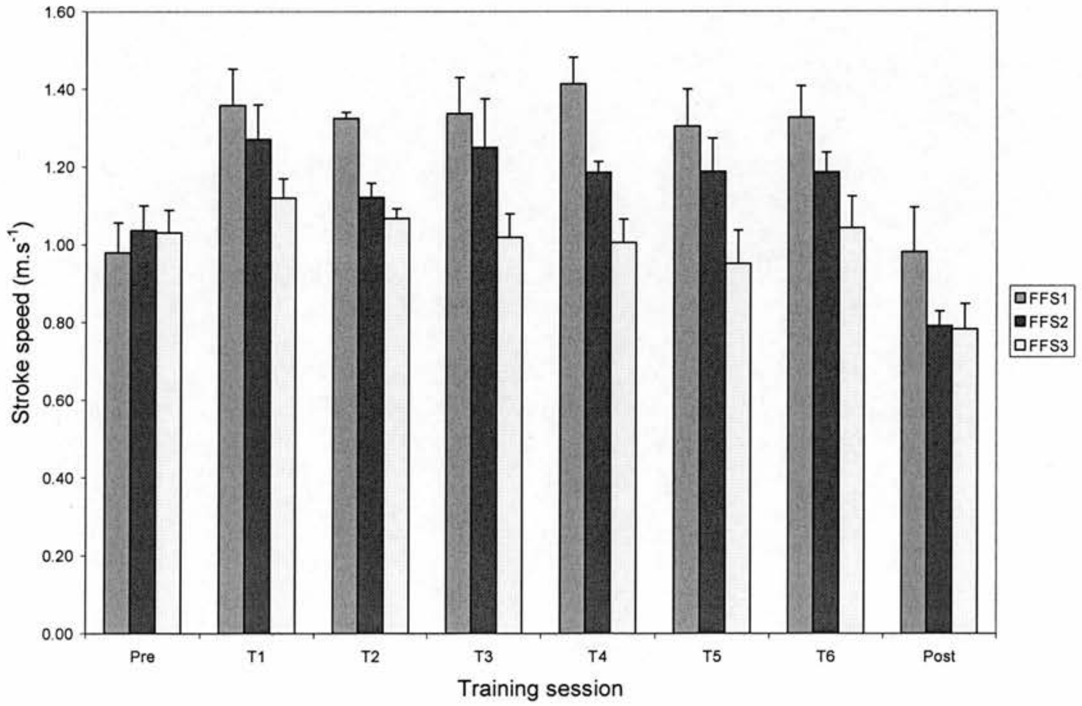


Figure 4.3.6 Stroke speed over all sessions for the FF group.

4.3.1.4 Stroke index

Stroke index is the product of stroke length multiplied by the average stroke speed and so is dependent on those. It is frequently used as a means of separating the performances of swimmers of similar speeds in terms of their efficiency. More efficient swimmers can travel at the same speed with longer stroke lengths and slower stroke frequencies.

Stroke index increased markedly from barefoot to flipper conditions from 0.29 to 0.45 $m^2.s^{-1}$ (E.S. 1.33) for the LF group and from 0.53 to 0.90 $m^2.s^{-1}$ (E.S. 3.98) for the FF group. Although the groups were quite different with respect to their stroke index for the barefoot condition, the greater increase in the FF group in terms of effect size indicated that the foot flippers provided a greater advantage than the leg flippers in terms of propulsive efficiency.

Table 4.3.5 Mean values, variability (SD) and effect size (E.S., mean values relative to the one in pre training session) of stroke index over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	0.29	0.43	0.53	0.45	0.44	0.42	0.42	0.27
	SD	0.12	0.12	0.17	0.12	0.10	0.08	0.07	0.08
	E.S.		1.17	2.02	1.31	1.24	1.08	1.04	-0.24
FF	Mean	0.53	1.01	0.85	0.90	0.86	0.92	0.89	0.40
	SD	0.09	0.17	0.15	0.10	0.19	0.16	0.10	0.08
	E.S.		5.07	3.38	3.98	3.45	4.10	3.79	-1.45

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

When the task constraints returned to the original barefoot condition, two swimmers (LFS3 and FFS1) had higher stroke indices than during the pre training session. The remaining swimmers' stroke indices were lower than that of the pre training session. One needs to be cautious when interpreting this apparent deficit in performance from pre to post training. Given that there was a deficit in performance for two of the control group it is likely that the deterioration was due, at least in part, to factors other than the effect of the training intervention. These could be, for example, motivation or fatigue levels on the day of testing. The likelihood of this is increased when one considers that many of the subjects decreased their stroke index over the period of the training intervention.

Given that all of the FF group had the highest of their stroke indices in T1 (Figure 4.3.8) and that all of the LF group had their highest indices in T2 (Figure 4.3.7) it appears likely that change in performance during the training sessions was affected predominantly by motivation or fatigue for both FF and LF groups but there is a possibility that the improvement in performance from T1 to T2 for the LF group was related to a learning effect. That is, adjustment to the new constraint environment may not have occurred completely in T1.

This must be considered in conjunction with the results for the percentage power in the first Fourier Harmonic and for the velocity index, both of which indicated that the movement patterns were appropriate for all LF subjects in T1. Thus, while the movement pattern may have been appropriate immediately after changing to the new constraint condition, there remained scope for improvement in stroke index by finding the best combination of kicking frequency and movement amplitude.

Although there were no obvious trends with respect to within participant variability for both LF and FF groups, it is noteworthy that the variability when returning to the barefoot condition was modest compared to that in many other sessions including the pre training session. Certainly, it can be concluded that returning to the barefoot condition after the flipper sessions did not 'throw the system into chaos' as far as stroke index, or any of the other stroke parameters were concerned.

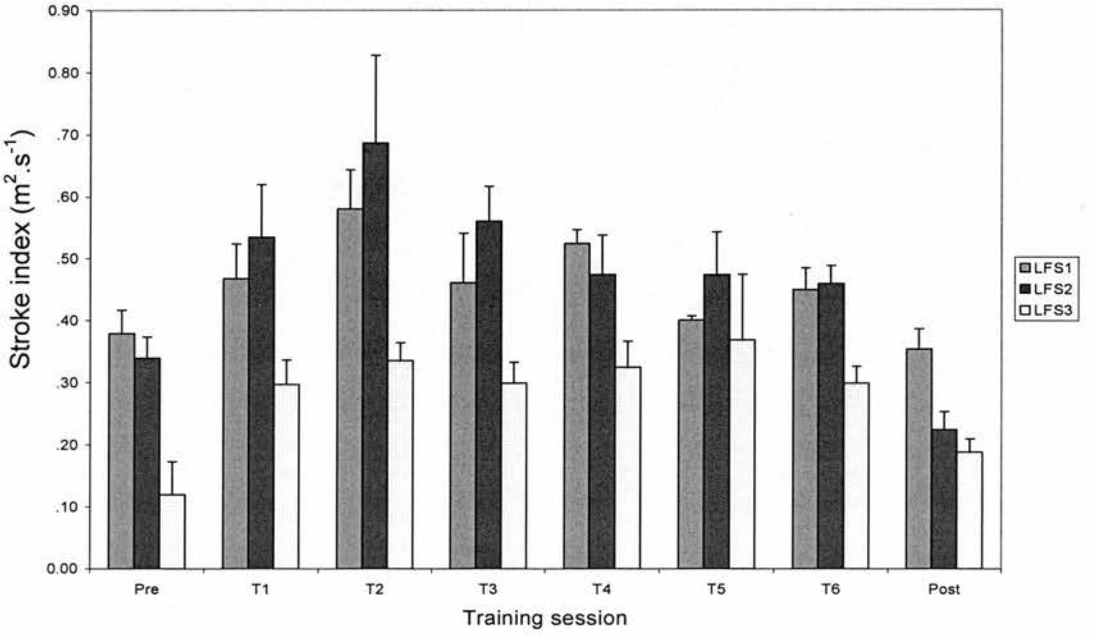


Figure 4.3.7 Stroke index over all sessions for the LF group.

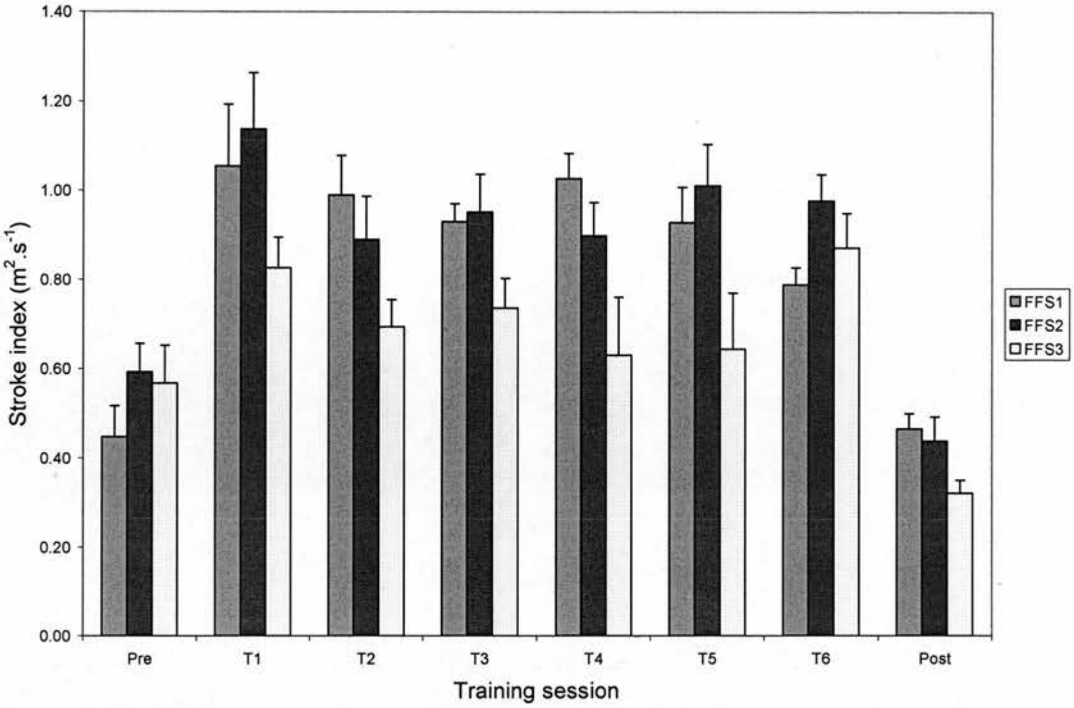


Figure 4.3.8 Stroke index over all sessions for the FF group.

4.3.2 Angular motion of joints

4.3.2.1 Angular displacement of the hip joint

Table 4.3.6 Mean values, variability (SD) and effect size (E.S., mean values relative to pre training session) of range of motion (ROM), maximum (Max.) and minimum (Min.) of hip joint in pre training, training (mean pooled) and post training session for LF, FF and CO groups.

		LF			FF			CO	
		Pre-train	Train-pool	Post-train	Pre-train	Train-pool	Post-train	Pre-train	Post-train
ROM	Mean	23.79	25.83	22.47	23.09	22.64	23.13	25.68	27.68
	SD	5.81	5.88	3.16	9.12	6.14	8.85	7.91	5.26
	E.S.		0.35	-0.23		-0.05	0.00		0.25
Max.	Mean	185.52	184.05	185.39	186.54	187.01	184.35	189.89	187.46
	SD	7.59	6.61	7.99	11.13	9.46	9.05	7.39	6.16
	E.S.		-0.19	-0.02		0.04	-0.20		-0.33
Min.	Mean	161.73	157.66	161.38	163.44	164.37	161.22	164.21	159.78
	SD	5.23	7.41	5.99	17.20	11.73	11.66	10.86	4.14
	E.S.		-0.78	-0.07		0.05	-0.13		-0.41

Table 4.3.6 presents the average values, variability and effect size of range of motion (ROM), maximum (Max.) and minimum (Min.) of hip joint in pre training, training (mean pooled) and post training session for LF, FF and CO groups. The only notable change in angular displacement across sessions was a moderately decreased minimum hip angle when using the leg flipper (E.S. 0.78) and this slightly increased the ROM (E.S. 0.35).

There were no distinct trends with respect to variability of hip joint measures across sessions. However, it is noteworthy that variability was larger for the FF group than LF or CO groups. Table 4.3.7 displays the ROM data of group across experimental sessions. There was a trend among both FF and LF groups to reduce the ROM in T5 and T6. This would appear to be linked to the previous observation that performances, in terms of swimming speed and stroke index but not with respect to the %power and wave velocity index, declined towards the end of the training sessions. Again, this indicates a decrement due to fatigue or reduced motivation.

Both LF and FF groups returned to ROM's in the post training that were similar to those in the pre training. However, inspection of the individual subject data (Figure 4.3.9 and 4.3.10) indicates that the members of the LF group all had considerably different ranges of motion in the post training compared to the pre training.

Table 4.3.7 Mean values, variability (SD) and effect size (E.S.) of ROM of the hip joint over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	23.79	27.18	28.01	25.98	26.62	23.43	23.60	22.47
	SD	5.81	7.51	8.82	3.72	5.28	3.98	2.85	3.16
	E.S.		0.58	0.73	0.38	0.49	-0.06	-0.03	-0.23
FF	Mean	23.09	24.12	25.48	23.65	20.32	21.94	20.15	23.13
	SD	9.12	7.47	5.19	6.52	5.39	5.96	4.95	8.85
	E.S.		0.11	0.26	0.06	-0.30	-0.13	-0.32	0.00

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

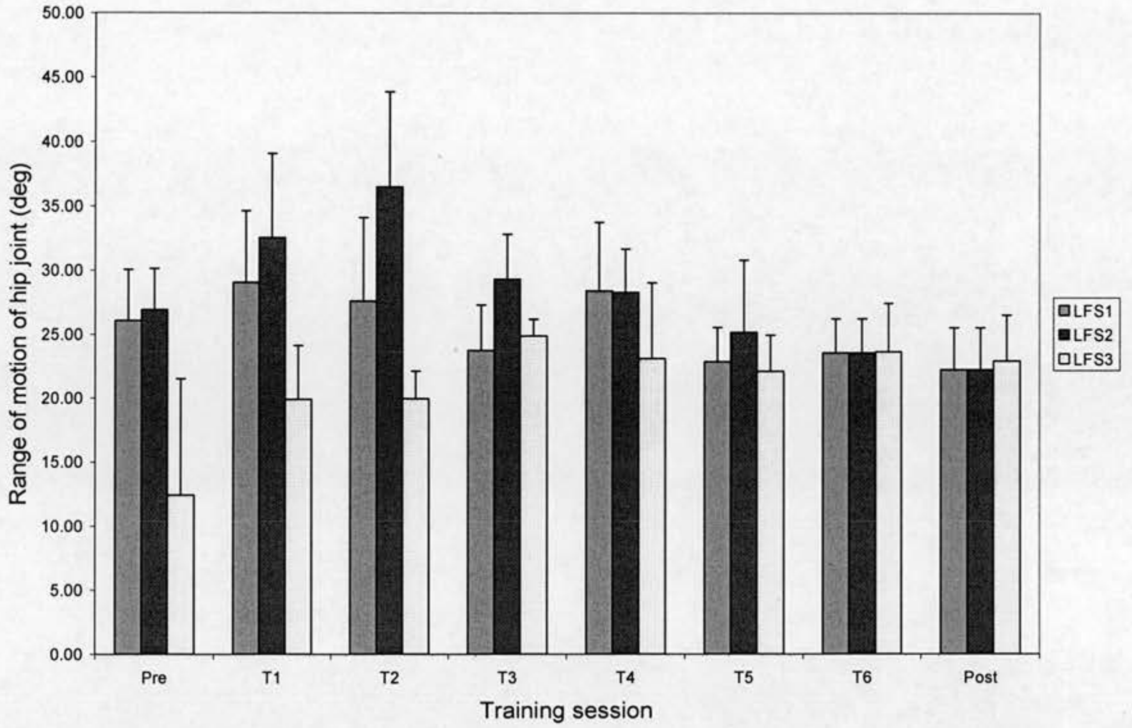


Figure 4.3.9 ROM of the hip joint over all sessions for the LF group.

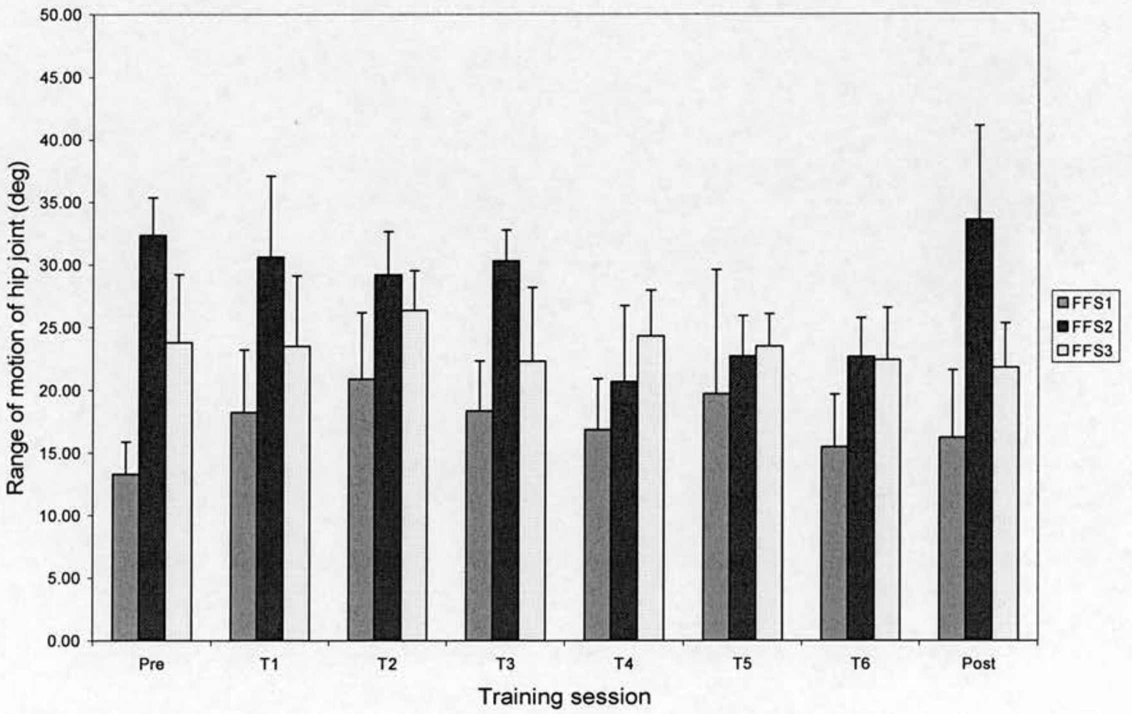


Figure 4.3.10 ROM of the hip joint over all sessions for the FF group.

Table 4.3.8 displays the maximum and minimum data of hip joint angle across experimental sessions. The data indicate that there were no real changes in maximum or minimum hip angle across the sessions for the FF group. In the LF group the reduction in minimum hip angle evident in the pooled training session's data was skewed towards the early training trials. Inspection of the individual data in Figure 4.3.13 indicates that this trend was apparent only for LF1 rather than for all members of the LF group.

Thus, with the exception of LF1 there was little change in hip angles across training sessions.

Table 4.3.8 Mean values, variability (SD) and effect size (E.S.) of maximum (Max.) and minimum (Min.) angles of the hip joint over all sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Max.									
LF	Mean	185.52	185.41	183.08	184.19	183.66	183.33	184.57	185.39
	SD	7.59	6.64	7.52	7.80	5.41	7.00	5.85	7.99
	E.S.		-0.01	-0.32	-0.17	-0.24	-0.29	-0.13	-0.02
FF	Mean	186.54	190.98	187.02	183.32	187.58	188.03	185.15	184.35
	SD	11.13	10.79	11.12	6.92	9.77	10.04	6.94	9.05
	E.S.		0.40	0.04	-0.29	0.09	0.13	-0.12	-0.20
Min.									
LF	Mean	161.73	155.65	155.07	158.21	157.04	159.31	160.62	161.38
	SD	5.23	10.94	5.90	6.37	5.79	7.48	6.70	5.99
	E.S.		-1.16	-1.27	-0.67	-0.90	-0.46	-0.21	-0.07
FF	Mean	163.44	166.87	161.53	159.68	167.25	166.09	165.00	161.22
	SD	17.20	12.09	13.44	9.04	13.36	12.59	9.02	11.66
	E.S.		0.20	-0.11	-0.22	0.22	0.15	0.09	-0.13

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

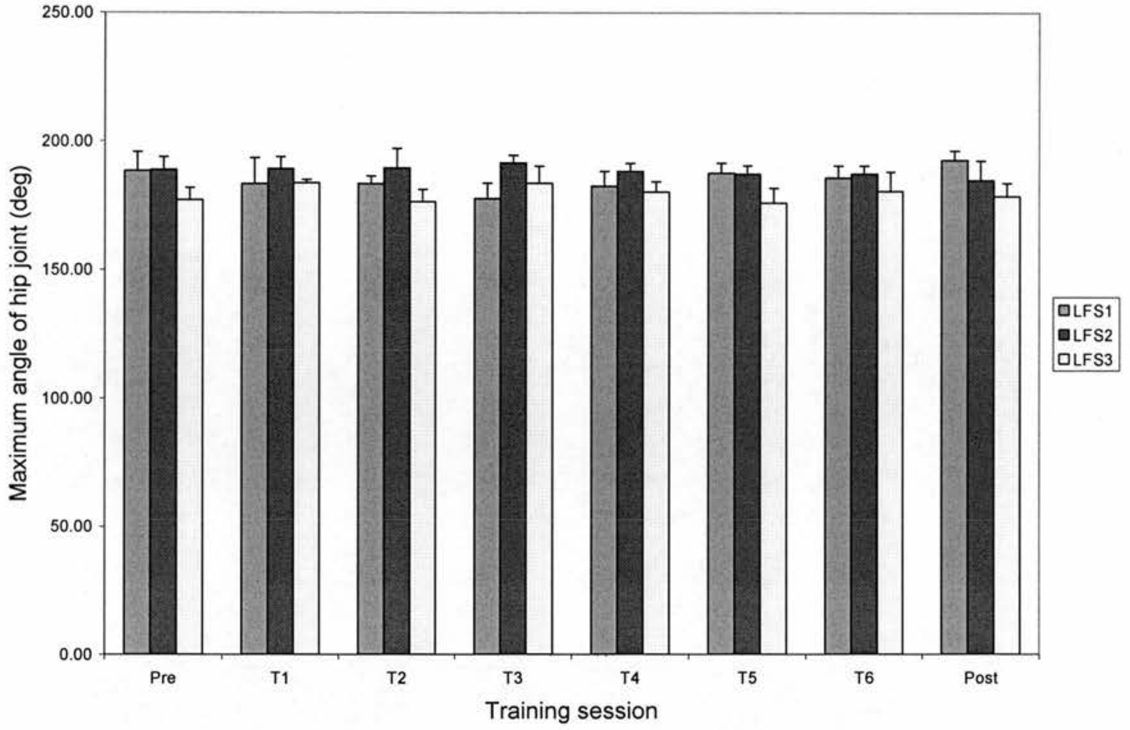


Figure 4.3.11 Maximum angle of the hip joint over all sessions for the LF group.

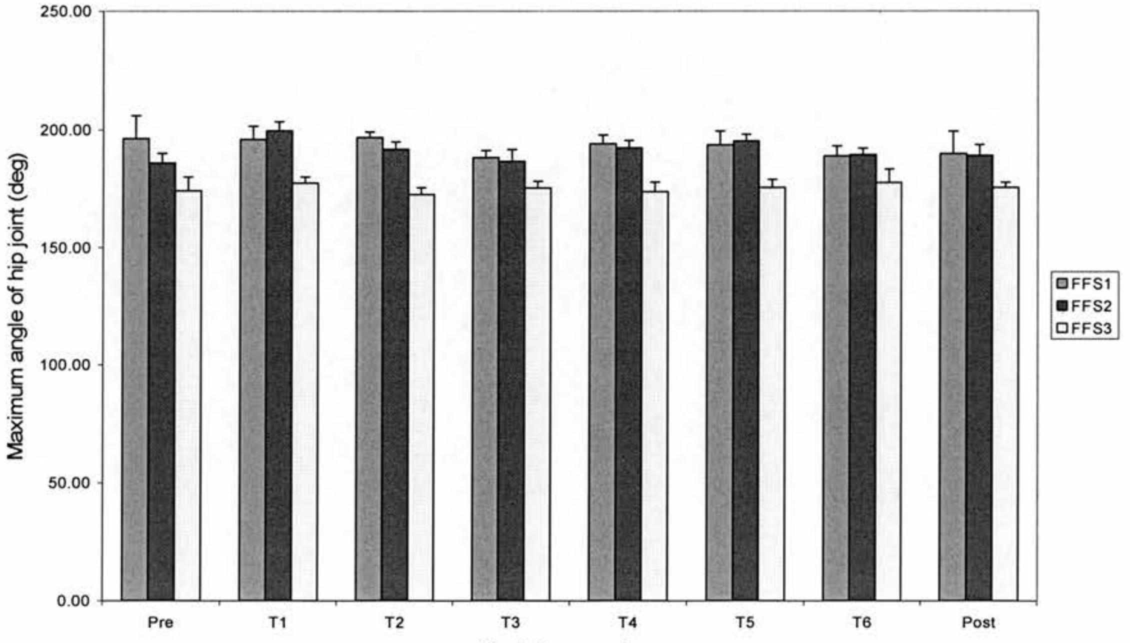


Figure 4.3.12 Maximum angle of the hip joint over all sessions for the FF group.

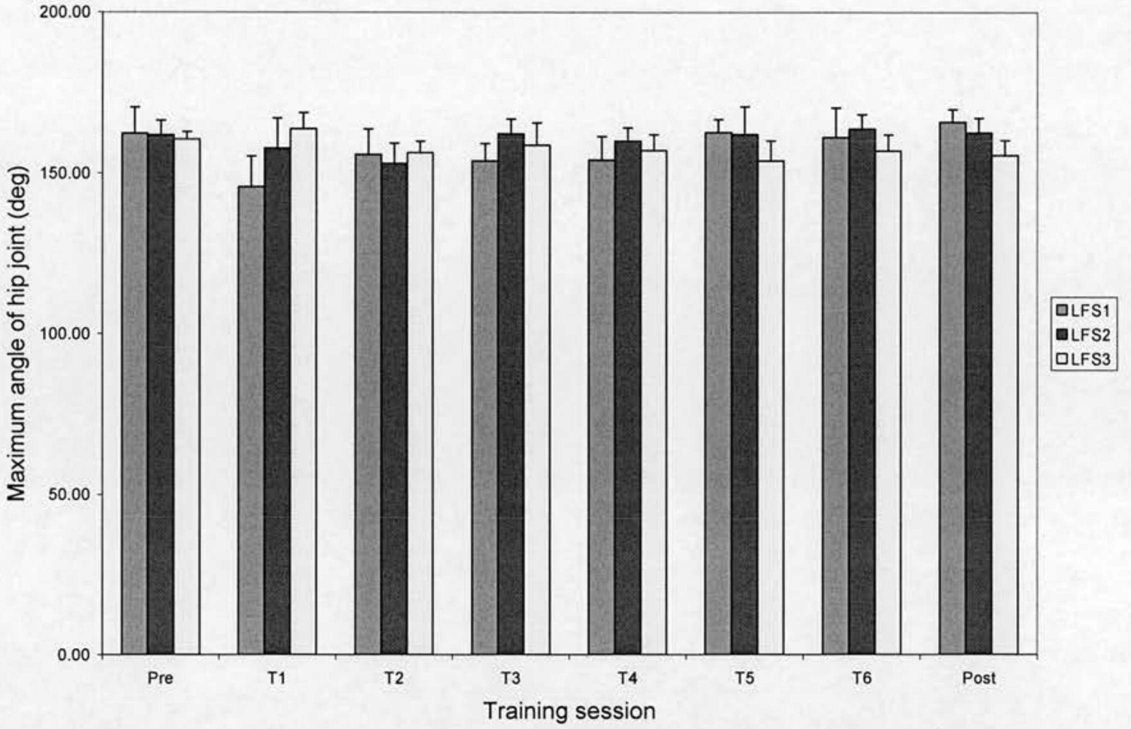


Figure 4.3.13 Minimum angle of the hip joint over all sessions for the LF group.

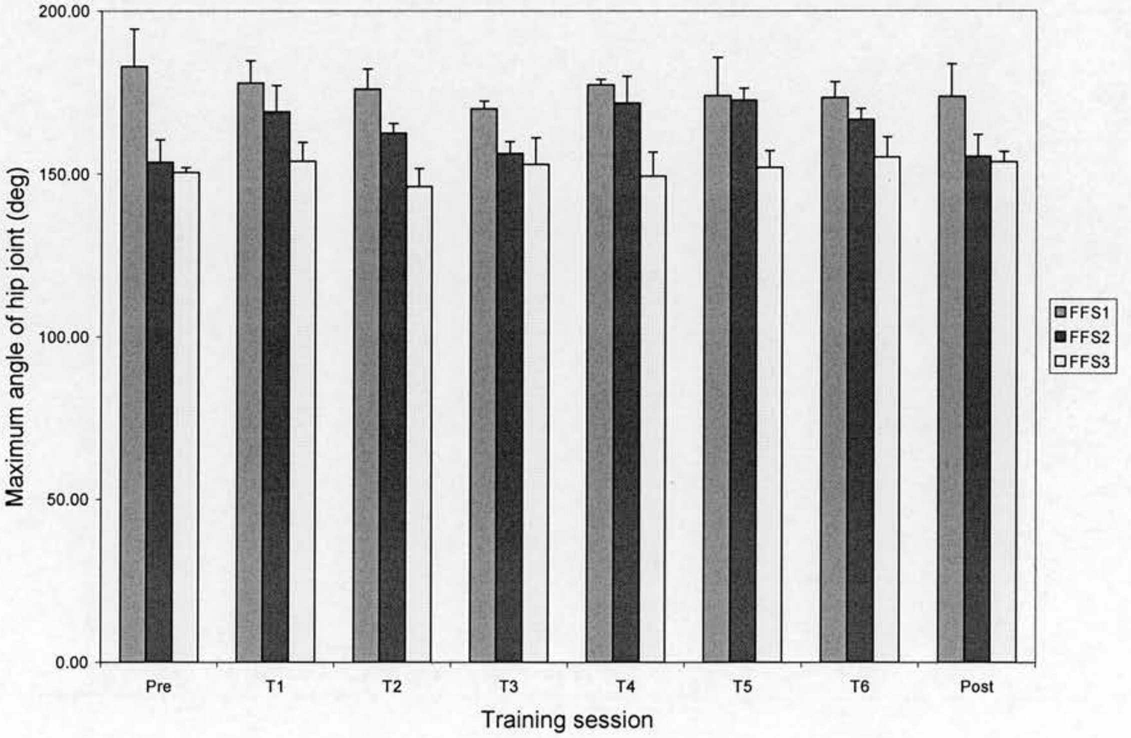


Figure 4.3.14 Minimum angle of the hip joint over all sessions for the FF group.

4.3.2.2 Angular displacement of the knee joint

Table 4.3.9 presents the average values, variability and effect size of maximum, minimum and range of motion (ROM) of knee joint in pre training, training (mean pooled) and post training session for LF, FF and CO groups. Table 4.3.10 presents those data for the individual training sessions.

There was considerable variability in knee angles among all groups and across all sessions. Thus, despite differences in means, effect sizes were small to modest. One exception is the maximum knee angle for the FF group when wearing flippers. The reduced mean angle (171.5 degrees) indicates that the swimmers were not fully extending the knee when wearing foot flippers (E.S. -1.68). A major difference in response to wearing flippers is evident in the mean minimum angles during the training sessions. The LF group decreased the minimum angle (increased flexion) while the FF group increased it. Thus, the ROM of the knee joint for LF group knee joints (63 degrees) was 25 degrees greater than that of the FF group (38 degrees) although there was 8 degrees of difference between the groups in the pre training session (Figure 4.3.15-16).

When returning to barefoot kicking both LF and FF group had a knee joint ROM similar to the pre training session. The relatively small variability indicated that adaptation back to the constraint environment associated with the barefoot condition was rapid.

Table 4.3.9 Mean values, variability (SD) and effect size (E.S., mean values relative to pre training session) of range of motion (ROM), maximum (Max.) and minimum (Min.) of knee joint in pre training, training (mean pooled) and post training session for LF, FF and CO groups.

		LF			FF			CO	
		Pre-train	Train-pool	Post-train	Pre-train	Train-pool	Post-train	Pre-train	Post-train
ROM	Mean	59.89	63.41	58.30	51.73	38.26	53.56	56.01	60.25
	SD	10.91	10.38	7.64	17.02	10.26	16.03	5.92	7.64
	E.S.		0.32	-0.15		-0.79	0.11		0.72
Max.	Mean	180.64	177.44	175.59	177.67	171.48	175.03	177.67	175.48
	SD	4.45	5.94	5.40	3.68	8.30	6.91	8.15	5.86
	E.S.		-0.72	-1.14		-1.68	-0.72		-0.27
Min.	Mean	120.76	114.03	117.29	125.94	133.25	121.46	121.66	115.23
	SD	10.61	9.70	10.86	16.09	11.50	11.55	11.12	5.19
	E.S.		-0.63	-0.33		0.45	-0.28		-0.58

Table 4.3.10 Mean values, variability (SD) and effect size (E.S.) of ROM of knee joint over all sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	59.89	57.59	68.13	67.03	65.26	62.78	59.63	58.30
	SD	10.91	16.07	8.75	8.34	9.68	6.24	7.09	7.64
	E.S.		-0.21	0.76	0.66	0.49	0.27	-0.02	-0.15
FF	Mean	51.73	38.98	39.23	39.94	40.01	38.03	33.36	53.56
	SD	17.02	10.46	14.02	14.94	7.35	4.51	5.62	16.03
	E.S.		-0.75	-0.73	-0.69	-0.69	-0.81	-1.08	0.11

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

Table 4.3.11 reveals interesting data regarding the trends across training sessions for minimum and maximum knee angles. In particular, the minimum knee angle increased in T1 compared to that in pre training. That is, there was less knee flexion and the range of motion was reduced. In T2 and subsequent training sessions, the minimum knee angle was reduced (more flexion) and the range of knee joint motion increased as a result. The fact that the first response was 'in the wrong direction', and was actually in the same direction as that used for the familiar task of kicking with foot flippers indicates that although an appropriate movement pattern was generated immediately (as indicated by the % power and velocity index results) the system had not yet 'discovered' the appropriate knee range of motion for the task (Figure 4.3.17-18).

This adds to the evidence that some learning was required, not in terms of the general movement pattern, but in terms of the range of joint motion that would optimize performance. This ties in well with the previous observation that performance indicators such as swimming speed and stroke index were higher in T1 than T2 for the LF group.

Figure 4.3.19 indicates that LF1 and LF2 both increased the minimum knee angle from pre training to T1. LF2 decreased the minimum knee angle slightly. All of LF1, LF2 and LF3 then reduced their minimum knee angle for T2 and maintained the angles at similar levels for T3 and T4. Thereafter the angles tended to increase. It is logical to assume that the reduced minima and ranges of motion in T5 and T6 were due to factors such as declining motivation rather than further searching for the optimal joint motion. This meshes well with the previously observed decrements in performance indicated by the swimming speeds and stroke indices.

Table 4.3.11 Mean values, variability (SD) and effect size (E.S.) of maximum (Max.) and minimum (Min.) angles of knee joint over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Max.									
LF	Mean	180.64	181.62	178.15	177.13	175.39	177.23	175.10	175.59
	SD	4.45	6.39	6.95	4.89	6.99	3.22	4.49	5.40
	E.S.		0.22	-0.56	-0.79	-1.18	-0.77	-1.25	-1.14
FF	Mean	177.67	177.39	171.83	171.79	171.59	167.48	168.83	175.03
	SD	3.68	7.19	8.23	9.41	7.20	8.61	6.35	6.91
	E.S.		-0.08	-1.59	-1.60	-1.65	-2.77	-2.40	-0.72
Min.									
LF	Mean	120.76	124.04	110.02	110.10	110.12	114.45	115.47	117.29
	SD	10.61	12.90	5.43	6.64	6.64	6.96	10.11	10.86
	E.S.		0.31	-1.01	-1.00	-1.00	-0.59	-0.50	-0.33
FF	Mean	125.94	138.41	132.60	131.85	131.63	129.45	135.47	121.46
	SD	16.09	8.00	14.33	14.32	11.52	10.55	8.26	11.55
	E.S.		0.77	0.41	0.37	0.35	0.22	0.59	-0.28

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

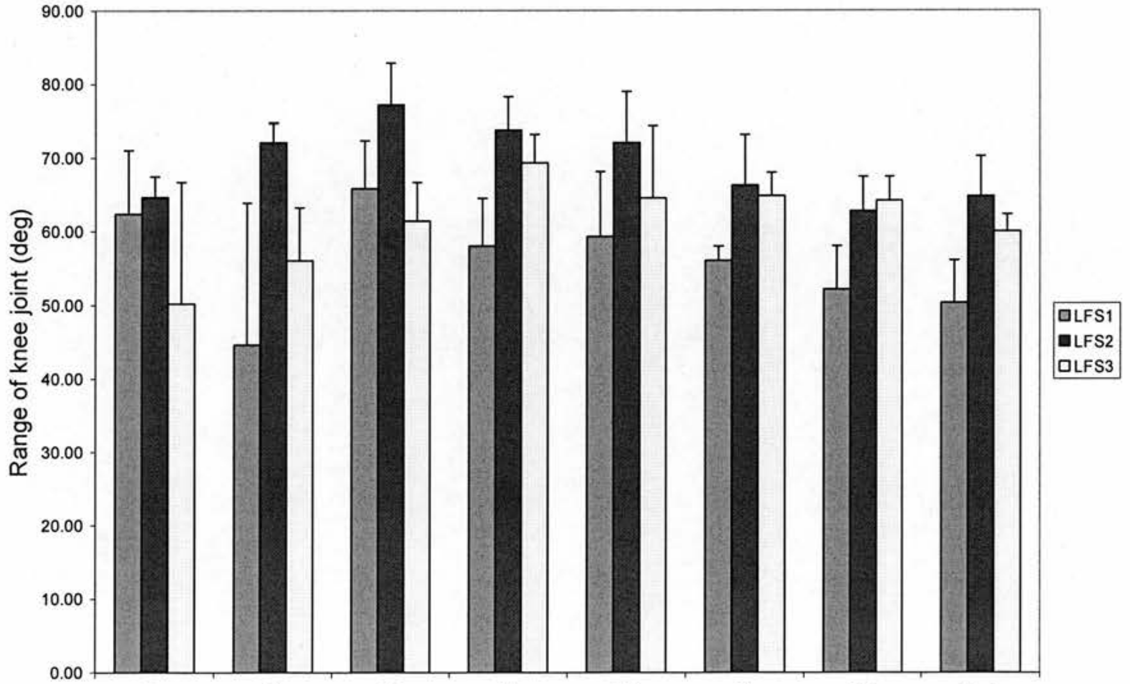


Figure 4.3.15 ROM of the knee joint over all sessions for the LF group.

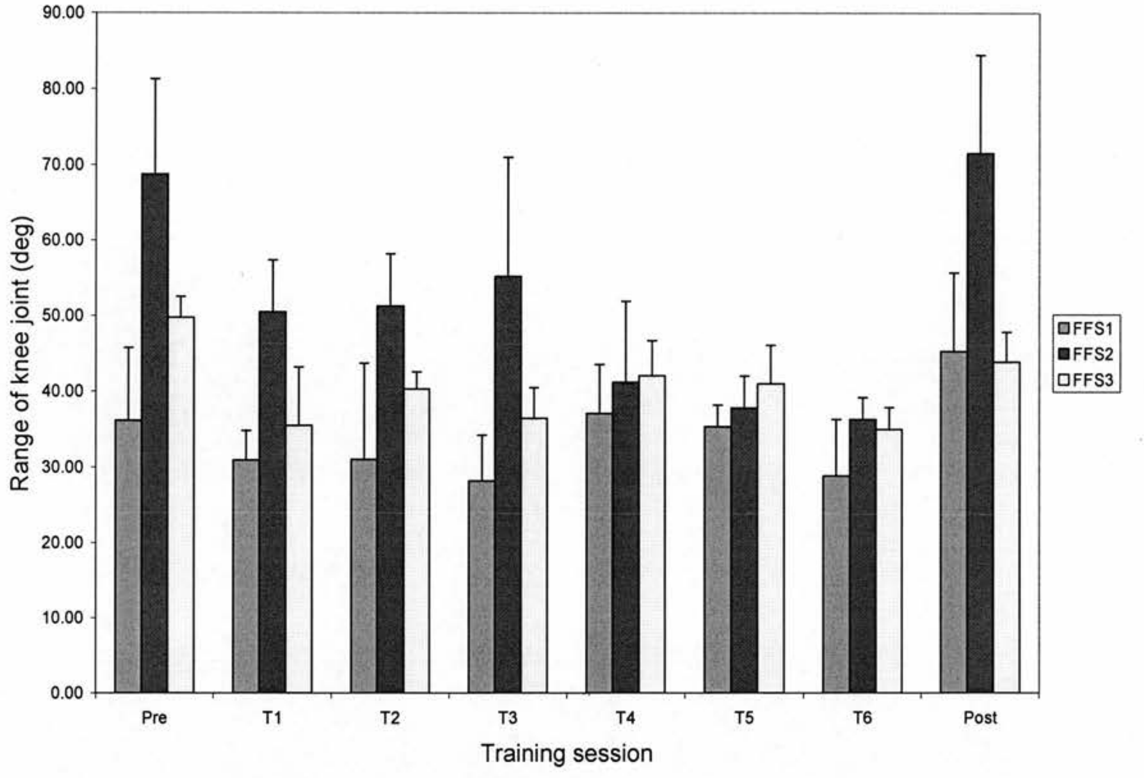


Figure 4.3.16 ROM of the knee joint over all sessions for the FF group.

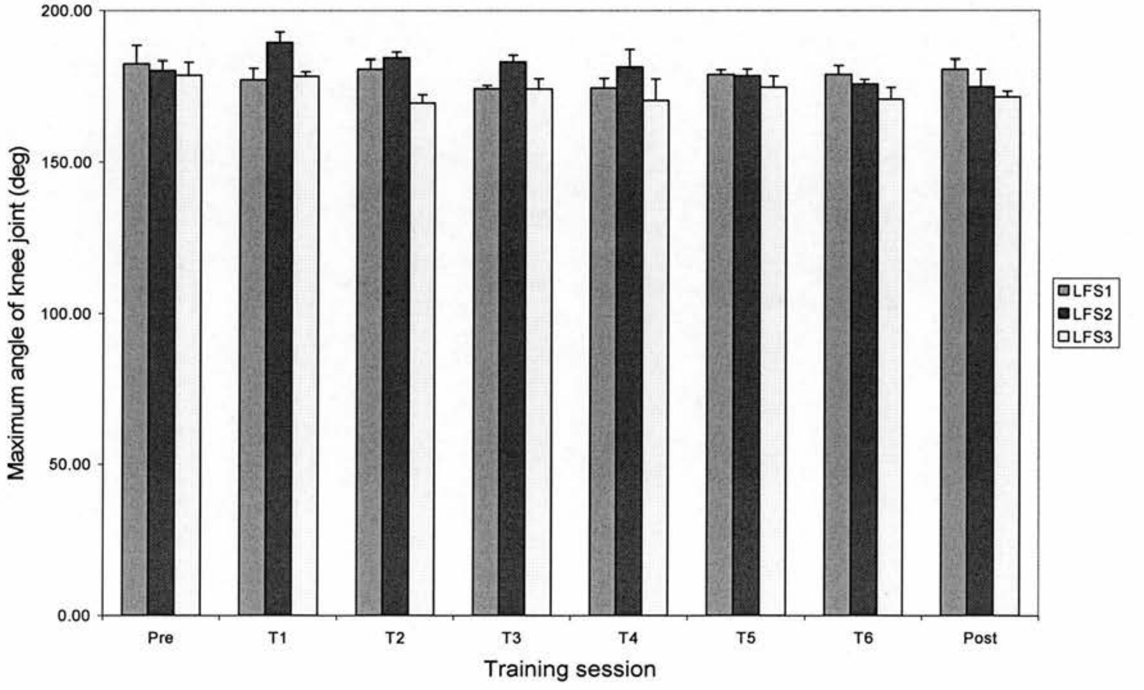


Figure 4.3.17 Maximum angle of the knee joint over all sessions for the LF group.

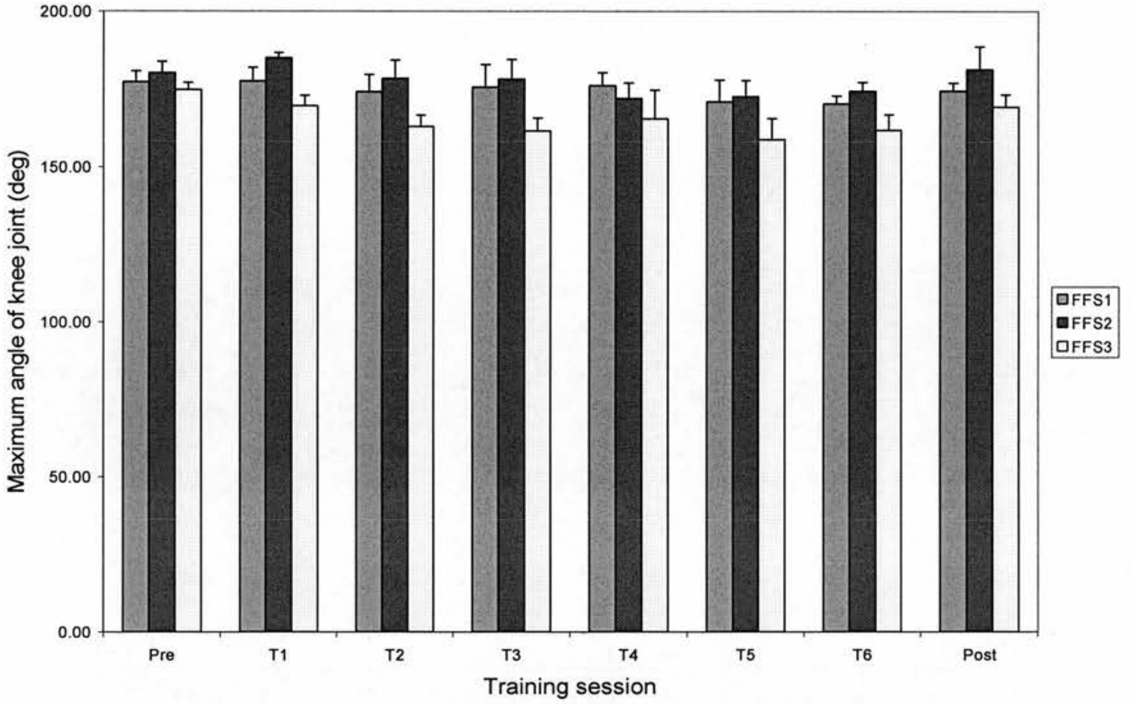


Figure 4.3.18 Maximum angle of the knee joint over all sessions for the FF group.

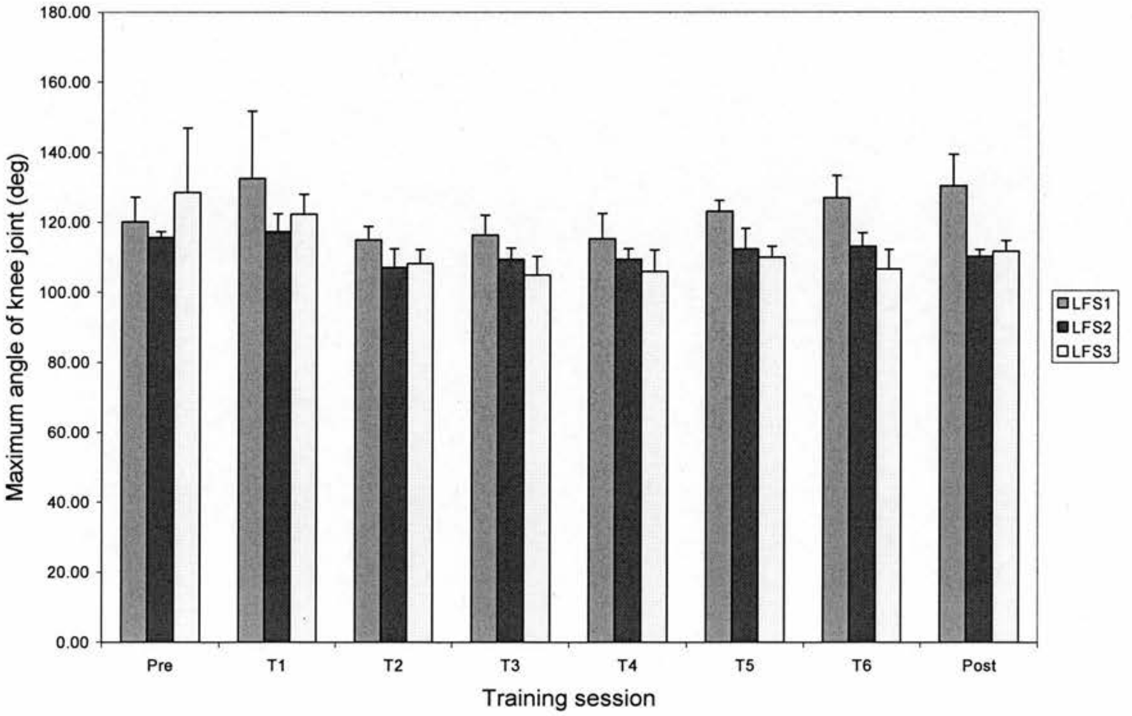


Figure 4.3.19 Minimum angle of the knee joint over all sessions for the LF group.

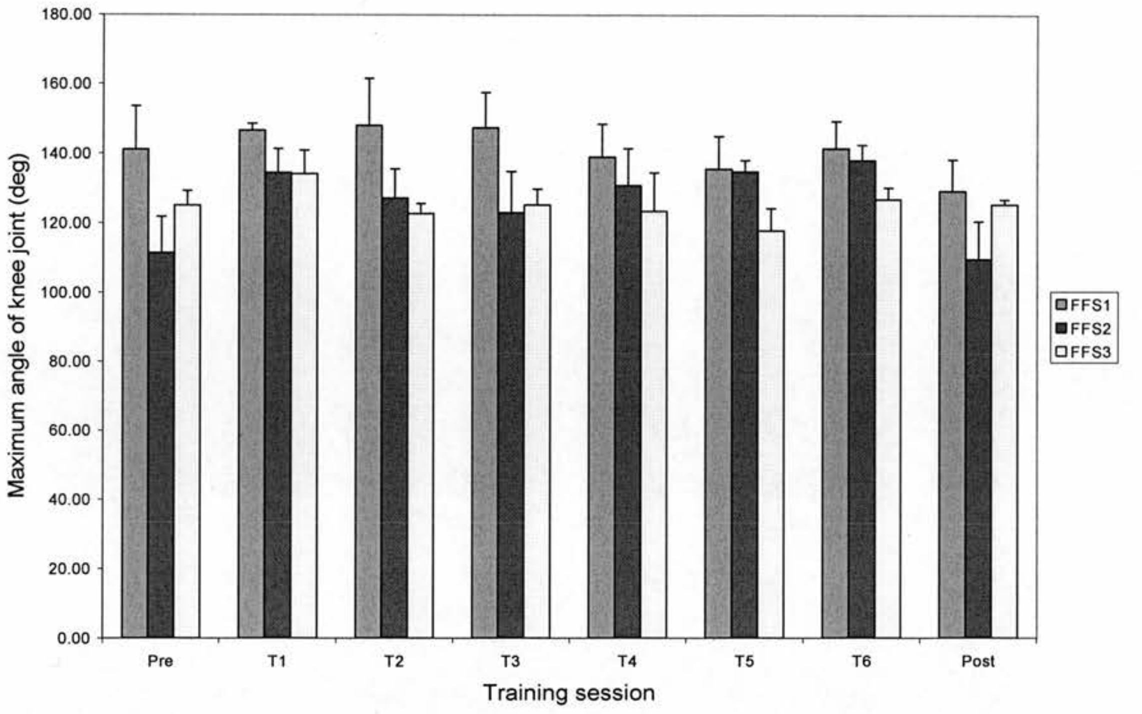


Figure 4.3.20 Minimum angle of the knee joint over all sessions for the FF group.

4.3.2.3 Angular velocities of hip and knee joints

Table 4.3.12 display mean values, variability and effect size of maximum and minimum hip joint angular velocity in pre training, training (mean pooled) and post training session for LF, FF and CO groups. Table 4.2.13 provides the details for the individual training sessions T1 to T6 for LF and FF groups.

Across all sessions the peak velocity of extension was smaller than that of flexion. It would appear that flexion was more vigorous than extension and drove the downbeat as the most propulsive part of the kick. When swimming with flippers, LF group had higher peak extension and flexion angular velocities than the FF group. This is not unexpected given that the moment arm of the foot flipper is greater than that of the leg flipper thereby requiring greater joint torques to move the flipper through the water.

When returning to barefoot kicking, the peak flexion velocities of LF and FF group were similar to that of the pre training session. The peak extension velocity of the LF group was larger and that of the FF group was slightly smaller than their corresponding values of the pre training session.

Table 4.3.12 Mean values, variability (SD) and effect size (E.S., mean values relative to pre training session) of maximum (Max.) and minimum (Min.) of hip joint angular velocity in pre training, training (mean pooled) and post training session for LF, FF and CO groups.

		LF			FF			CO	
		Pre-train	Train-pool	Post-train	Pre-train	Train-pool	Post-train	Pre-train	Post-train
Max.	Mean	131.53	153.14	153.72	149.10	118.51	137.81	172.21	182.59
	SD	34.24	48.48	35.31	53.27	30.99	46.36	40.82	28.28
	E.S.		0.63	0.65		-0.57	-0.21		0.25
Min.	Mean	-166.54	-178.10	-171.16	-157.45	-132.79	-164.36	-203.89	-217.12
	SD	32.64	45.91	38.34	58.08	41.72	54.12	47.29	49.52
	E.S.		-0.35	-0.14		0.42	-0.12		-0.28

The peak hip flexion velocities of the LF group were greatest in T2 and corresponded to the peak performance in other variables previously observed. As in the case of swimming speed, stroke index, and range of knee motion there was a trend of decreasing hip flexion velocity for both LF and FF groups. This is further evidence that there was a loss of motivation or an effect of fatigue in the later sessions.

Table 4.3.13 Mean values, variability (SD) and effect size (E.S.) of maximum (Max.) and minimum (Min.) angular velocity of the hip joint over all sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Max.									
LF	Mean	131.53	133.60	151.29	159.42	162.16	160.10	149.78	153.72
	SD	34.24	32.97	38.68	64.17	48.03	51.32	50.48	35.31
	E.S.		0.06	0.58	0.81	0.89	0.83	0.53	0.65
FF	Mean	149.10	120.51	132.87	123.43	108.13	118.73	107.73	137.81
	SD	53.27	24.86	27.58	32.56	36.65	31.60	29.10	46.36
	E.S.		-0.54	-0.30	-0.48	-0.77	-0.57	-0.78	-0.21
Min.									
LF	Mean	-166.54	-182.27	-193.50	-184.06	-174.05	-165.62	-168.26	-171.16
	SD	32.64	56.81	47.62	46.80	41.16	37.46	44.46	38.34
	E.S.		-0.48	-0.83	-0.54	-0.23	0.03	-0.05	-0.14
FF	Mean	-157.45	-142.13	-149.70	-140.27	-126.58	-119.53	-118.51	-164.36
	SD	58.08	38.79	45.39	51.96	35.50	39.02	33.32	54.12
	E.S.		0.26	0.13	0.30	0.53	0.65	0.67	-0.12

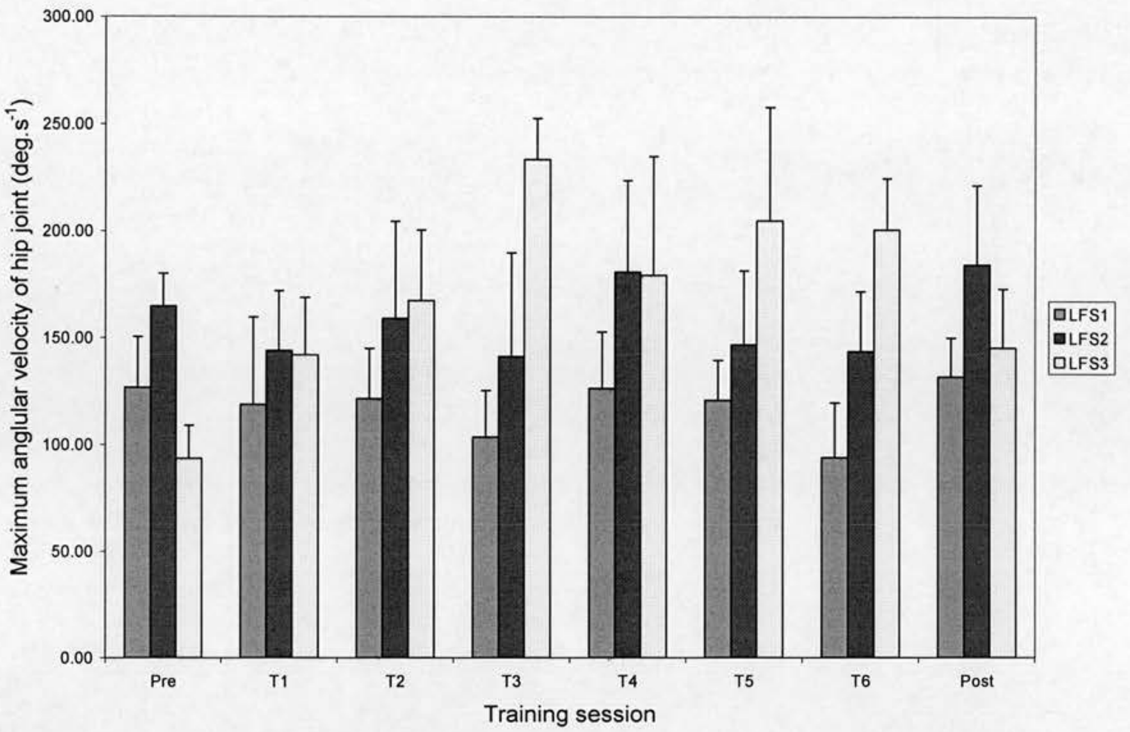


Figure 4.3.21 Maximum angular velocity of the hip joint over all sessions for the LF group.

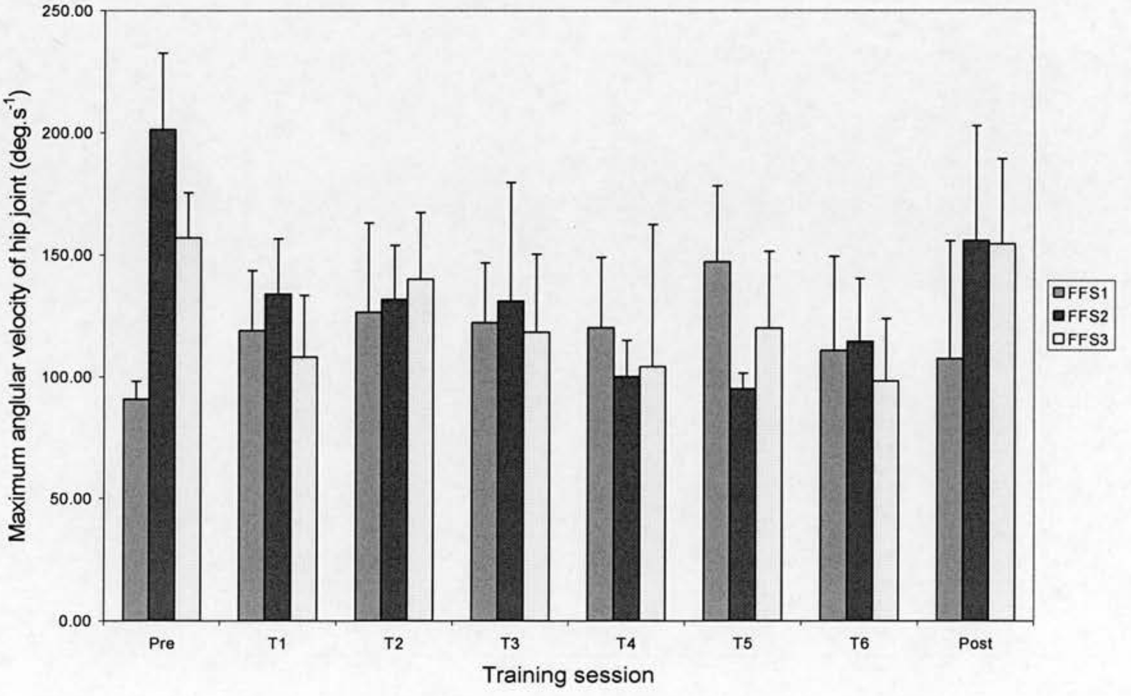


Figure 4.3.22 Maximum angular velocity of the hip joint over all sessions for the FF group.

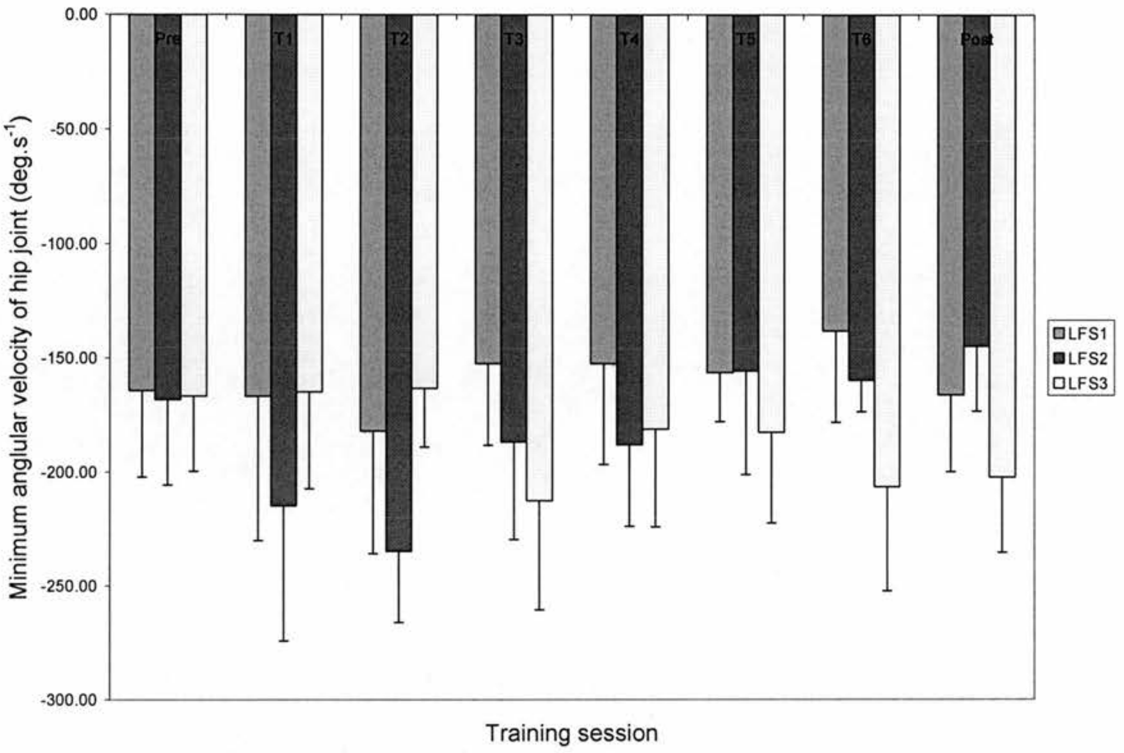


Figure 4.3.23 Minimum angular velocity of the hip joint over all sessions for the LF group.

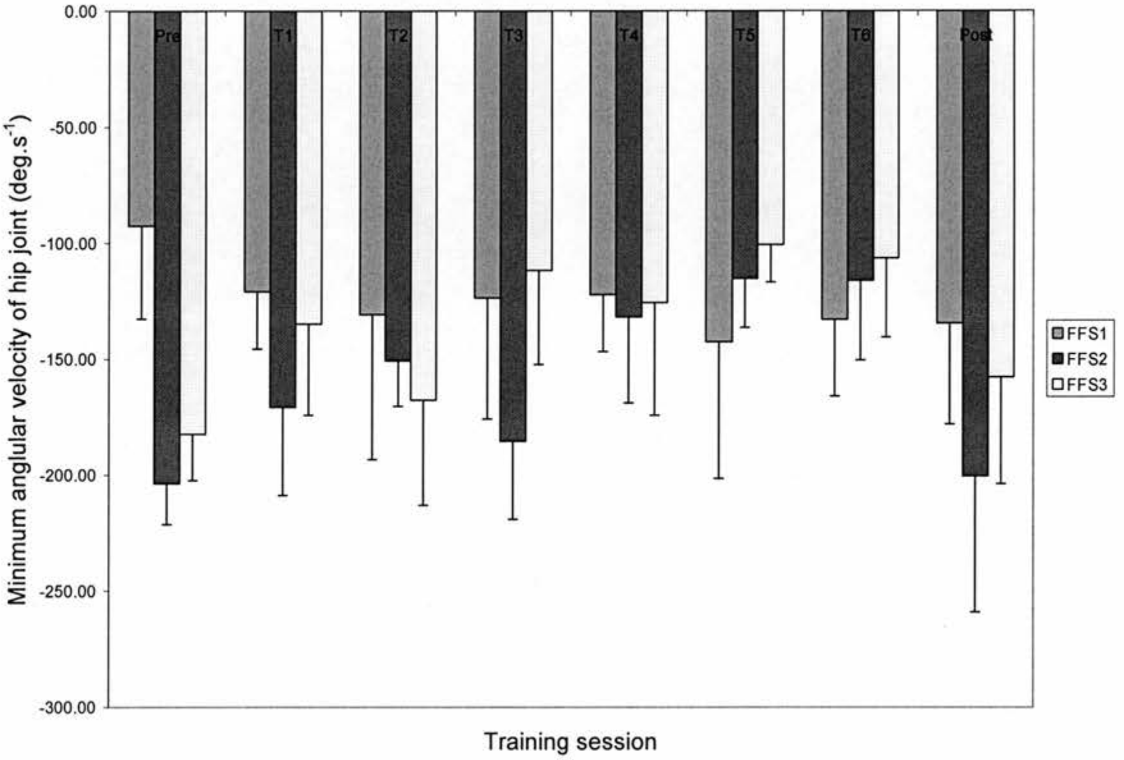


Figure 4.3.24 Minimum angular velocity of the hip joint over all sessions for the FF group.

Table 4.3.14 displays mean values, variability and effect size of maximum and minimum knee joint angular velocity in pre training, training (mean pooled) and post training session for LF, FF and CO groups. Table 4.3.15 provides detail of those measures for the individual training sessions.

Table 4.3.14 Mean values, variability (SD) and effect size (E.S., mean values relative to pre training session) of maximum (Max.) and minimum (Min.) of knee joint angular velocity in pre training, training (mean pooled) and post training session for LF, FF and CO groups.

		LF			FF			CO	
		Pre-train	Train-pool	Post-train	Pre-train	Train-pool	Post-train	Pre-train	Post-train
Max.	Mean	376.91	414.16	418.36	326.09	214.68	350.16	404.73	479.23
	SD	58.89	92.74	112.78	52.64	57.64	76.83	69.13	82.65
	E.S.		0.63	0.70		-2.12	0.46		1.08
Min.	Mean	-319.64	-273.86	-328.14	-278.32	-184.97	-260.28	-368.02	-315.98
	SD	64.00	56.86	64.66	36.06	45.31	45.76	69.92	58.52
	E.S.		0.72	-0.13		2.59	0.50		0.74

In all sessions of all groups the maximum velocities (knee extension) were greater than the minimum velocities (knee flexion). This is opposite to the hip velocity data where the flexion velocities were greater than extension velocities. However, it is congruent with that data given that the downbeat is produced by flexion of the hip and extension of the knee. Therefore, the interpretation that the downbeat is more vigorous than the upbeat is reinforced.

When swimming with flippers the LF group presented higher extension and lower flexion angular velocities while the FF group displayed smaller peak extension and flexion angular velocities than that in barefoot kicking. In the case of knee extension a decrease in angular velocity would be expected for both foot flippers and leg flippers due to the greater resistance offered than when kicking in bare feet. As expected, the decrease in velocity is greater in the foot flipper than leg flipper because the lever arm is longer, thereby requiring greater torque from the knee joint. Also, for any given rate of knee extension, the foot flipper must move faster due to the longer lever arm. Faster motion against water means greater resistive force. Thus, the difference between the two tasks in terms of the kinetics and associated kinematics is manifest by the difference in knee angular velocities.

When returned to the barefoot kicking, the peak flexion velocities of LF group were similar to that of the pre training session. However, the peak extension velocity of the LF group was larger than the values of pre training session (E.S. 0.70). The FF group had moderately reduced knee flexion velocities (E.E. 0.50) and moderately increased knee extension velocities (E.S. 0.46) in the post training relative to the pre training.

Large variability in knee joint peak extension velocities resulted from the individual differences of peak velocities but the trends were similar to each other (Figure 4.3.25-28). There was considerable variability in angular velocities within participants within sessions, within participants across sessions, and between participants. Being a derivative, velocity is sensitive to variability in peaks. However, it represents a further indication that the system is not behaving in a static manner and is freely 'exploring' movement possibilities while retaining the rudiments of the underlying kinematic features associated with efficient flutter kicking (indicated by %power and velocity index in the previous section).

Table 4.3.15 Mean values, variability (SD) and effect size (E.S.) of maximum (Max.) and minimum (Min.) angular velocity of knee joint over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Max.									
LF	Mean	376.91	396.56	425.23	419.26	410.88	418.97	410.78	418.36
	SD	58.89	55.15	67.60	118.76	108.66	96.74	104.80	112.78
	E.S.		0.33	0.82	0.72	0.58	0.71	0.58	0.70
FF	Mean	326.09	215.99	255.10	206.74	235.93	192.22	189.15	350.16
	SD	52.64	63.72	44.87	59.78	61.57	38.66	52.56	76.83
	E.S.		-2.09	-1.35	-2.27	-1.71	-2.54	-2.60	0.46
Min.									
LF	Mean	-319.64	-240.38	-277.56	-309.93	-274.82	-276.89	-263.76	-328.14
	SD	64.00	58.12	43.83	53.05	61.51	31.73	69.01	64.66
	E.S.		1.24	0.66	0.15	0.70	0.67	0.87	-0.13
FF	Mean	-278.32	-184.85	-199.05	-187.79	-202.97	-181.86	-156.55	-260.28
	SD	36.06	36.85	36.45	53.12	40.79	44.33	49.44	45.76
	E.S.		2.59	2.20	2.51	2.09	2.67	3.38	0.50

Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

All swimmers adjusted rapidly to the change in task constraints when switching to flippers. The decrement of LFS1 from T3 contributed greatly to the high variability within the LF group and some what clouded the data and its interpretability. However, in keeping with the earlier observations, changes to the peak knee angular velocities from T1 to T2 indicated that the LF group had not fully adjusted their kinematics to the new constraint environment during T1. Of all the training sessions, both peak extension velocity and peak flexion velocities had the smallest magnitudes in T1 for the LF group. In agreement with other measures, adaptation of knee angular velocity appeared to have occurred fully in T2 although LSF3 continued an upward trend in knee extension velocity in T3 (Figure 4.3.25).

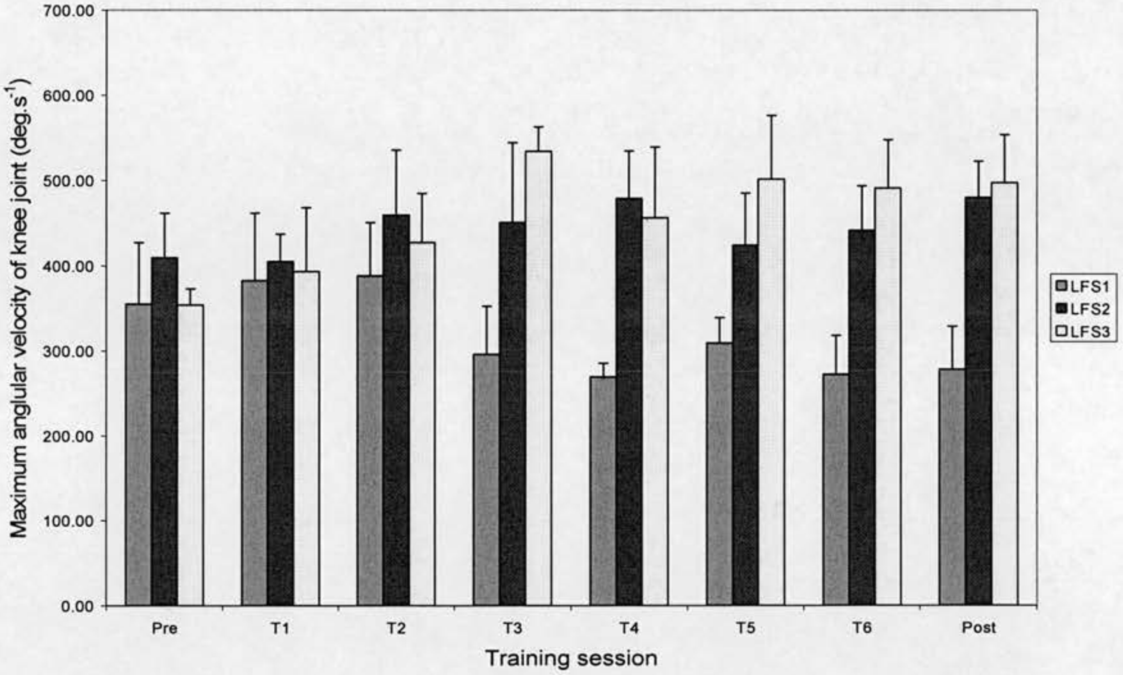


Figure 4.3.25 Maximum angular velocity of the knee joint over all sessions for the LF group.

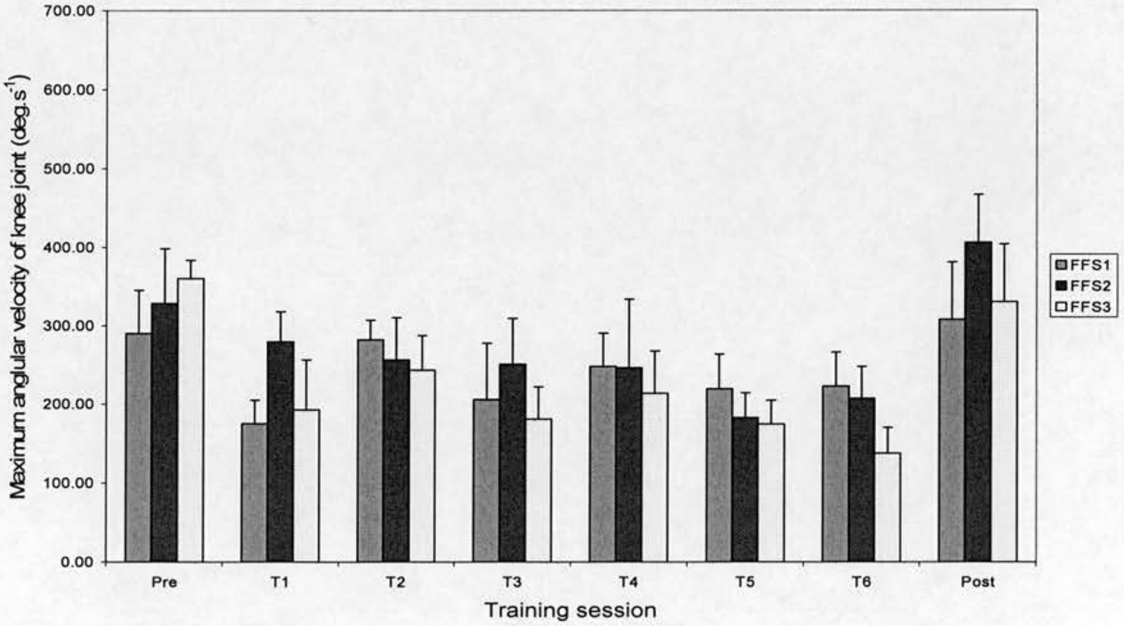


Figure 4.3.26 Maximum angular velocity of the knee joint over all sessions for the FF group.

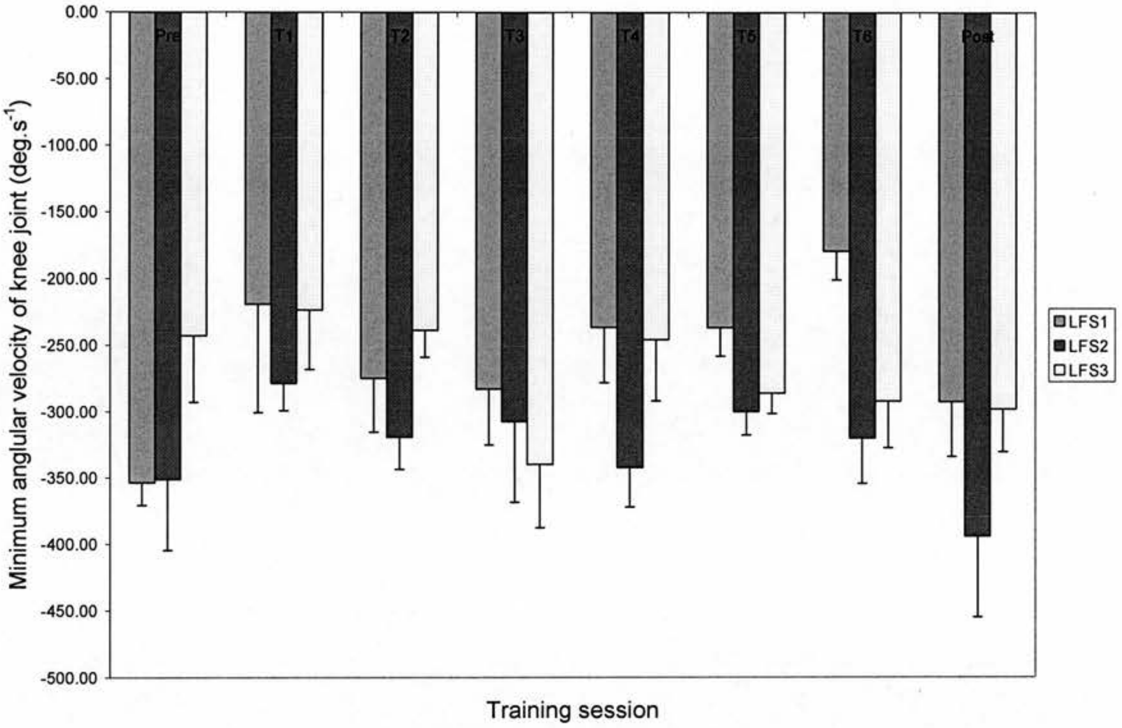


Figure 4.3.27 Minimum angular velocity of the knee joint over all sessions for the LF group.

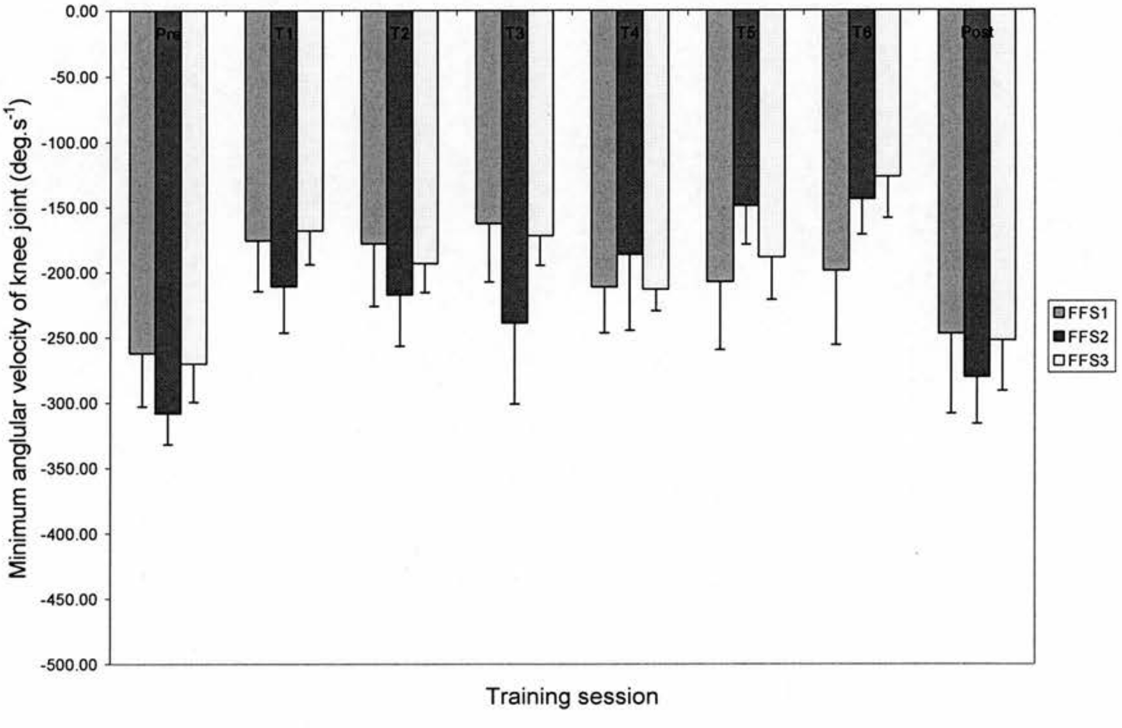


Figure 4.3.28 Minimum angular velocity of the knee joint over all sessions for the FF group.

4.3.3 Amplitude of vertical displacement of the joint centers

Table 4.3.16 lists the pre training, pooled training and post training session mean values, variability, and effect size of vertical amplitude of hip, knee and ankle joint for LF, FF and CO groups.

The data showed that the lower extremity motion in flutter kicking is a 'whip-like' pattern. That is the vertical amplitudes increased from hip – knee – ankle joints regardless of whether flippers were used. There was a considerable increase in knee joint vertical amplitude when using leg flippers (from 0.15 to 0.23 m, E.S. 1.71) and a slight increase for foot flippers swimmers (from 0.17 to 0.18, E.S. 0.23). Both LF and FF group had decrements in ankle joint vertical amplitude compared to the barefoot condition (0.33-0.27 m, E.S. -1.25 for LF group, 0.35-0.32 m, E.S. -0.42 for FF group). The increase in knee motion of the LF group combined with a decrease in ankle motion indicates that the motion has become less 'whip-like' than the bare foot and foot flipper conditions.

Table 4.3.16 Mean values, variability (SD) and effect size (E.S.) of vertical displacement of hip, knee and ankle joint in pre training, training (mean pooled) and post training sessions for LF, FF and CO groups.

		LF			FF			CO	
		Pre training	Pooled training	Post training	Pre training	Pooled training	Post training	Pre training	Post training
Hip									
	Mean	0.07	0.08	0.06	0.06	0.06	0.05	0.06	0.06
	SD	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.01
	E.S.		0.75	-0.56		0.72	-0.85		-0.12
Knee									
	Mean	0.15	0.23	0.16	0.17	0.18	0.18	0.19	0.19
	SD	0.04	0.04	0.02	0.05	0.04	0.04	0.03	0.04
	E.S.		1.71	0.12		0.23	0.15		0.24
Ankle									
	Mean	0.33	0.27	0.32	0.35	0.32	0.36	0.36	0.37
	SD	0.05	0.06	0.05	0.08	0.05	0.05	0.08	0.09
	E.S.		-1.25	-0.31		-0.42	0.03		0.17

Table 4.3.17 presents the mean values, variability and effect size of vertical amplitude of hip, knee and ankle joint for LF and FF group's data for all sessions.

When using flippers, both LF and FF groups adjusted to changed task constraint rapidly with respect to all of hip, knee, and ankle amplitudes. Although not much greater than the amplitudes in T1, the amplitudes in T2 were the highest of the training sessions. They tended to decline thereafter in a similar manner to the changes noted for other variables. Once again, this would appear to be related to a reduction in effort by the participants. The data for individuals displayed in Figures 4.3.29-4.3.34 indicates that these trends were common across individuals.

Table 4.3.17 Mean values, variability (SD) and effect size (E.S.) of vertical displacement of hip, knee, and ankle joints over all sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
Hip									
LF	Mean	0.07	0.09	0.09	0.09	0.07	0.07	0.07	0.06
	SD	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02
	E.S.		1.18	1.35	1.07	0.31	0.18	0.27	-0.56
FF	Mean	0.06	0.07	0.06	0.07	0.06	0.06	0.07	0.05
	SD	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01
	E.S.		1.27	0.09	1.08	0.28	0.75	0.86	-0.85
Knee									
LF	Mean	0.15	0.23	0.25	0.24	0.22	0.21	0.21	0.16
	SD	0.04	0.04	0.05	0.04	0.03	0.02	0.02	0.02
	E.S.		1.70	2.21	2.05	1.58	1.41	1.22	0.12
FF	Mean	0.17	0.18	0.18	0.19	0.17	0.18	0.18	0.18
	SD	0.05	0.05	0.04	0.05	0.03	0.03	0.04	0.04
	E.S.		0.35	0.18	0.41	0.09	0.17	0.18	0.15
Ankle									
LF	Mean	0.33	0.28	0.29	0.28	0.26	0.25	0.25	0.32
	SD	0.05	0.06	0.09	0.07	0.03	0.05	0.04	0.05
	E.S.		-1.06	-0.81	-0.94	-1.48	-1.63	-1.67	-0.31
FF	Mean	0.35	0.34	0.32	0.31	0.31	0.33	0.30	0.36
	SD	0.08	0.05	0.04	0.05	0.05	0.04	0.06	0.05
	E.S.		-0.20	-0.37	-0.51	-0.54	-0.26	-0.65	0.03

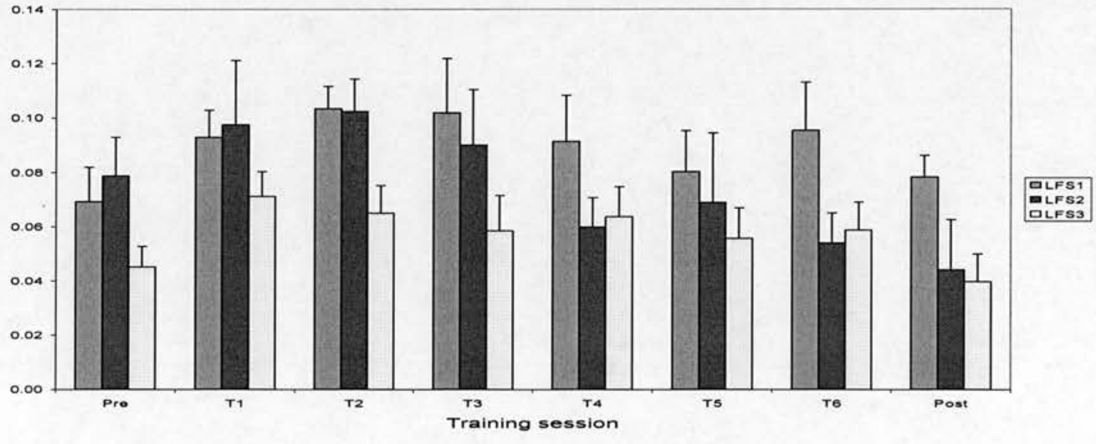


Figure 4.3.29 Amplitude of the hip joint vertical displacement over all sessions for the LF group.

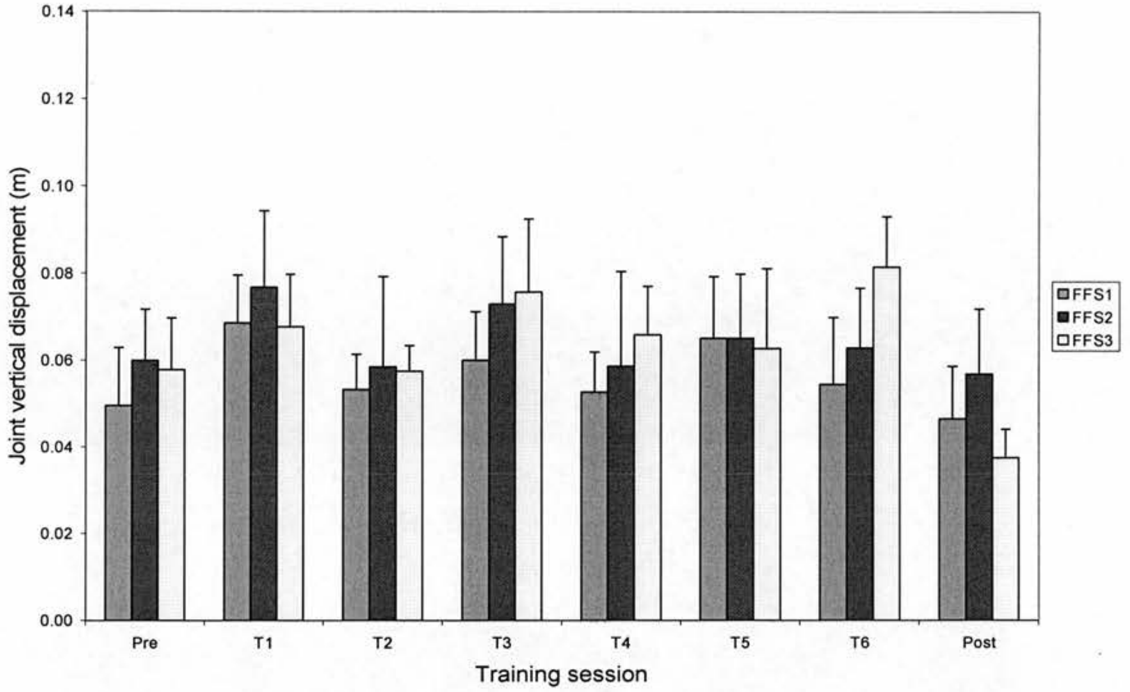


Figure 4.3.30 Amplitude of the hip joint vertical displacement over all sessions for the FF group.

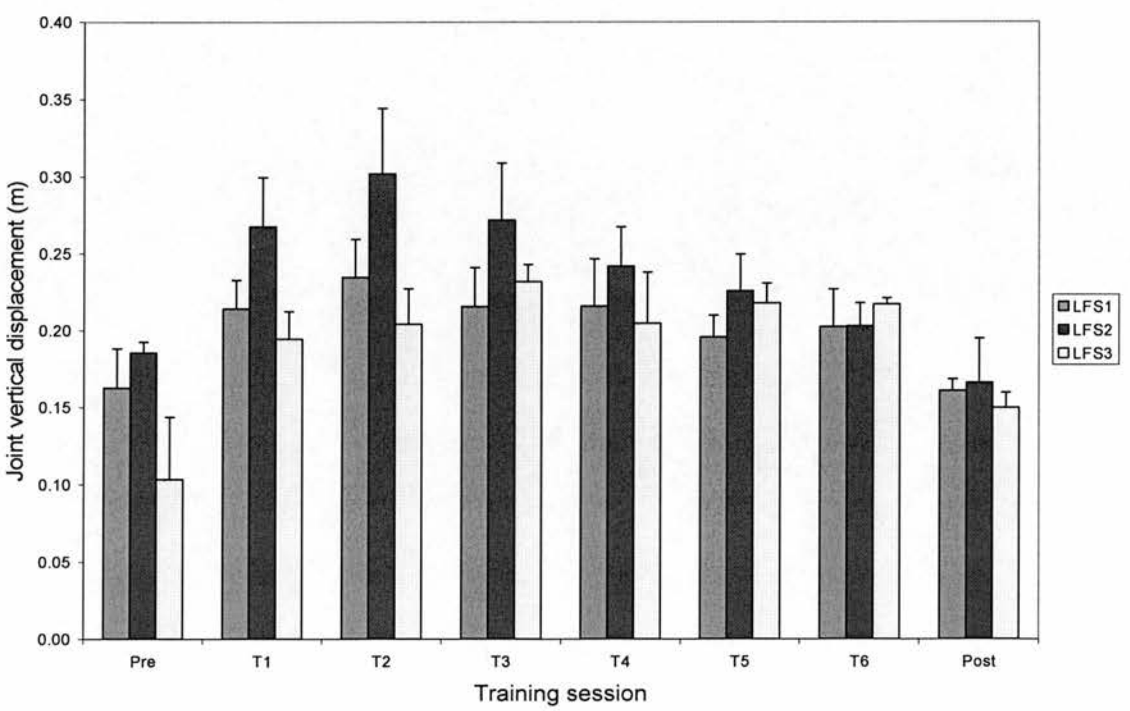


Figure 4.3.31 Amplitude of the knee joint vertical displacement over all sessions for the LF group.

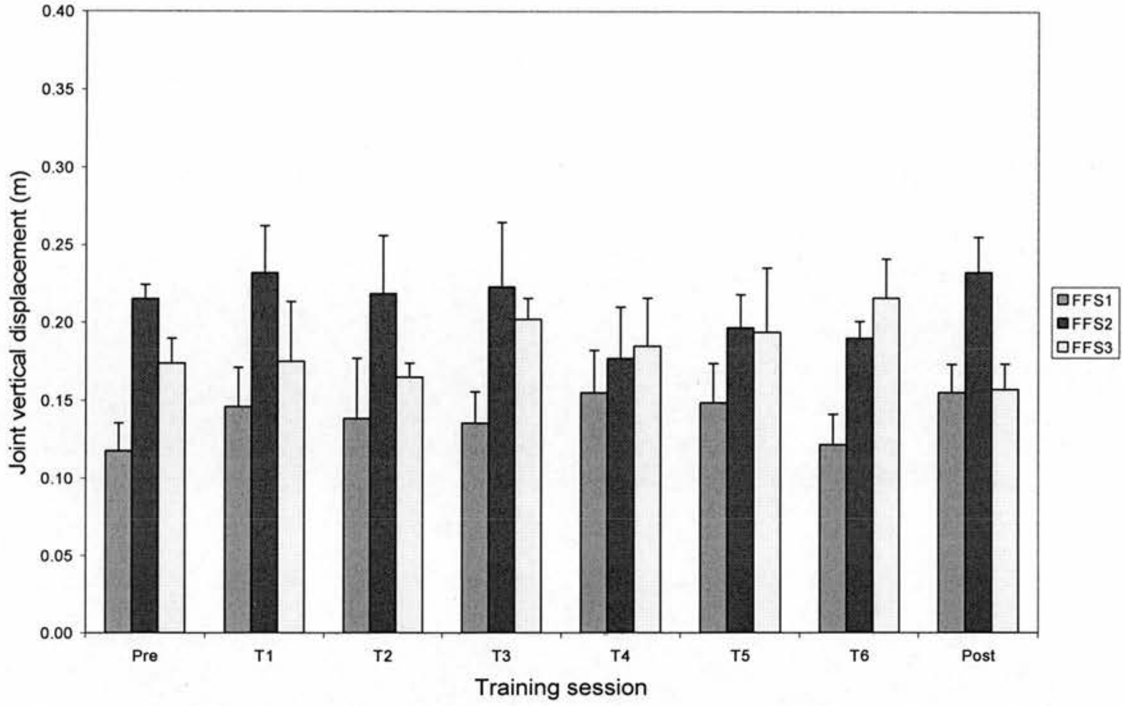


Figure 4.3.32 Amplitude of the knee joint vertical displacement over all sessions for the FF group.

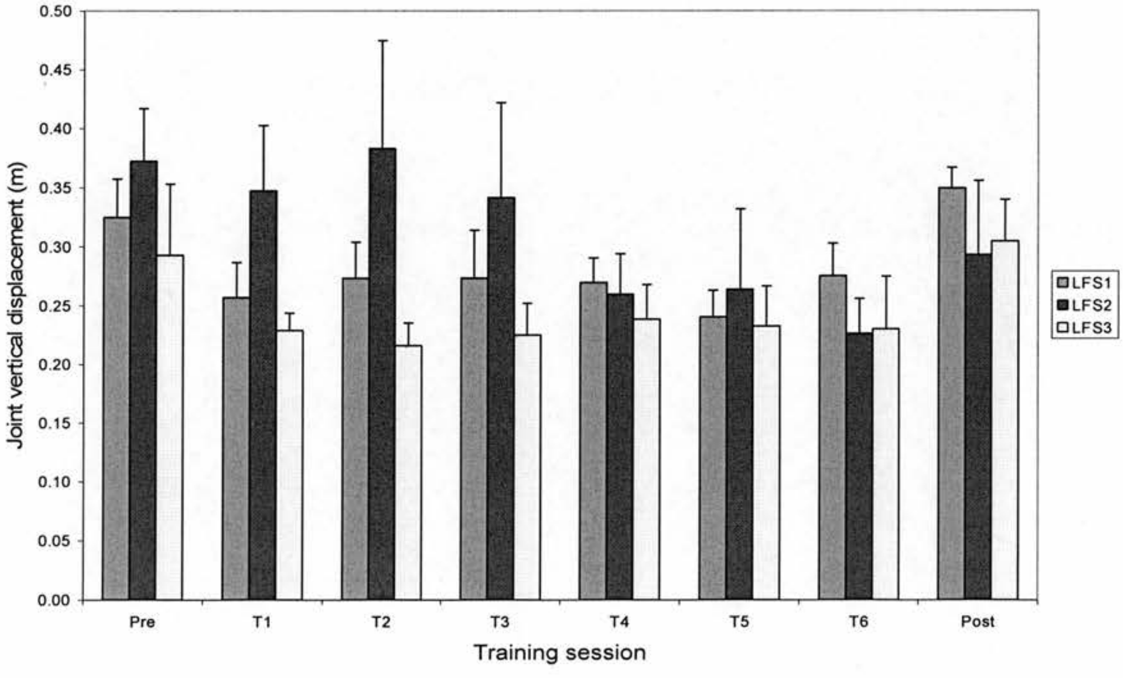


Figure 4.3.33 Amplitude of the ankle joint vertical displacement over all sessions for the LF group.

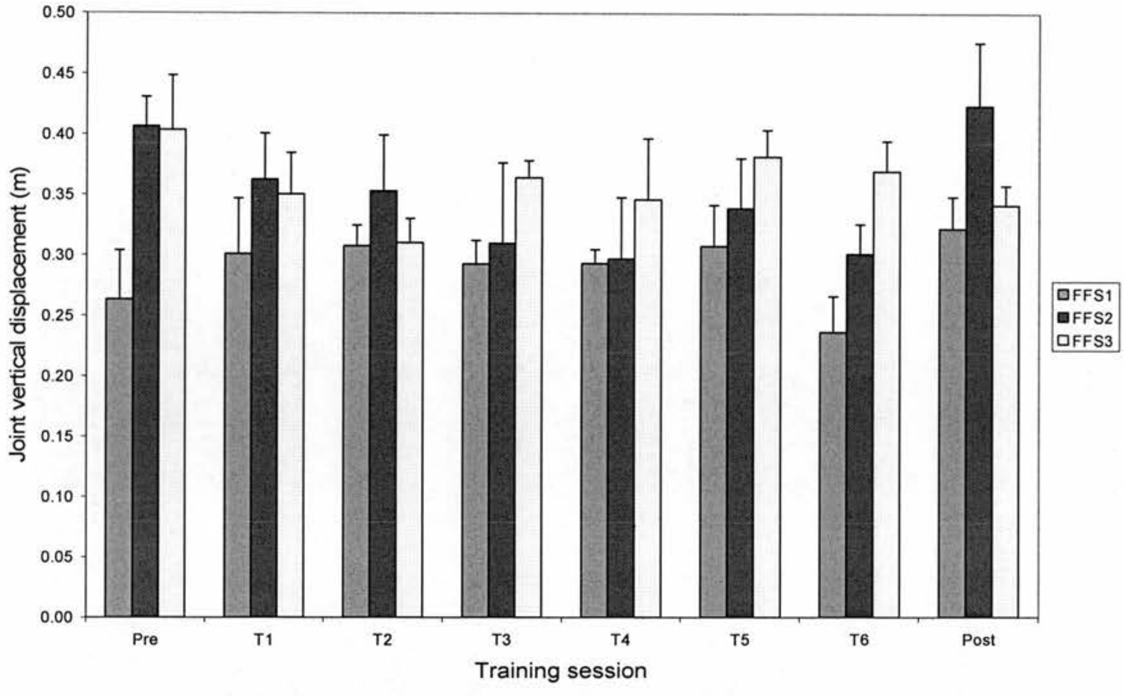


Figure 4.3.34 Amplitude of the ankle joint vertical displacement over all sessions for the FF group.

4.3.4 Summary

This section presented results for analysis of stroke parameters – stroke length, stroke frequency, swimming speed and stroke index; angular motion of the hip and knee joints; and amplitude of vertical displacement of the joint centers.

Interpretation of the results and accompanying discussion focused on the central issue of how rapidly swimmers adjusted to a change in constraint environment, that is, changing between a familiar constraint environment of foot flippers and the familiar constraint environment of bare feet, and changing between an unfamiliar constraint environment of leg flippers and the familiar constraint environment of bare feet.

The data indicated:

1. A rapid adjustment from bare foot to foot flipper for all variables.

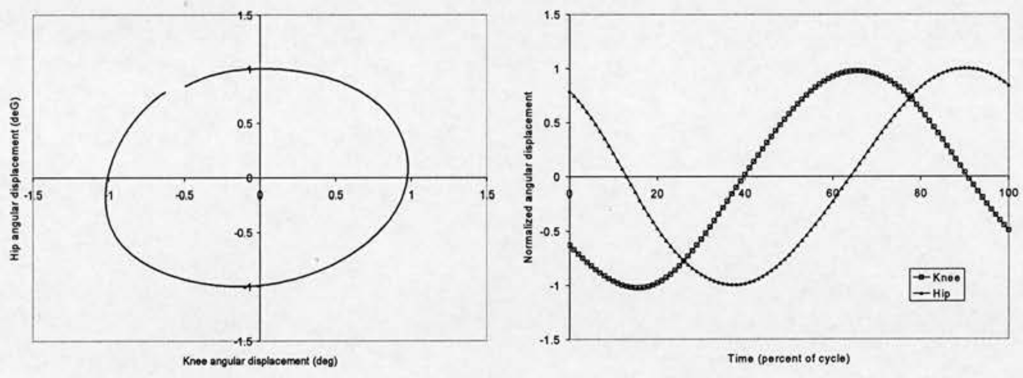
2. A rapid adjustment from bare foot to leg flipper for all variables with differences between T2 and T1 for many variables indicating that kinematics were not fully adjusted for optimal performance in the T1 trials.
3. A tendency to reduce performance in both FF and LF in the latter training trials. This was also reflected in 'tapering off' of hip and knee joint angular displacement and velocities, and vertical displacements of hip, knee, and ankle. The evidence indicated that this was a motivation or fatigue effect rather than a learning effect.
4. A rapid adjustment to the barefoot condition from both the LF and FF conditions to return to values similar to those in the pre training session. Some small or big changes in some variables were noted but deemed trivial given that similar effects were observed for the post training in the control group.
5. Unremarkable patterns of within participant, within participant across sessions, and within group across session variability. There was little evidence that variability either increased or decreased when changing from one constraint environment to another. However, it was noted that variability of the LF group in T1 was smaller, though not markedly so, relative to other sessions. The level of variability throughout indicated that participants' dynamical systems were 'exploring' movement possibilities continuously.
6. The kinematics of flutter kicking under the three constraint conditions were considerably different. This reflects the major changes to the kinetics wrought by changed hydrodynamic resistance, moment arms, and segment lengths and inertias. Therefore, it could be assumed that the demands on the system to adapt to each constraint condition were considerable. Despite this, the system adapted rapidly when the constraint environment was familiar and within a few trials when the constraint environment was unfamiliar. With respect to the unfamiliar constraint environment, the %power and wave velocity index indicated that an appropriate movement pattern was established rapidly. The results shown in this section indicated that only fine tuning of variables relating to frequency and amplitude of motion was required to attain optimal performance.

4.4 Dynamical systems approach to lower extremity coordination pattern

The purpose of this section was to investigate the effect of change in task constraints on the inter-joint coordination pattern by means of dynamical systems approaches. The dynamics systems approaches focus on relationships between movement units such as segments and joints to provide sufficiently sensitive measurement to identify changes in multi-joint coordination. In this study angle-angle plots, angular displacement – velocity (phase plane) plots, and continuous relative phase were applied to all flutter kicking trials of all swimmers across all conditions and sessions.

4.4.1 Coordination of coupling angular displacement of hip-knee joint

The angle–angle plots of hip–knee joint were produced by plotting the angular displacement of hip as a function of knee angular displacement over complete kicking cycle. Figure 4.4.1 shows a typical amplitude normalized angle–angle plot of the hip–knee joint produced from the out of phase sinusoidal angle time of the hip and knee. The motion direction of the oval from the point of start is anti-clockwise. When the sinusoids are exactly in phase the ellipse is 'squashed' to a straight line. When the sinusoids are 90 degrees out of phase the ellipse is a circle. Thus, the shape characteristics change according to the coupling relationship of the joint motions.



(a) (b)

Figure 4.4.1 A sample angle-angle plot (a) and its associated time-angular displacement curves (b). All were normalized by amplitude.

In the present study, the normalized (to unit cycle) hip and knee joint angular displacement were employed to produce the angle-angle plot. Some studies reported that it is not necessary to normalize the data when using the angle-angle plot to investigate the relationship of hip-knee joint angular displacement (Burgess-Limerick, Abernethy and Neal, 1993; Hamill, Haddad and McDermott, 2000). The reason is probably that this type of relationship doesn't link to the time parameter. In those studies there were specific fixed starting points such as in weight lifting.

The present study is of data that are cyclical in nature and in which relationships among joints can be retained despite joints moving through different ranges. Using normalized data in angle-angle plots for cyclical data enables comparison between trials and conditions in terms of the shape of the movement pattern. This means that movements of different amplitude may have the same shape characteristics, thereby showing that the relationship between the joints in terms of their positions relative to their range of motion remains consistent despite changes in the overall range. This is important because in the previous section it was apparent that amplitudes of motions changed considerably across conditions and sessions. However, it is unclear whether the relationships between the joints relative to the ranges of motion also change.

Figure 4.4.2 displays one swimmer's angle-angle plot in non-normalized (a) and normalized (b) coupling graphs of the mean value of pre and post training session. It is easy to assess the extent to which the coordination pattern of this swimmer is similar between pre training and the post training sessions by means of normalized graphs.

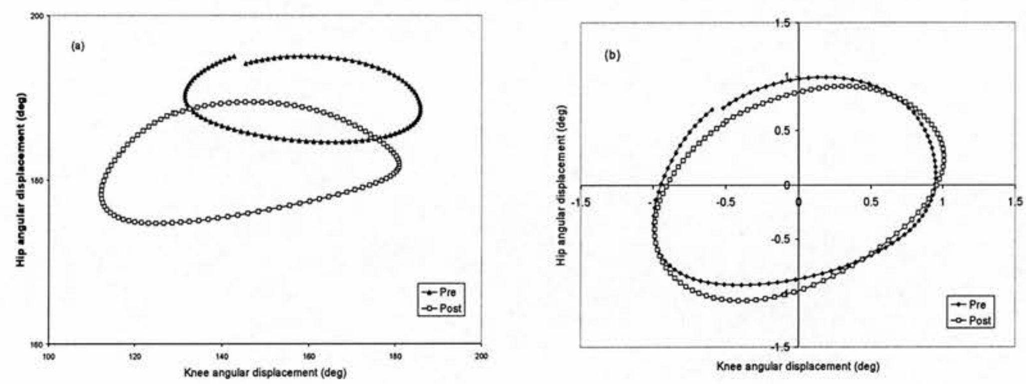


Figure 4.4.2 A sample of non-normalized angle-angle plot (a) and its normalized plot (b).

4.4.1.1 Angle-angle plots pattern of hip-knee joint

Angle-angle plots for knee-hip joint angular displacement relationships of LFS1 are shown in each trial of the experimental session (Figure 4.4.3) as an example of the data and as an indication of its variability. Angle-angle data for individual trials of the remaining participants are presented in Appendix C.

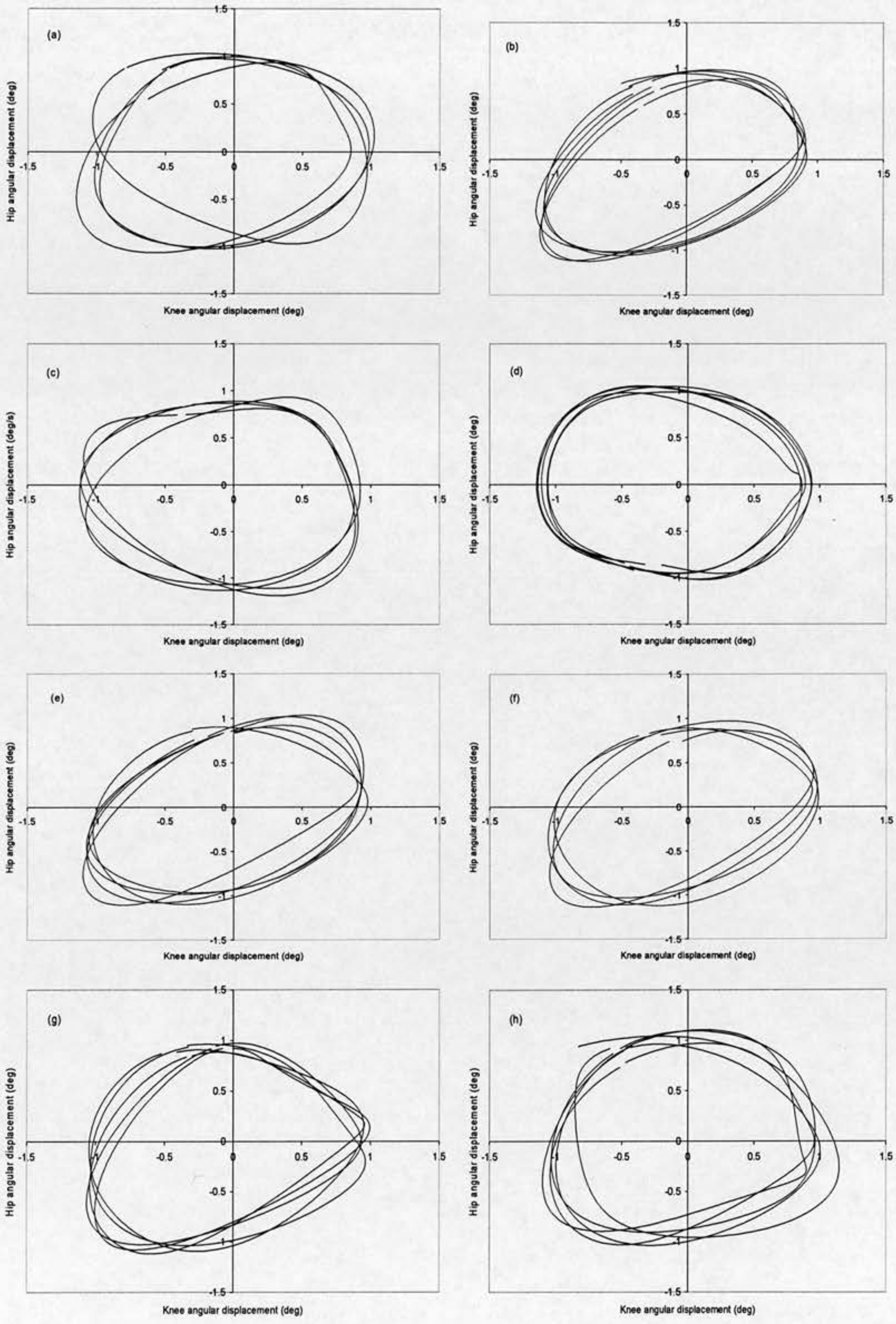


Figure 4.4.3 Knee-hip angular displacement plots of (a) pre training (b) T1 (c) T2 (d) T3 (e) T4 (f) T5 (g) T6 and (h) post training sessions for swimmer LFS1.

Figure 4.4.4 presents comparisons of mean plots for the same swimmer (LFS1). From these plots it is easy to see that the angle-angle pattern changed considerably from the pre-test to T1, only slightly from T1 to T6, and considerably from T6 to post. The mean pattern of the post training trials was very similar to that of the mean pre training trials.

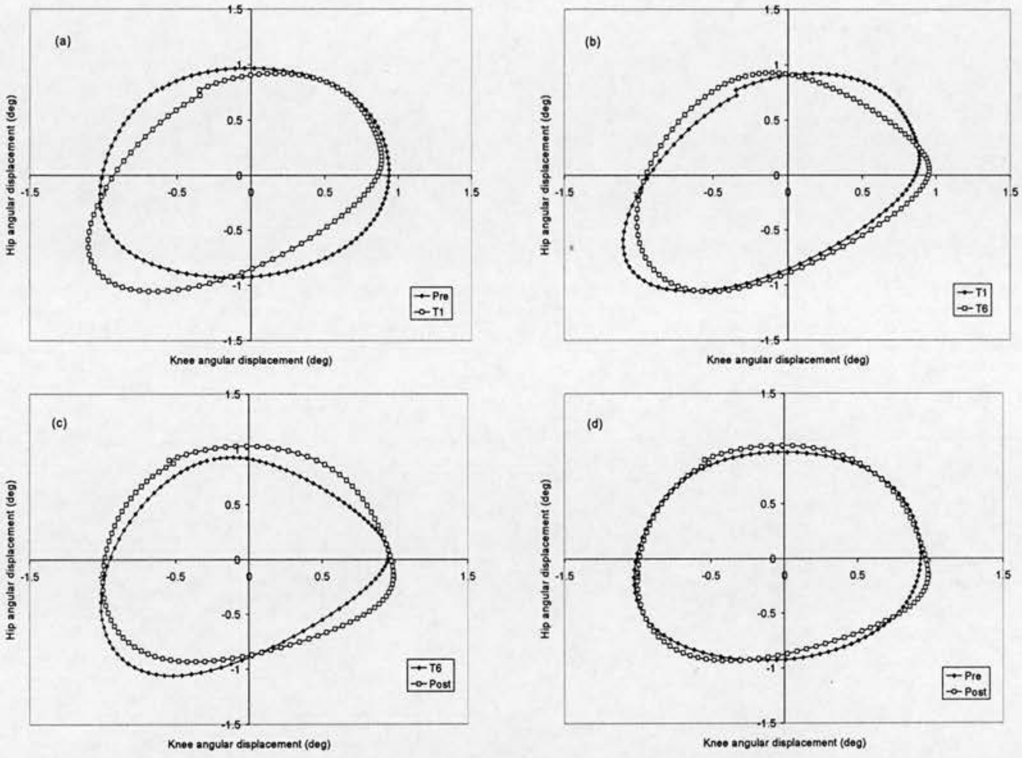
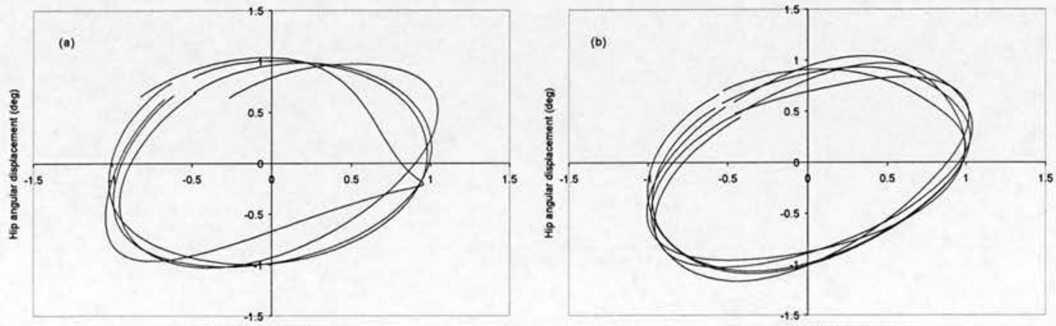


Figure 4.4.4 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS1.

The angle-angle plots for the remaining swimmers are shown in Figures 4.4.5-7 for CO1-3, Figures 4.4.8-9 (LFS2 and LFS3) and Figures 4.5.10-12 for FF1-FF3



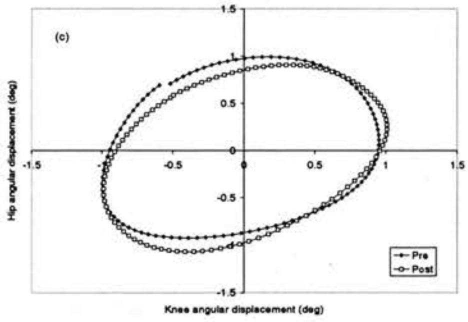


Figure 4.4.5 Knee-hip joint angle-angle plots of pre training, post training, and comparison of mean of pre training and post training for swimmer COS1.

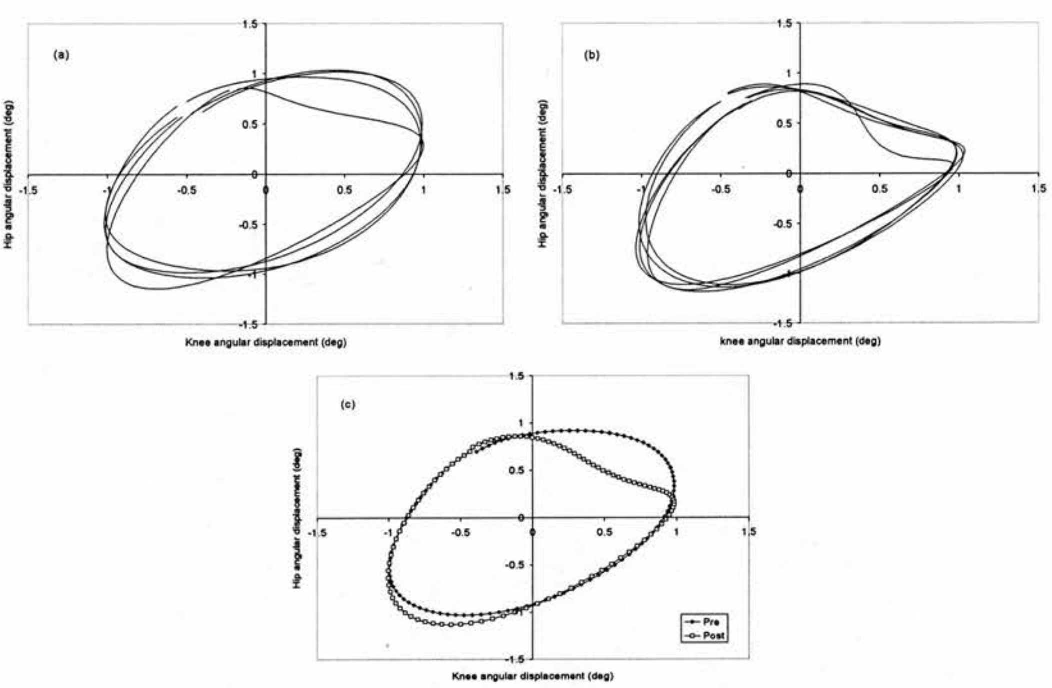
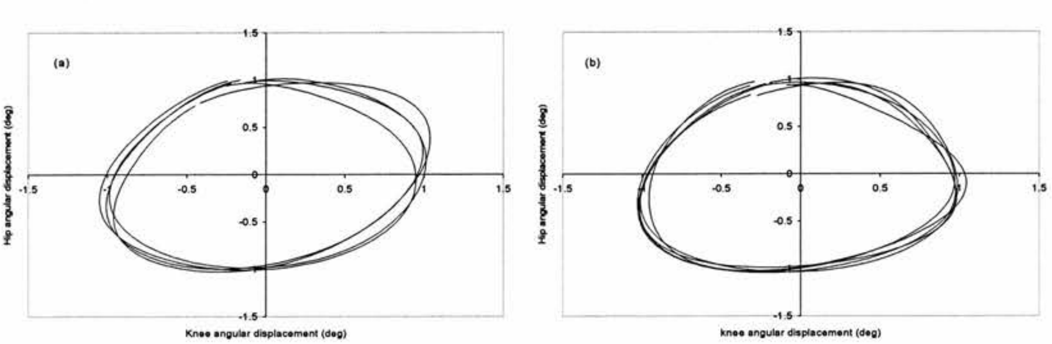


Figure 4.4.6 Knee-hip joint angle-angle plots of pre training, post training, and comparison of mean of pre training and post training for swimmer COS2.



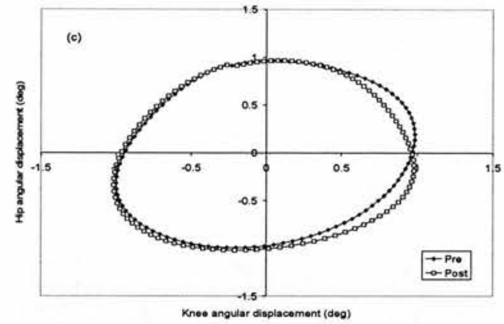


Figure 4.4.7 Knee-hip joint angle-angle plots of pre training, post training, and comparison of mean of pre training and post training for swimmer COS3.

To assess whether the movement pattern has been influenced by a change from one condition to another it is necessary to first assess how close a match can be expected between means of a small number of trials given the natural variability between trials. For this purpose the data of the control group are very important. The results for COS1-3 for pre-test and post-test indicate that even without the influence of changes in task constraints mean plots will differ. However, it can be seen that some similarities remain in terms of the width and orientation of the ellipses.

The data for LFS2 (Figure 4.4.8) indicate that the first trials with the leg flipper produced a change in the coupling of the hip and knee. The angle-angle patterns for T1 are closer in shape to T6 than to the pre training patterns. This supports the interpretations of the kinematic data presented in the previous section in that most of the adjustment occurred rapidly. Interestingly, the post training angle-angle pattern bears as much resemblance to T6 as it does to the pre training pattern. This raises the possibility that, for this swimmer, the training sessions influenced the pattern used in barefoot kicking when returning to that condition.

This possibility appears to be supported by the data of LFS3 (Figure 4.4.9). Again, there was a rapid adjustment away from the pre training pattern evident in T1 but not as far as the pattern in T6. Then the post training pattern appears to have moved back towards the pre training pattern but not as far as the pre training pattern. Again the evidence suggests that the relationship between the hip and knee joint has been influenced by the previous constraint conditions.

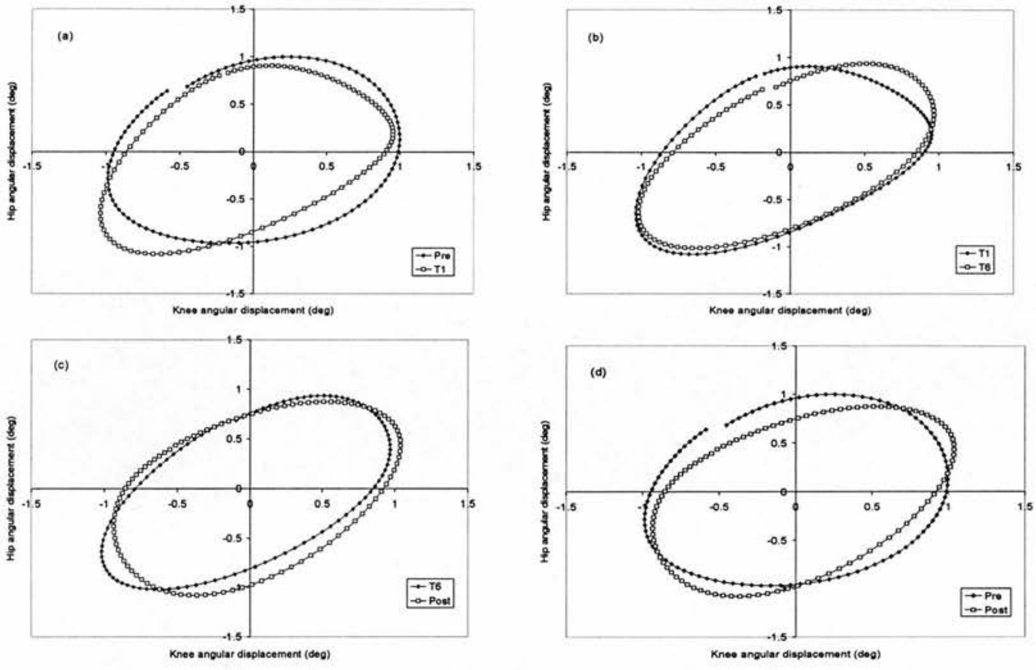


Figure 4.4.8 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS2.

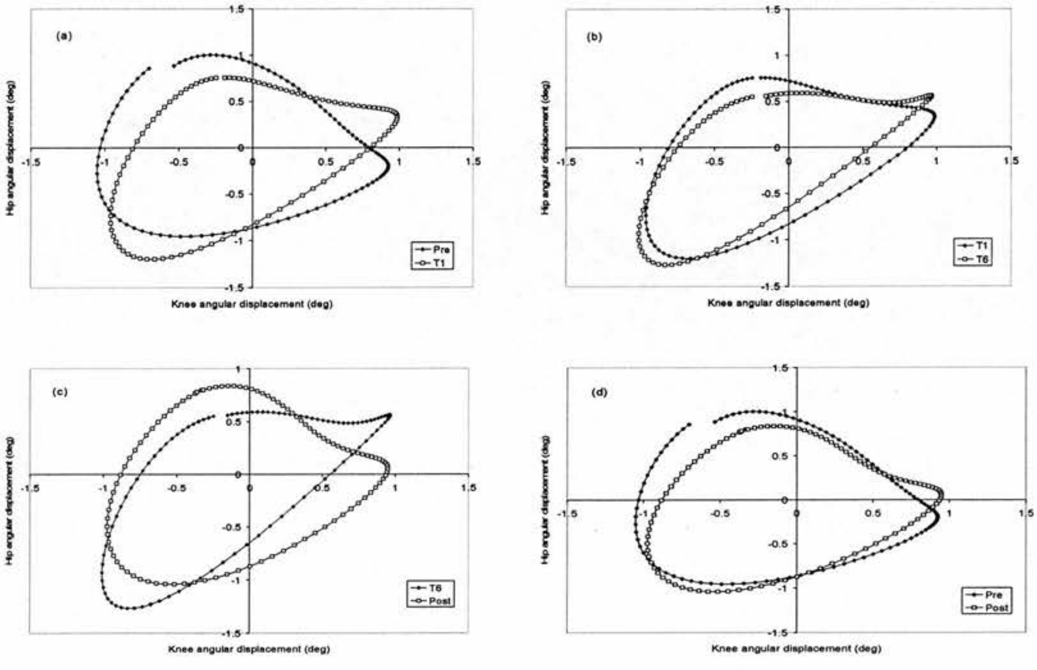


Figure 4.4.9 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS3.

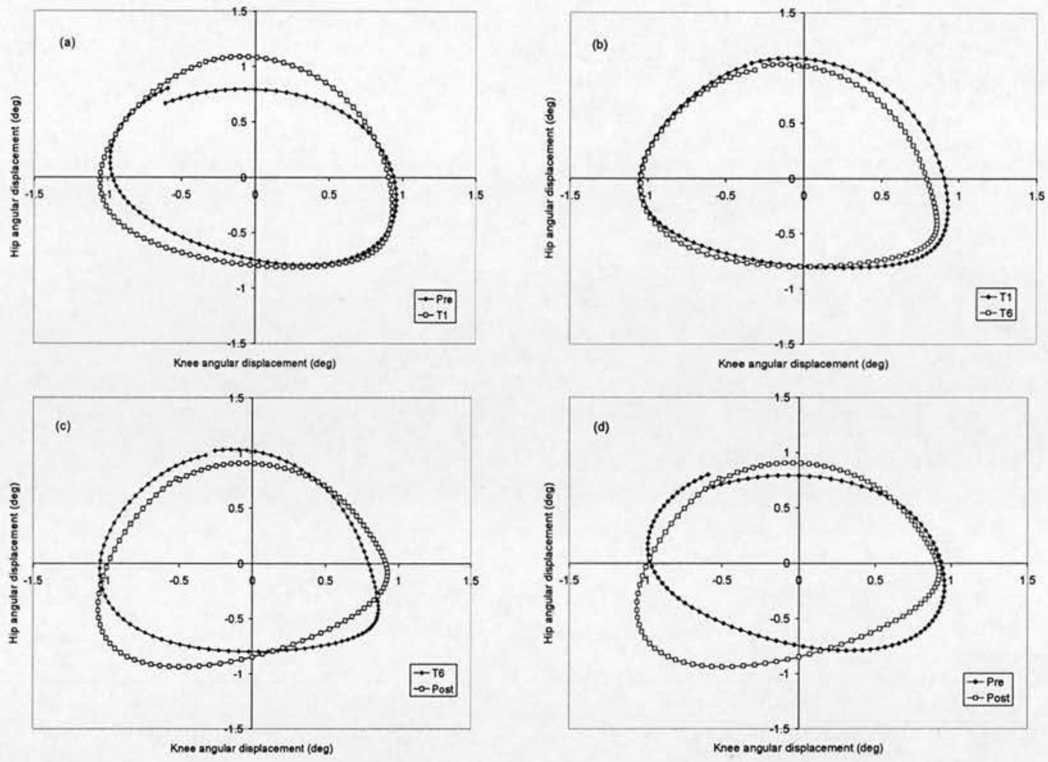


Figure 4.4.10 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS1.

FFS1 clearly makes a rapid adjustment to the foot flippers. The angle-angle plot for T1 is different from the pre training pattern and similar to T6. When returning to the barefoot condition in post training the mean angle-angle plot changed considerably compared to T6. However, the mean post training pattern differs greatly from the mean pre training pattern. Thus, it is possible that the training with flippers influenced the post training performance without flippers. However, reference to the individual plots of FFS1 (Appendix C Figure 4) indicates that the angle-angle patterns were highly variable. Therefore differences in mean patterns do not necessarily indicate an influence of the training condition on the barefoot condition.

FFS2 maintained a very similar pattern throughout. In fact, the pattern for T6 is very similar to the pre training pattern. However, it is possible that the change to the foot flippers caused a change from the pre training pattern. There was then adjustment back towards the pre training pattern so that T6 had a similar pattern to pre training. Then in changing back to the barefoot condition the pattern was perturbed again.

FFS3 maintained a pattern in T1 that was very similar to the pattern in the pre training session. There was a small change in pattern during the training sessions evident in small differences between T1 and T6. However, the post training pattern was very similar to the pre training pattern.

In summarizing the angle-angle plot data and its implications, it appears that, for both LF and FF groups, there was considerable exploration of movement possibilities indicated by the variability in hip-knee angle relationships. There is evidence of adjustment of the angle-angle coupling following change in constraint environment. There is also some evidence that angle-angle relationships following a change in constraint environment were influenced by the pattern established for the preceding constraint environment. This is interesting given the results presented in the earlier sections. In the first section it was apparent that %power and wave velocity index remained appropriate for the task following a change in both FF and LF constraint environments. In Section 2 it was apparent that, in general, there was a rapid return to the pre training condition in stroke parameters, angular ranges of motion and angular velocities and joint vertical displacements.

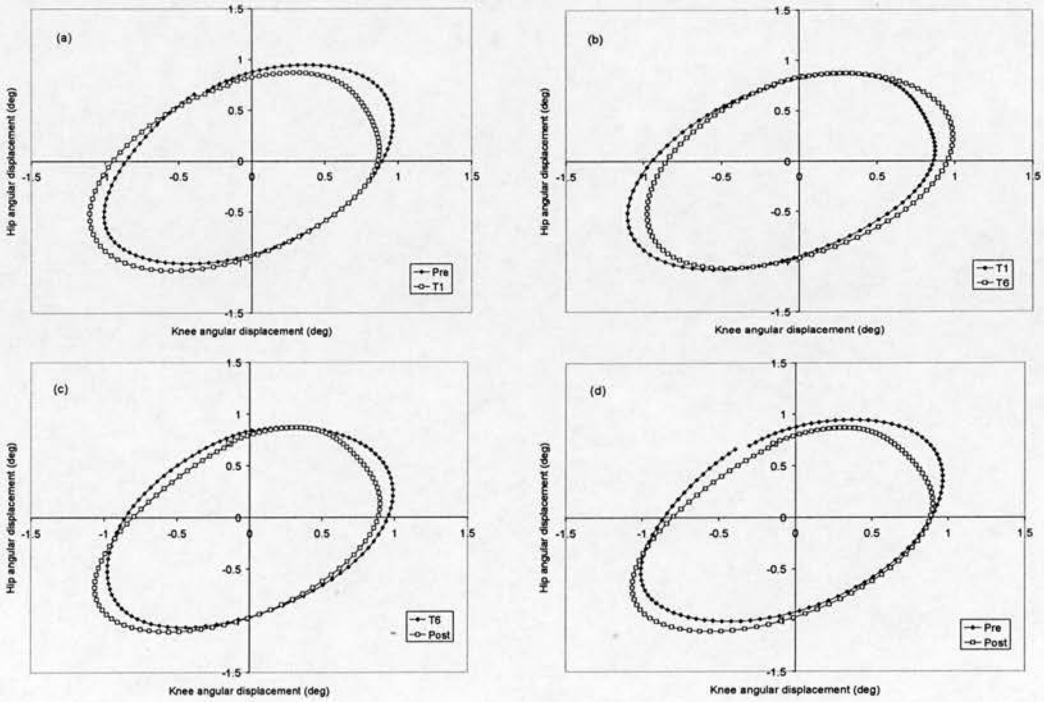


Figure 4.4.11 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS2.

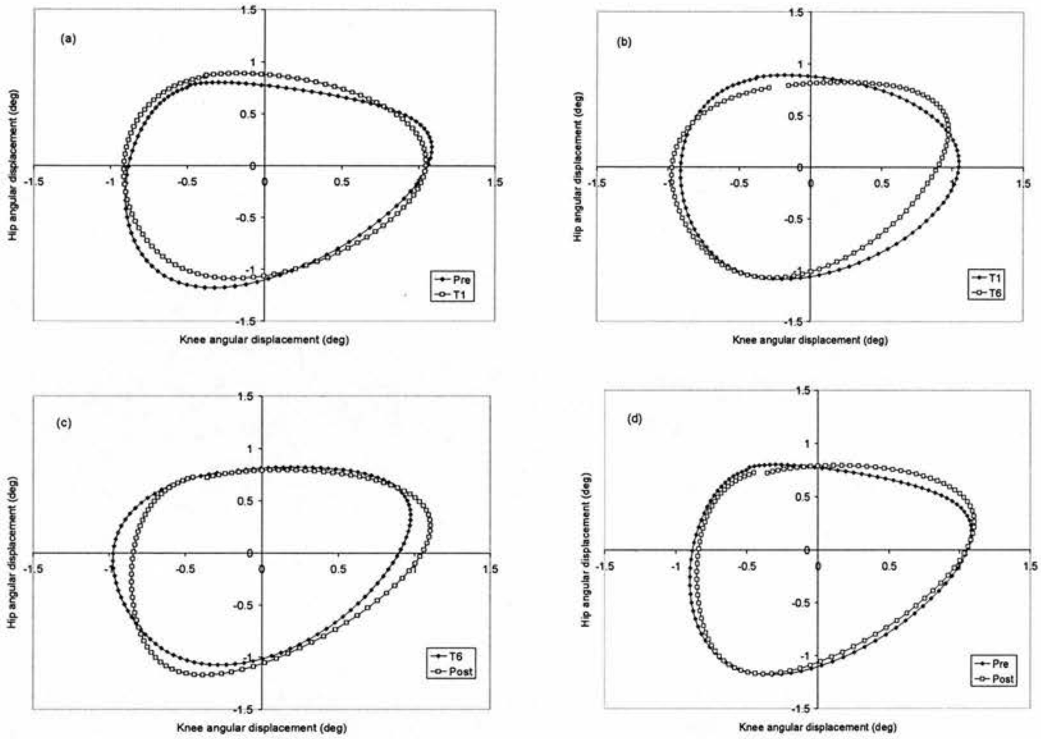


Figure 4.4.12 Mean knee-hip joint angle-angle plot: comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS3.

<u>4.4.1.2 Variability of angle-angle patterns for the knee-hip joint</u>

Variability of the angle-angle plots within each session was calculated for each swimmer using the method described in the method section.

Table 4.4.1 displays the variability in all sessions of all swimmers. When the task constraints changed from barefoot to flipper kicking, all swimmers responded immediately with a decrease of variability except FFS2 who increased variability in T1. This is in keeping with the observation of lower variability in T1 for the stroke frequency reported in the previous section.

All swimmers' had the greatest variability in the second training session (T2). Then, the variability decreased and varied in the remaining training sessions. When returning to the barefoot condition all swimmers had lower variability than in the pre training barefoot condition except LFS2.

Therefore, it may be hypothesized that when swimmers adjust to a new constraint environment the system first seeks stability and low variability. In this case, the system is familiar to the rudiments of the movement pattern appropriate for performance of the task adequately (as opposed to optimally). Thus, it seeks to establish this pattern with stability rather than exploring how to optimize performance. Then, the system 'explores' to determine the optimal movement pattern. In the case of kicking in swimming, the 'exploration' is to ensure that the reversed Kármán vortex street is utilised effectively.

Such an hypothesis is supported not only by the variability data, but also by the fact that the %power and wave velocity index data indicated that the system did adjust rapidly to generate a pattern appropriate for the performance of the task. The stroke parameter data indicated that this pattern then needed to be 'fine tuned' in terms of movement amplitudes and frequencies to optimize performance. This optimum was found in T2 and subsequent training sessions through 'exploration' of movement possibilities. This exploration was reflected in increased variability until the optimal movement characteristics were established.

Table 4.4.1 Variability of the angle-angle plot patterns for the knee-hip joints within experiment session for swimmers of LF, FF and control groups.

	Pre	T1	T2	T3	T4	T5	T6	Post
LFS1	0.171	0.092	0.291	0.128	0.115	0.180	0.117	0.117
LFS2	0.077	0.075	0.105	0.092	0.100	0.164	0.124	0.141
LFS3	0.199	0.135	0.248	0.134	0.196	0.142	0.140	0.150
FFS1	0.310	0.144	0.380	0.194	0.263	0.179	0.242	0.207
FFS2	0.128	0.147	0.207	0.151	0.183	0.178	0.159	0.108
FFS3	0.182	0.127	0.312	0.145	0.180	0.165	0.163	0.120
COS1	0.172							0.073
COS2	0.130							0.073
COS3	0.181							0.067

4.4.2 Coordination of coupling angular displacement and velocity of hip and knee joints

4.4.2.1 Phase plane of the knee joint

4.4.2.1.1 Phase plane pattern of the knee of the control group

Knee joint phase plane data for each trial of the pre training, post training sessions, and means of pre training and post training are presented in figures 4.13, 4.14, and 4.15 for COS1, COS2, and COS3 respectively. The direction of the plots is clockwise.

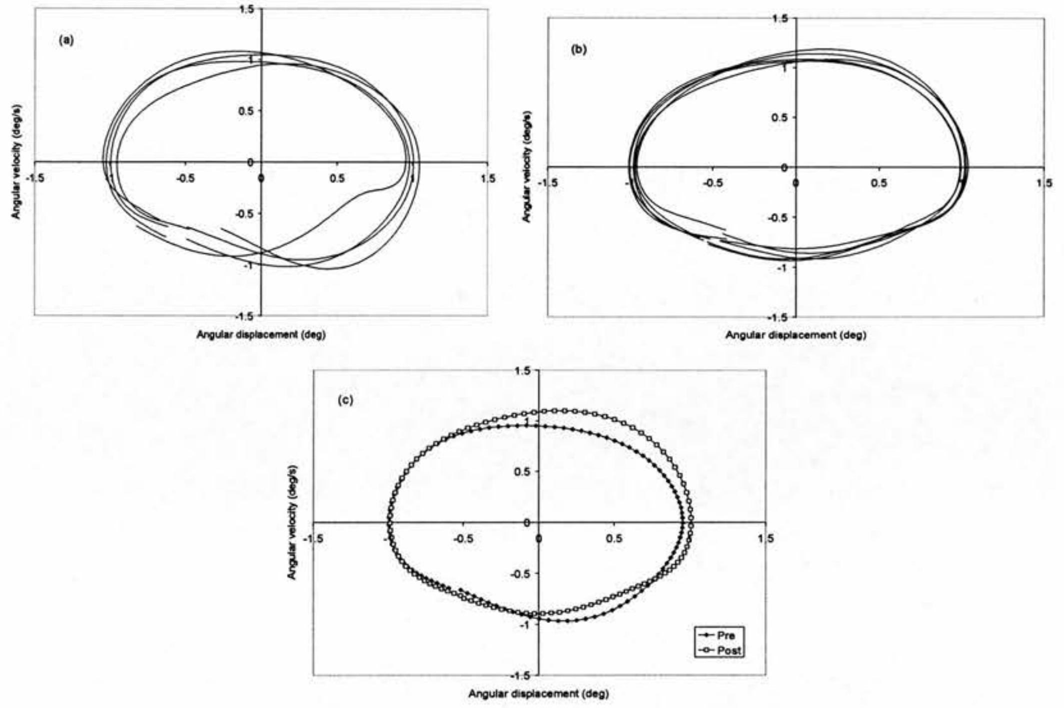


Figure 4.4.13 Knee joint phase planes of pre (a), post (b) and mean of pre and post training (c) for COS1.

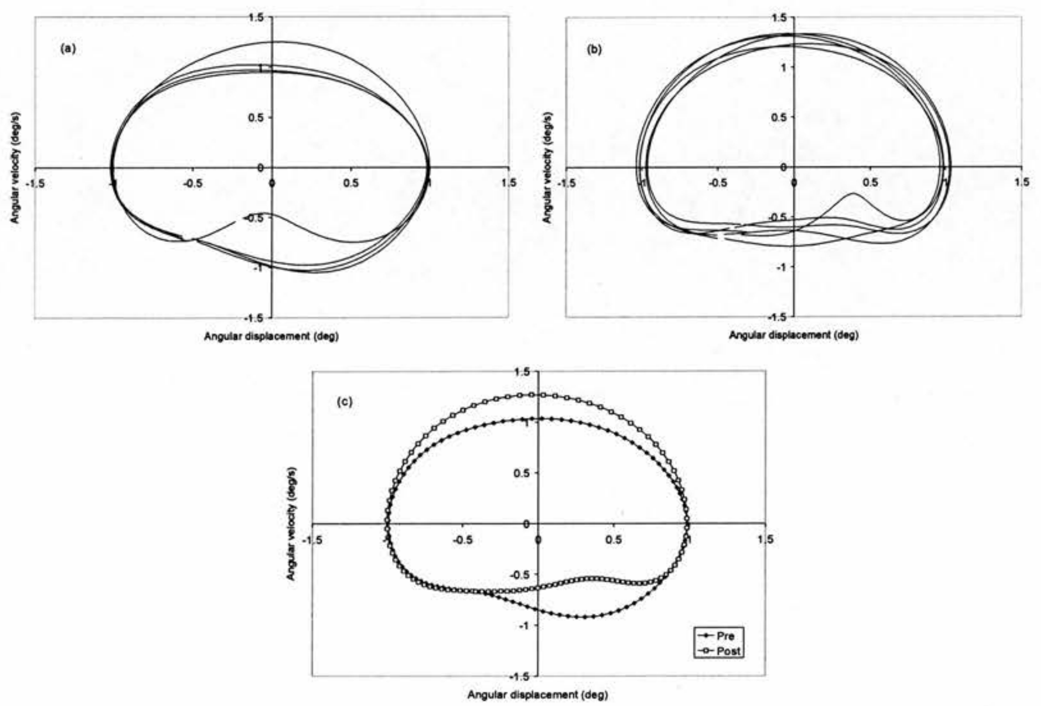


Figure 4.4.14 Knee joint phase planes of pre (a), post (b), and mean of pre and post training (c) for COS2.

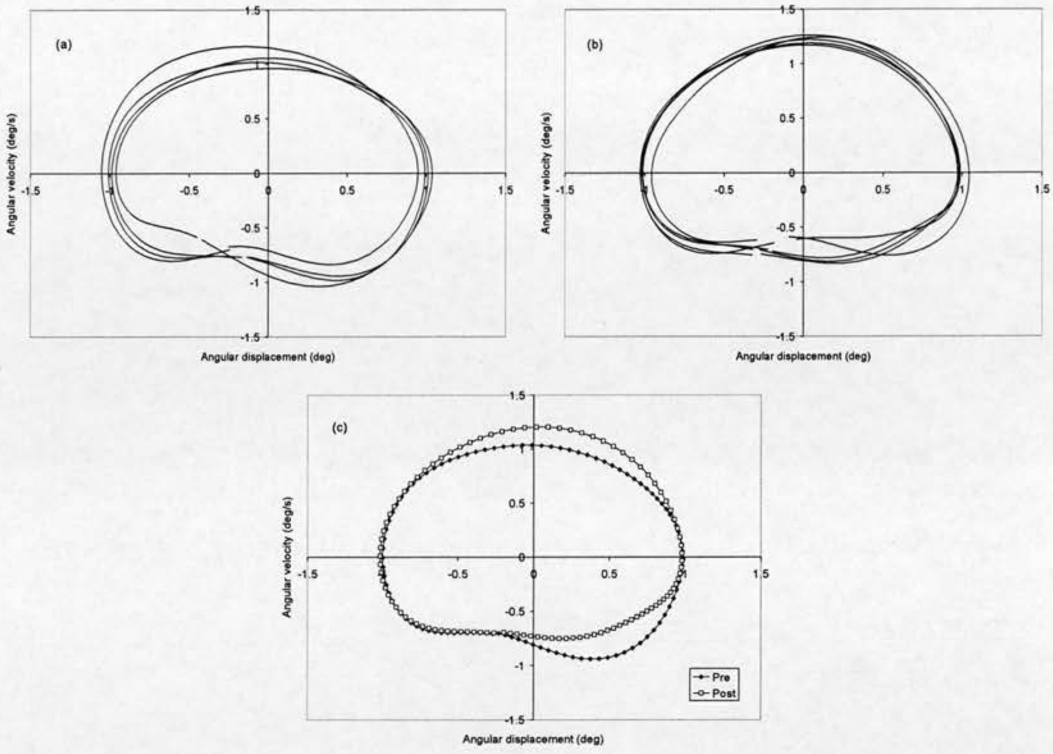


Figure 4.4.15 Knee joint phase planes of pre (a), post (b) and mean of pre and post training (c) for COS3.

The data for the control group show that there was considerable variability within the sessions and that the mean plots from pre training to post training differed considerably. However, given that the data in Section 1 indicated that the movement pattern remained appropriate in terms of the vertical undulations, and that there had been no change in task constraints in terms of flippers for the control group, it appears that the variability reflects the system exploring knee joint angular motion to continuously 'fine tune' to the current conditions of the fluid environment. For example, this may reflect fine adjustments to take advantage of the reversed Kármán vortex street to maximize propulsion and efficiency.

Therefore, when assessing changes in coordination pattern due to changes in task constraints, one must take into account the natural variability as indicated by the swimmers in the control group.

4.4.2.1.2 Phase plane pattern of the knee of the leg flipper group

For the LF group, mean phase planes for each swimmer for pre training compared to T1, T1 compared to T6, T6 compared to post training, and post training compared to pre training are presented in figures 4.4.16 to 4.4.18. Data for each trial are presented in Appendix D.

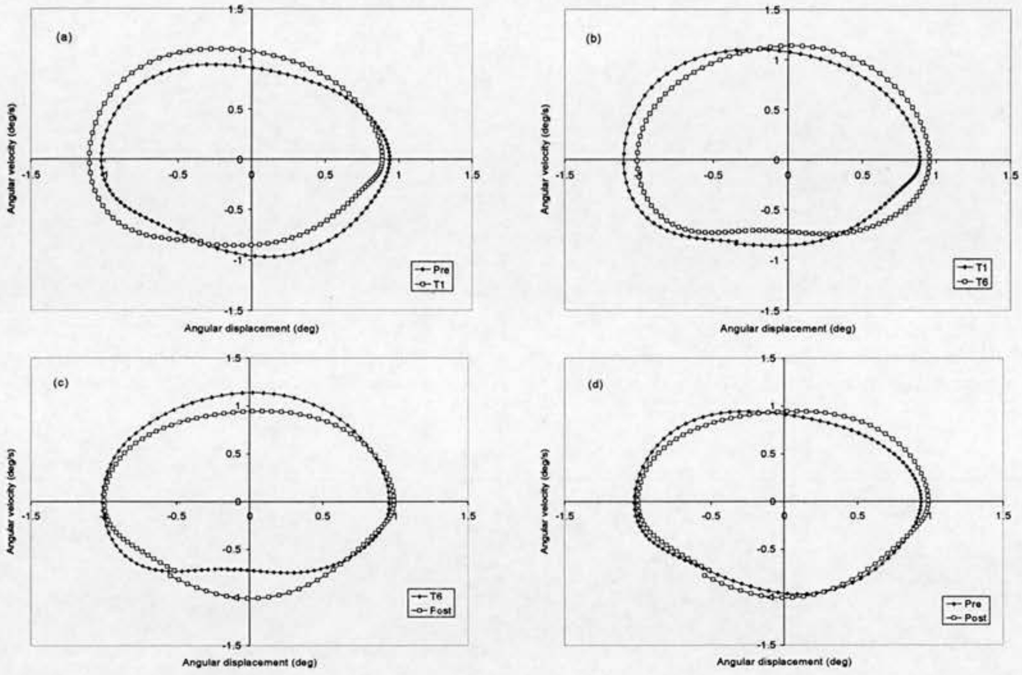


Figure 4.4.16 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS1.

There was a distinct change in the shape of the phase plane of LFS1 from pre training to T1. Unlike the phase planes for the control group there were no parts of the plots for pre training and T1 that were coincident. Similarly there was a considerable change in mean pattern from T1 to T6 and again from T6 to post training. However, the post training mean was as similar to the pre training mean as any of those of any of the control group swimmers. This indicates a rapid change in pattern following the introduction of the new constraint environment, continuing change from T1 to T6, and a rapid return to the pre-pattern when returning to the constraint environment of the barefoot condition.

LFS2 followed a similar trend to LFS1 except that T6 was very similar to T1. Like LFS1 there was a rapid shift to a different pattern when changing to the leg flipper constraint environment and a rapid return to the pattern of the barefoot pre training session in the post training session.

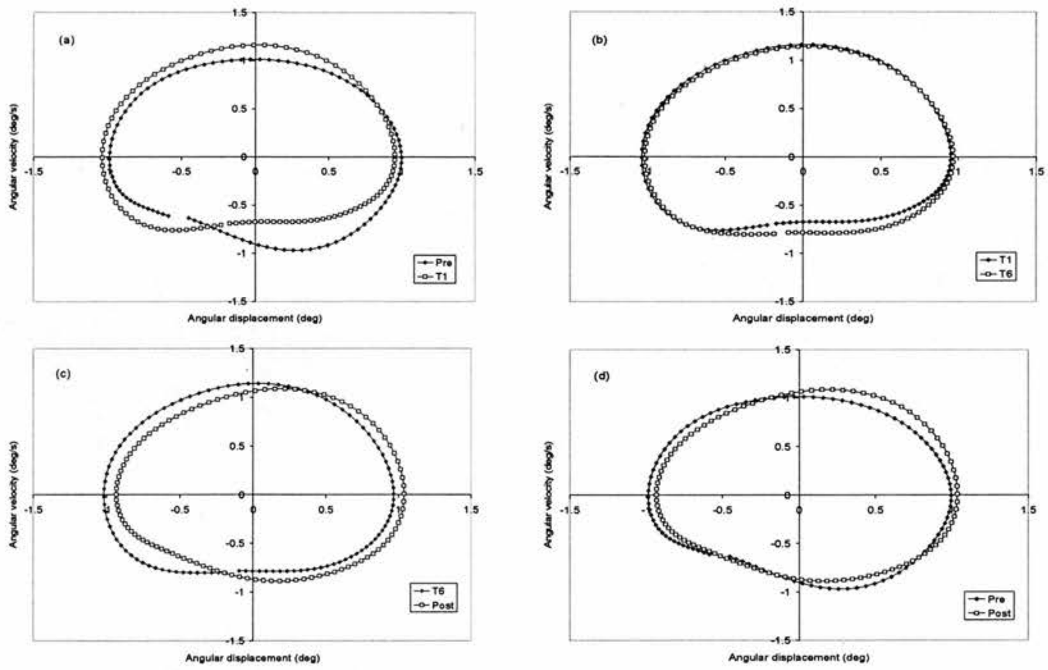


Figure 4.4.17 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS2.

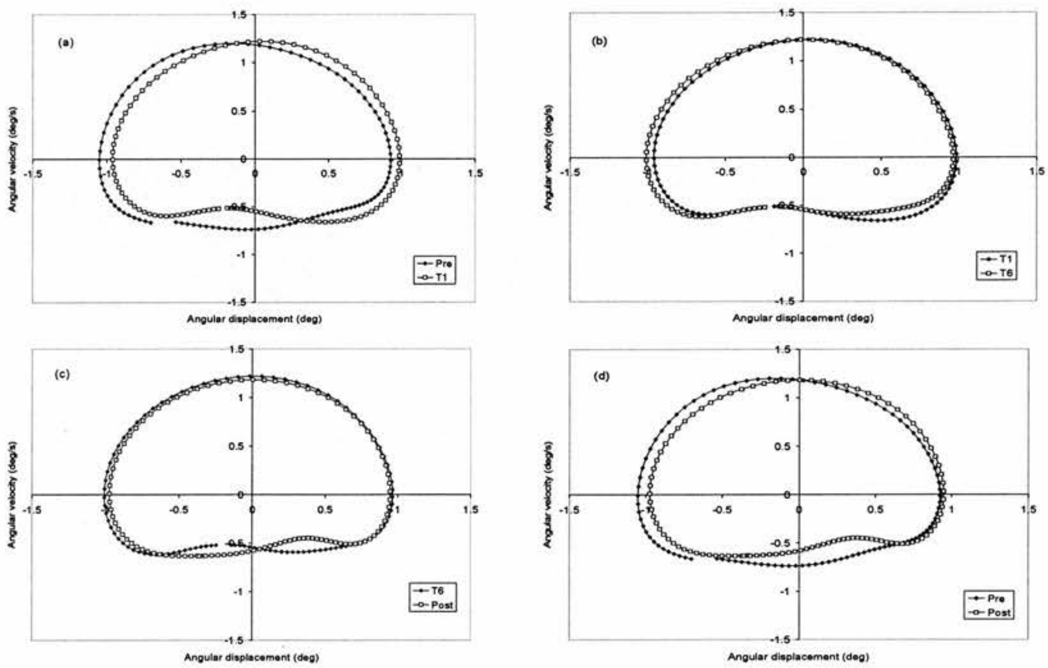


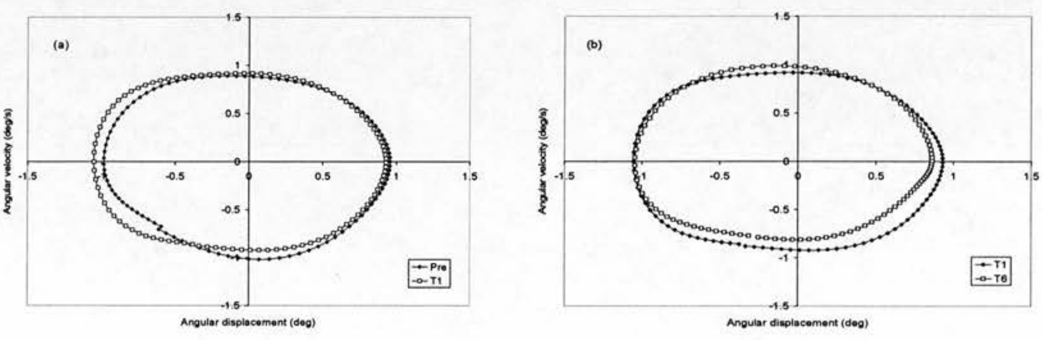
Figure 4.4.18 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS3.

LFS3 also had a rapid shift to a new pattern from pre training to T1 and, similar to LFS2 maintained a similar pattern in T6. However, an interesting difference in the post-test to pre-test was that the concavity at the base of the phase plot that was characteristic of T1 and T6 tended to be retained in the post training session although in a position shifted to the right. This raises the possibility that, for this swimmer, the flippers influenced the pattern when returning to the barefoot condition. That is, the return to the pattern prior to using the flippers was slower than for LFS1 and LFS2.

4.4.2.1.3 Phase plane pattern of the knee of the foot flipper group

For the FF group, mean knee joint phase planes for each swimmer for pre training compared to T1, T1 compared to T6, T6 compared to post training, and post training compared to pre training are presented in figures 4.4.19 to 4.4.21. Data for each trial are presented in the Appendix D.

There were differing responses among the three swimmers in the FF group. FFS1 and FFS3 did not change their phase plane pattern for the knee joint very much from pre training to T1. However, both changed considerably from T1 to T6. This indicates that as far as normalized phase plane movement patterns are concerned, participants initially retained a pattern similar to that of the barefoot condition despite the change in constraint environment prior to changing the pattern during the training sessions. FFS2 decreased knee angular velocity during the early part of knee flexion in T1 compared to pre training but increased it again in T6. Interestingly, when returning to the barefoot condition the velocity of knee flexion in the early part of flexion was again slow. This indicates that this participant was rather 'cautious' and tentative with respect to the downbeat each time there was a change in task constraints. FFS1 had slower knee flexion velocities in the post-test than in the pre-test. This may have been due to a decreased effort as noted previously. The post training session of FFS3 was almost identical to the pre training session in phase plane pattern of the knee.



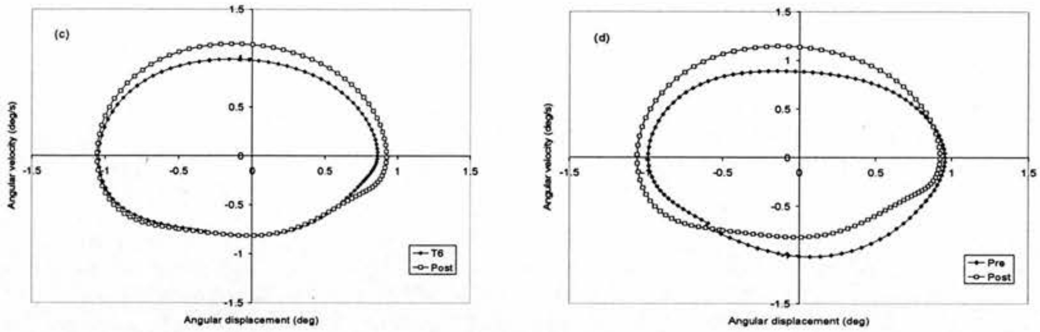


Figure 4.4.19 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS1.

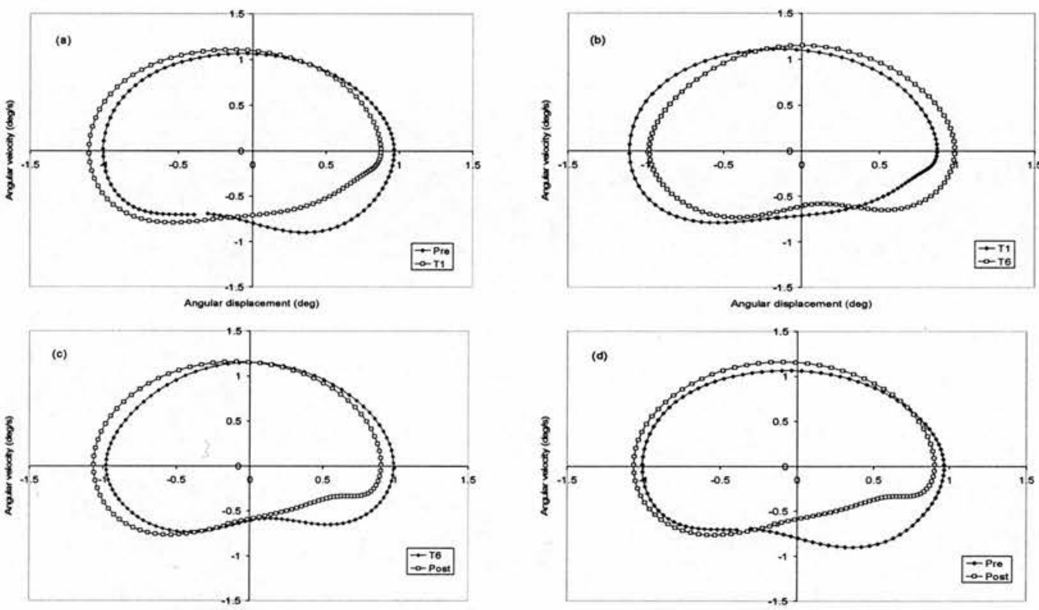
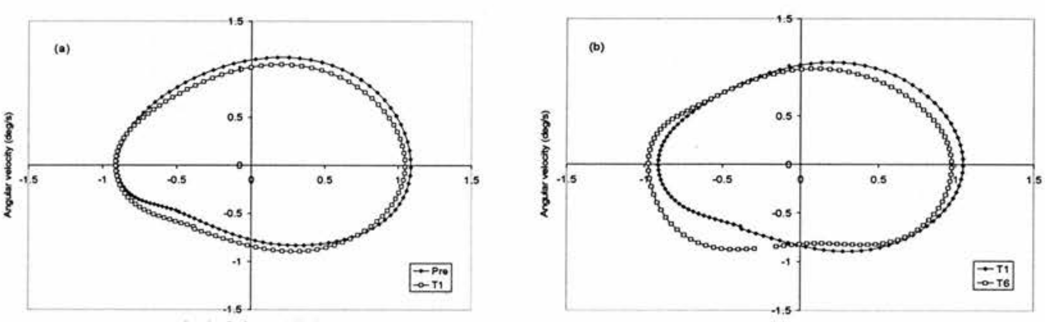


Figure 4.4.20 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS2.



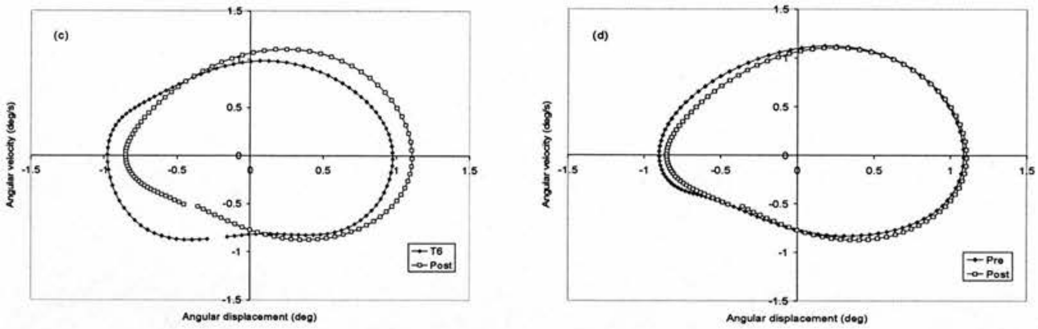


Figure 4.4.21 Mean knee joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS3.

4.4.2.1.4 Variability of phase plane patterns for the knee joint

Table 4.4.2 displays the variability in knee phase plane patterns for all sessions of all swimmers. Similar to the variability of hip-knee joints angle-angle plots, when the task constraints changed from barefoot to flipper kicking, all swimmers except FFS2 responded immediately by decreasing variability in T1. However, for FFS2 the variability in T1 was lower than in any of the other training sessions. For all swimmers the variability differed considerably across the training sessions. The session of highest variability was different for swimmers. In the post training session all swimmers had smaller variability than in the pre training barefoot kicking except LFS2 and FFS2. However, given that the control group swimmers also reduced variability in the post training session the effect cannot be attributed to an effect of changing tasks constraints.

Table 4.4.2 Variability of the phase plane patterns for the knee joint within experiment session for swimmers of LF, FF and control groups.

	Pre	T1	T2	T3	T4	T5	T6	Post
LFS1	0.136	0.074	0.075	0.128	0.095	0.167	0.123	0.108
LFS2	0.081	0.076	0.105	0.068	0.100	0.183	0.085	0.113
LFS3	0.195	0.151	0.172	0.094	0.175	0.114	0.117	0.177
FFS1	0.160	0.133	0.230	0.198	0.179	0.183	0.204	0.114
FFS2	0.091	0.120	0.122	0.122	0.163	0.156	0.131	0.115
FFS3	0.174	0.125	0.160	0.120	0.173	0.158	0.156	0.108
COS1	0.214							0.056
COS2	0.186							0.096
COS3	0.206							0.066

4.4.2.2 Phase plane of the hip joint

4.4.2.2.1 Phase plane pattern of the hip of the control group

Hip joint phase plane data for each trial of the pre training, post training sessions, and means of pre training and post training of the control group are presented in figures 4.4.22 to 4.4.24. The direction of the plots is clockwise.

In the post training session, there was less variability than in the pre training session. COS1 and COS2 had mean pre training hip phase plane plots that were considerably different from those of the post training session. COS3 was the most consistent of the control group and had pre training and post training means that matched closely. Given the natural variability in the phase planes one must be cautious when interpreting differences in phase plane patterns across constraint conditions for the LF and FF groups.

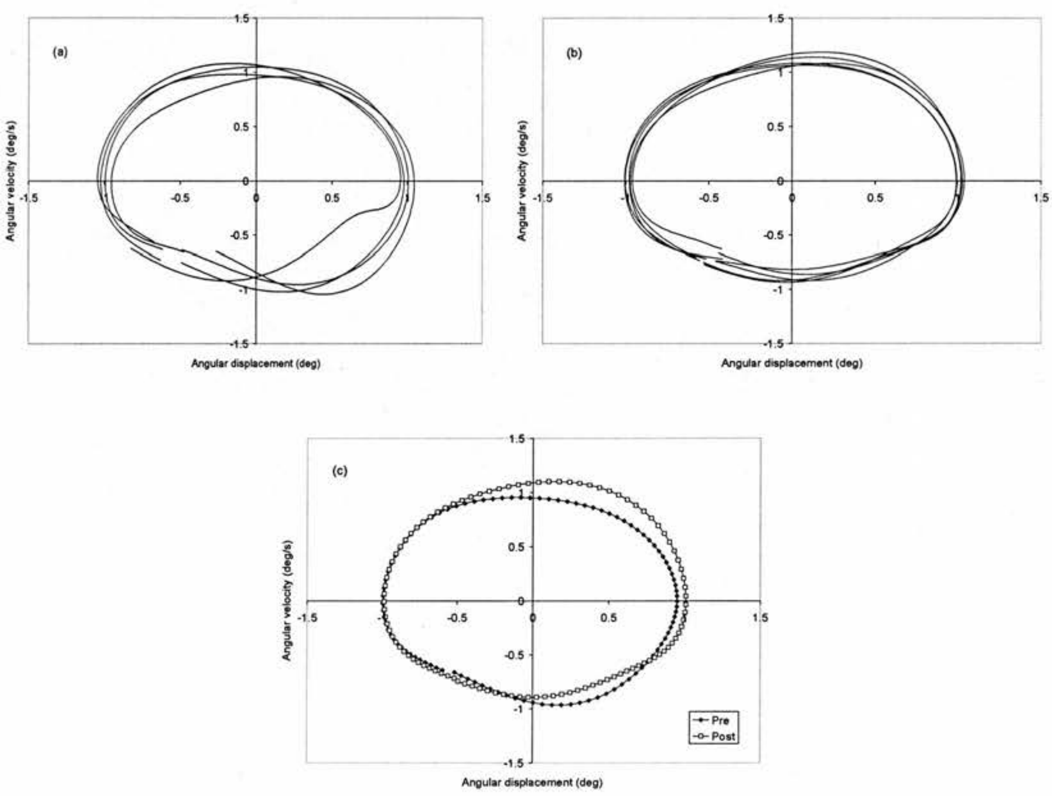


Figure 4.4.22 Hip joint phase planes of pre (a), post (b) and mean of pre and post (c) training session for COS1.

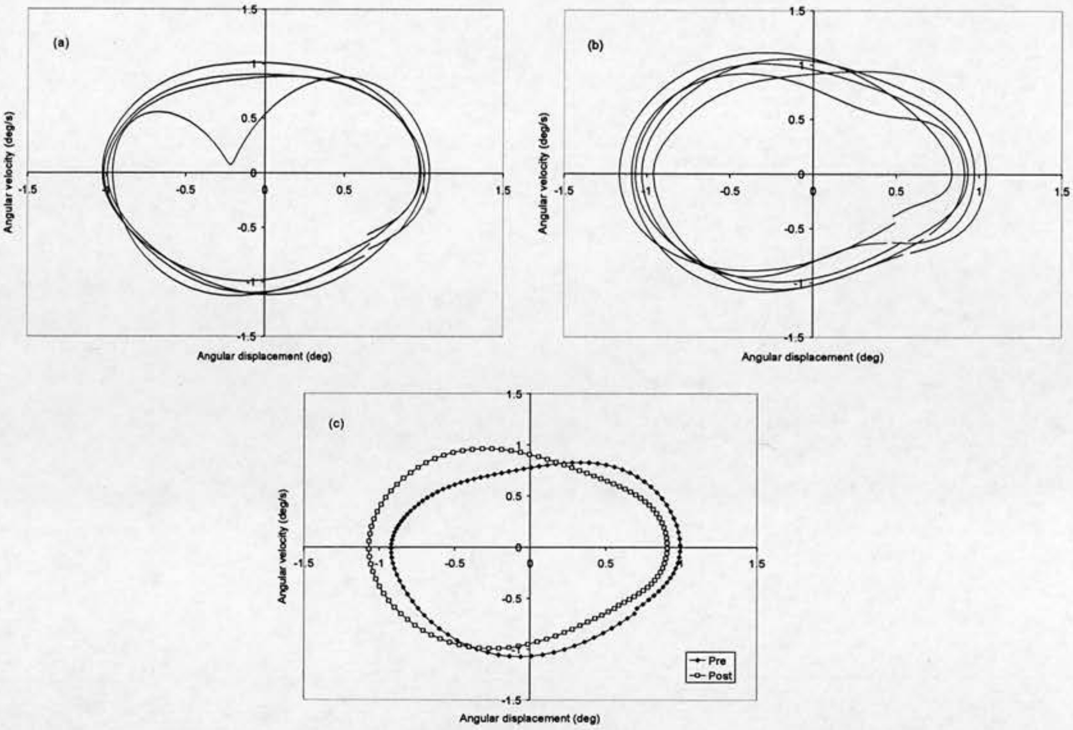


Figure 4.4.23 Hip joint phase planes of pre (a), post (b) and mean of pre and post (c) training session for COS2.

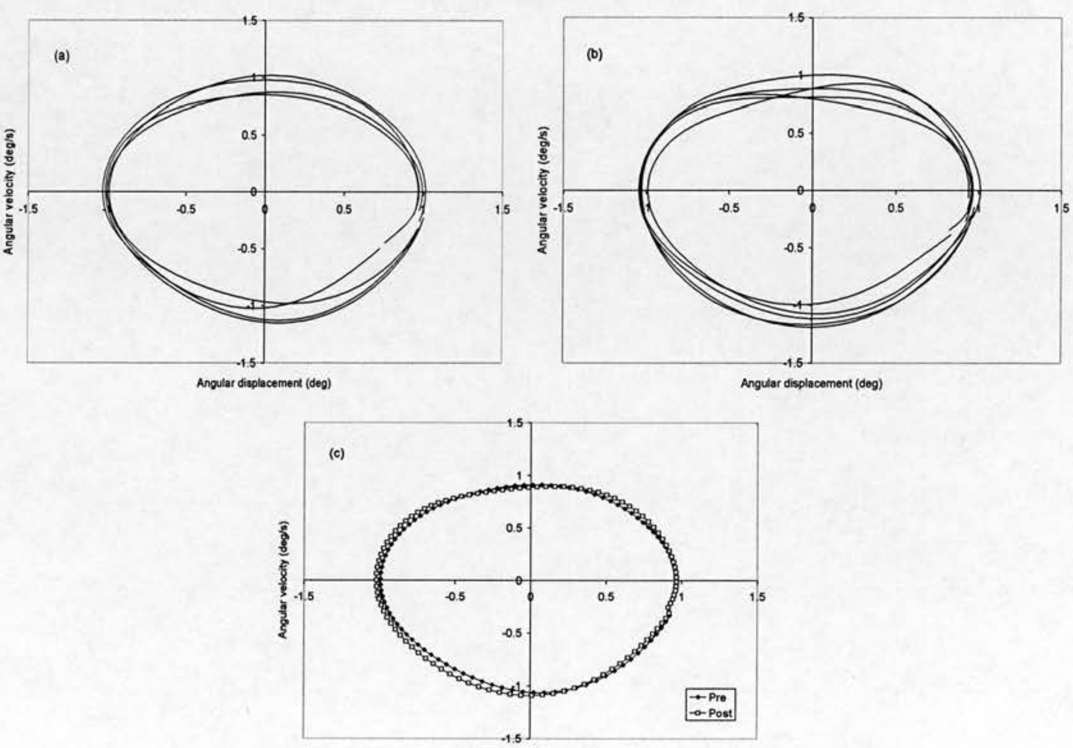


Figure 4.4.24 Hip joint phase planes of pre (a), post (b) and mean of pre and post (c) training session for COS3.

4.4.2.2.2 Phase plane pattern of the hip of the leg flipper group

Hip joint phase plane data for each trial of the pre training, post training sessions, and means of pre training and post training of the LF group are presented in Figures 4.4.25 to 4.4.27.

It is helpful when interpreting the phase planes for the hip to recognize that a rhythmical flexion and extension, that is, if angular displacement was plotted against time it would resemble a sinusoidal curve, yields a very circular phase plane plot. A plot that departs from being very circular and has indentations indicates the existence of a pattern that has something other than a smooth sinusoidal pattern of flexion and extension superimposed on it, for example a 'bounce'.

LFS1 had quite circular phase portraits in the barefoot condition of the pre training session but developed a small 'bounce' when switching to the leg flippers. However, this pattern remained through to T6. In the post training session the portrait returned to a more round pattern similar to the pre training session. However, it is noteworthy that remnants of a 'bounce' remained. This raises the possibility that, although there was a rapid adjustment back to the original pattern, there was some influence of the previous constraint condition.
LFS2 was similar to LFS1 with quite a circular pre training phase portrait and a small 'bounce' when switching to leg flippers. However, unlike LFS1, LFS2 had removed the 'bounce' by T6. Interestingly, the post training portrait was similar to the pre training portrait but with a slight 'bounce'. However, the 'bounce' in the post training session was in a very different part of the kicking cycle to that in T1. Again this raises the possibility of an influence of the previous constraint condition.

The phase portraits of swimmer LFS3 were strongly influenced by a 'bounce' that was variable (Appendix E Figure 3 (b)-(g)). When switching to the leg flippers the position in the cycle of the 'bounce' changed to near the time when hip joint angular velocity was zero. It remained in that location in T6. When returning to the barefoot condition the pattern returned to that of the pre training sessions except that the position of the 'bounce' was midway between the position in the pre training session and in the training sessions.

Thus, all three swimmers in the LF group, while different in terms of their phase portraits, provided evidence that there was rapid change in hip phase portrait when changing to a different constraint environment. When returning to the barefoot condition there was a rapid change back towards the hip phase pattern of the pre training session. However, there was evidence that the post training pattern was influenced by the previous constraint environment associated with wearing the leg flippers. That is complete readjustment to the original re-training condition did not occur in the first five trials post training.

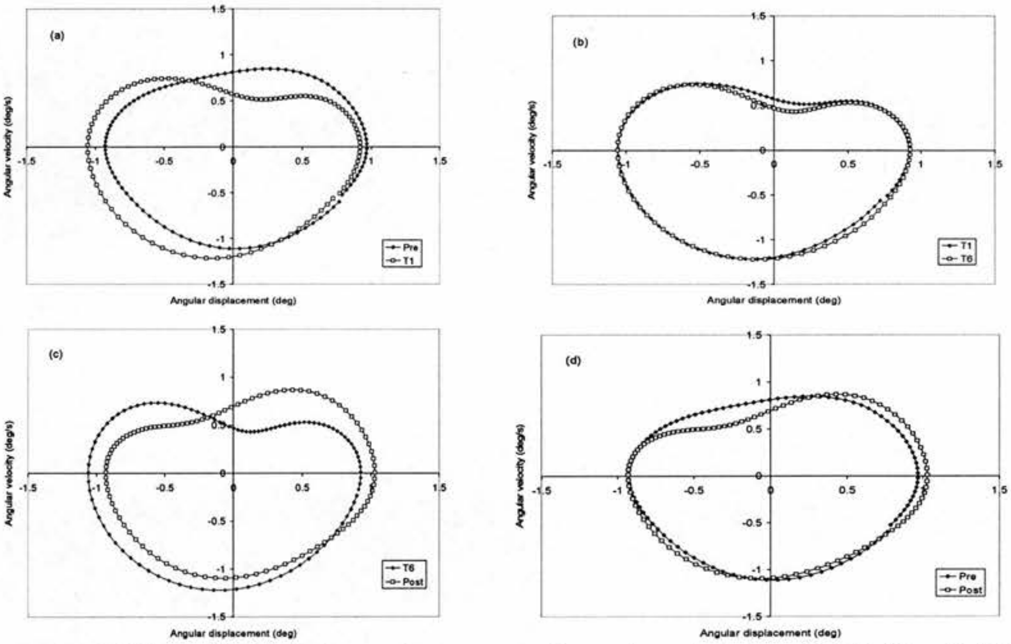


Figure 4.4.25 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS1.

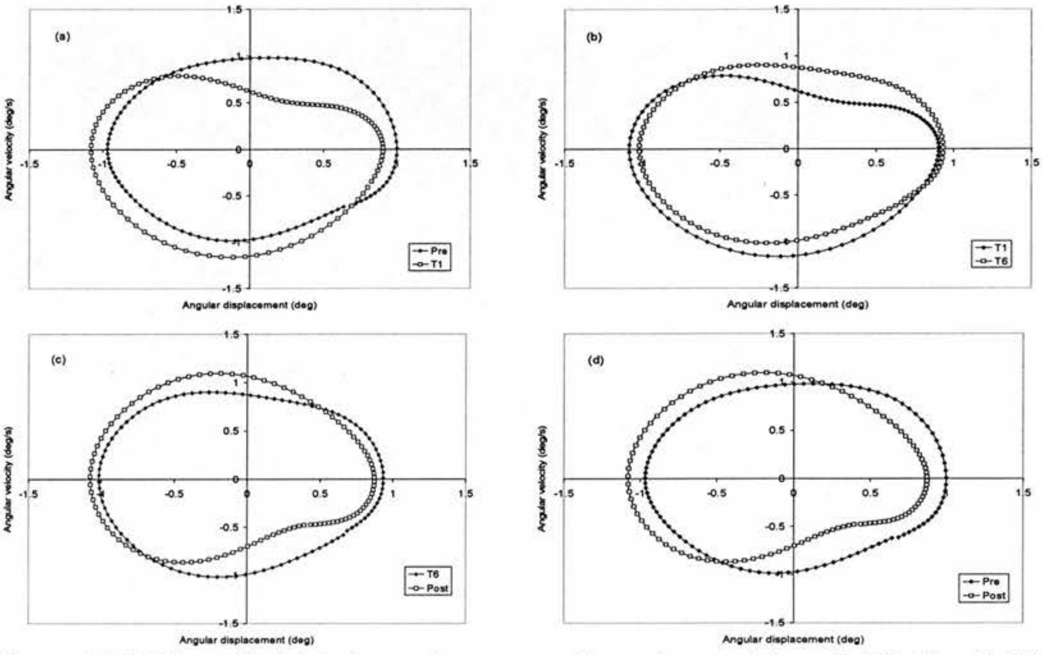


Figure 4.4.26 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS2.

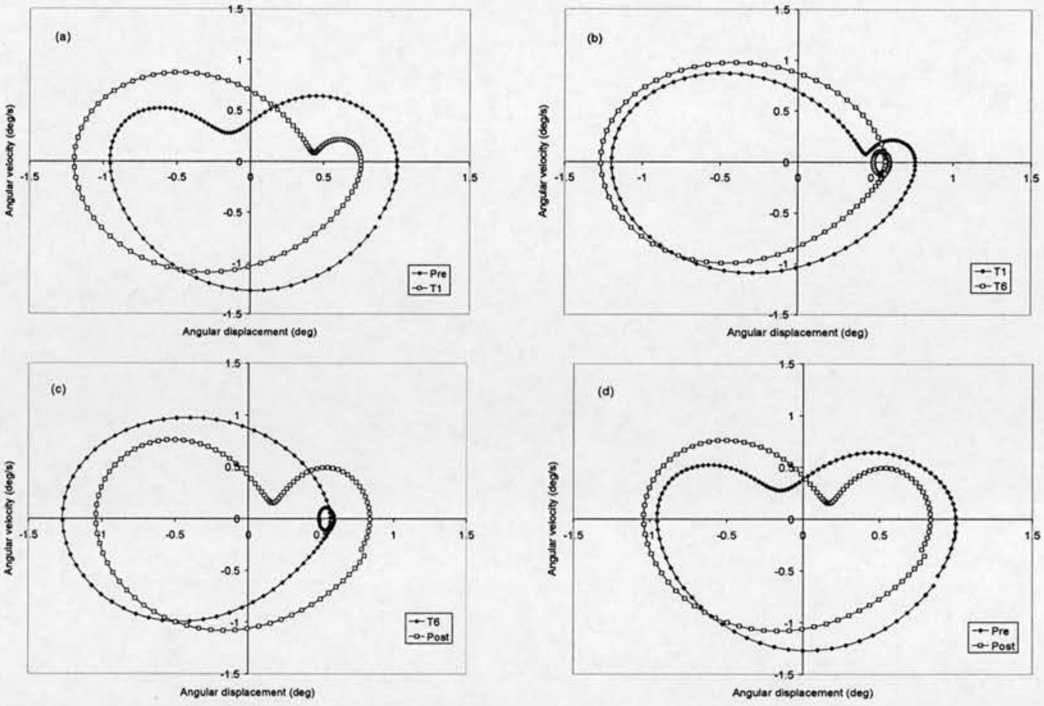


Figure 4.4.27 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer LFS3.

4.4.2.2.3 Phase plane pattern of the hip of the foot flipper group

Hip joint phase plane data for each trial of the pre training, post training sessions, and means of pre training and post training of the foot flipper group are presented in figures 4.4.28 to 4.4.30.

All the FF group changed rapidly to a different hip phase plane pattern when switching to foot flippers. In view of the level of natural variability evident in the control group data, all then maintained similar patterns from T1 to T6. Differences between pre training and post training appear to be due to a slower extension, particularly in the case of FFS1 and remaining close to full extension for a longer period in the case of FFS2 and FFS3. These results reflect the decline in effort indicated by other variables in Section 2 of the results.

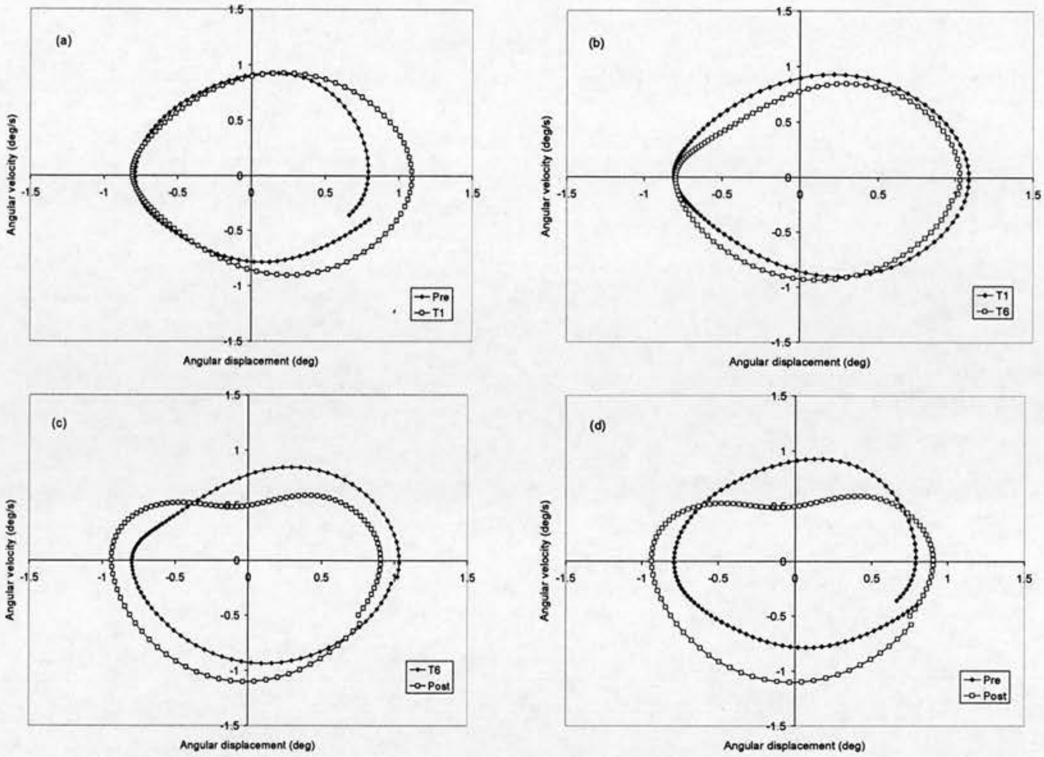


Figure 4.4.28 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS1.

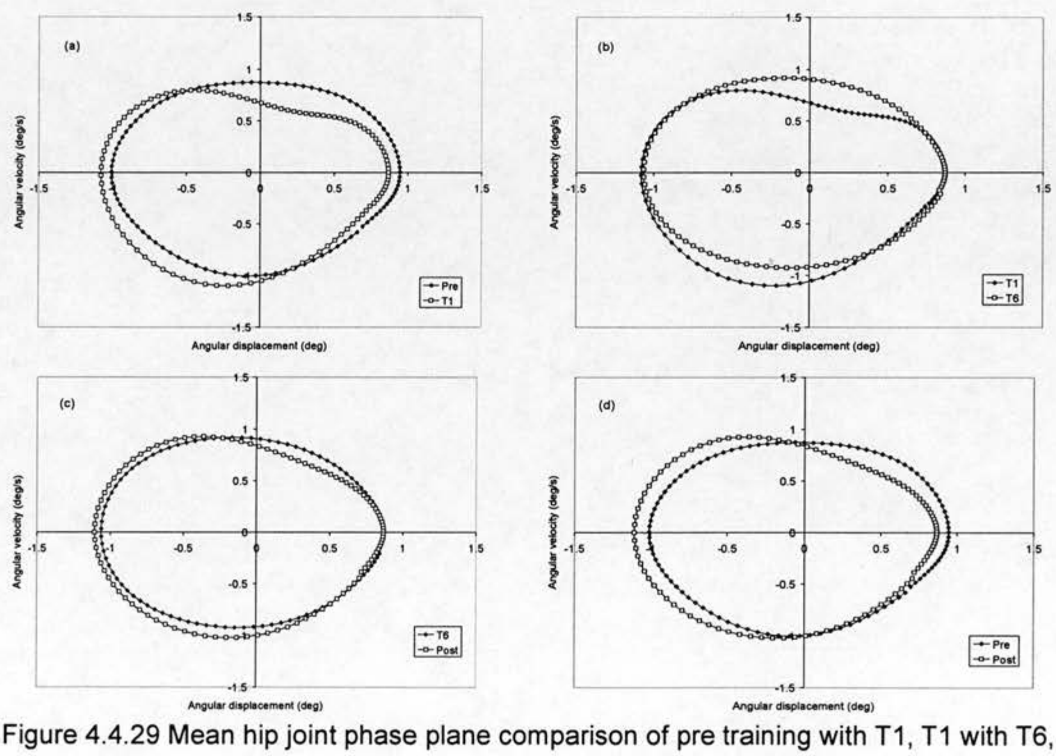


Figure 4.4.29 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS2.

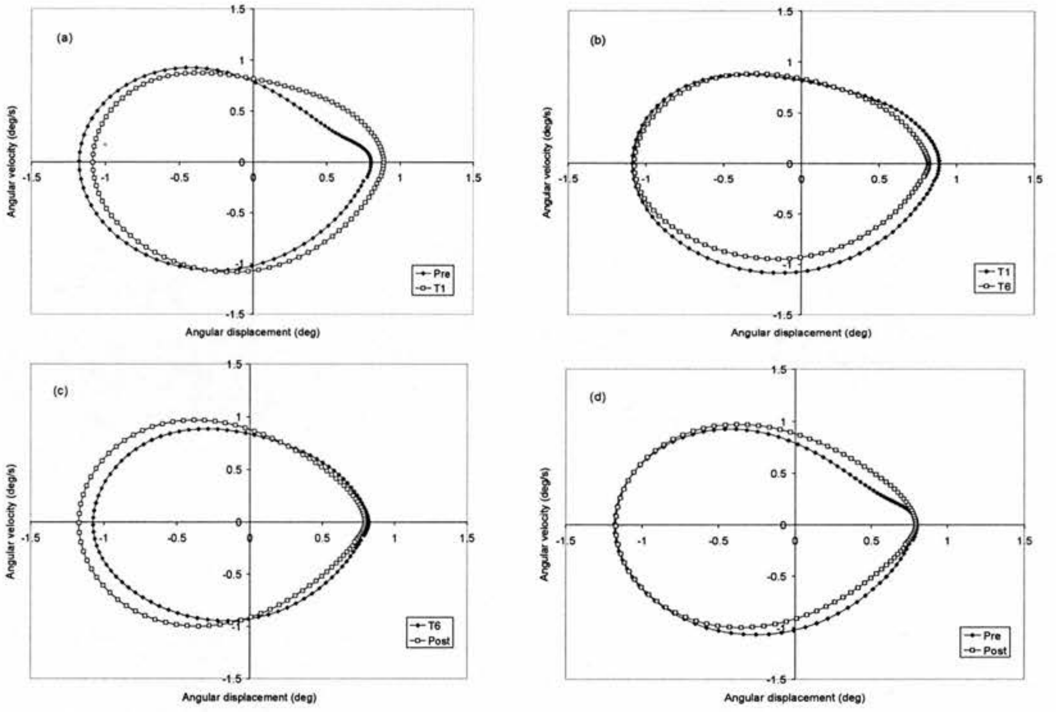


Figure 4.4.30 Mean hip joint phase plane comparison of pre training with T1, T1 with T6, T6 with post training, and pre training with post training for swimmer FFS3.

4.4.2.2.4 Variability of phase plane patterns for the hip joint

Table 4.4.3 displays the variability in hip phase patterns for sessions of all swimmers. When the task constraints changed from barefoot to flipper kicking (T1), all swimmers immediately reduced variability. All swimmers' then increased variability in the second training session (T2). Then, the variability was changeable in the remaining training sessions. For LFS1, LFS3, FFS2 and FFS3 the variability was highest in T2. When the task constraints returned from flipper kicking to barefoot kicking, all swimmers except LFS2 had lower variability than in the pre training barefoot kicking. However, the same effect was apparent for the control group and so cannot be attributed to the training sessions.

Table 4.4.3 Variability of the phase plane patterns for the hip joint within experiment session for swimmers of LF, FF and control groups.

	Pre	T1	T2	T3	T4	T5	T6	Post
LFS1	0.187	0.106	0.295	0.144	0.129	0.175	0.090	0.134
LFS2	0.116	0.086	0.109	0.130	0.118	0.164	0.158	0.150
LFS3	0.196	0.110	0.271	0.142	0.188	0.169	0.125	0.176
FFS1	0.331	0.182	0.317	0.236	0.330	0.132	0.262	0.231
FFS2	0.164	0.153	0.310	0.159	0.185	0.150	0.177	0.093
FFS3	0.153	0.097	0.295	0.145	0.182	0.183	0.179	0.110
COS1	0.214							0.056
COS2	0.217							0.101
COS3	0.212							0.082

4.4.3 Continuous relative phase (CRP) of the hip and knee joints

CRP provides a measure of the interaction or coordination of two joints during the flutter kicking cycle. CRP analysis has been considered an efficient way of investigating the special temporal relationships (coupling) of joint actions. In the present study the phase angles of the hip and knee were calculated from phase plane data amplitude normalized on both angular displacement and angular velocity axes as described in the Method Section. The analysis process included comparison of the changes of CRP between pre and post training, pre training and T1, T6 and post training as well as the trend over all training sessions (kicking with flippers).

A sample CRP plot from the trials of the pre training session of swimmer FFS3 is displayed in Figure 4.4.31. The knee was 123 degrees out-of-phase with the hip when the ankle joint was at its the highest point (the start point of the complete kicking cycle), decreased to the point of the minimum angle of the knee joint (23% of the kicking cycle), remained almost level during the period of knee joint extension (23–66% of the kicking cycle) and then increased during knee flexion. Variability across trials is indicated by ensemble curves ± one standard deviation.

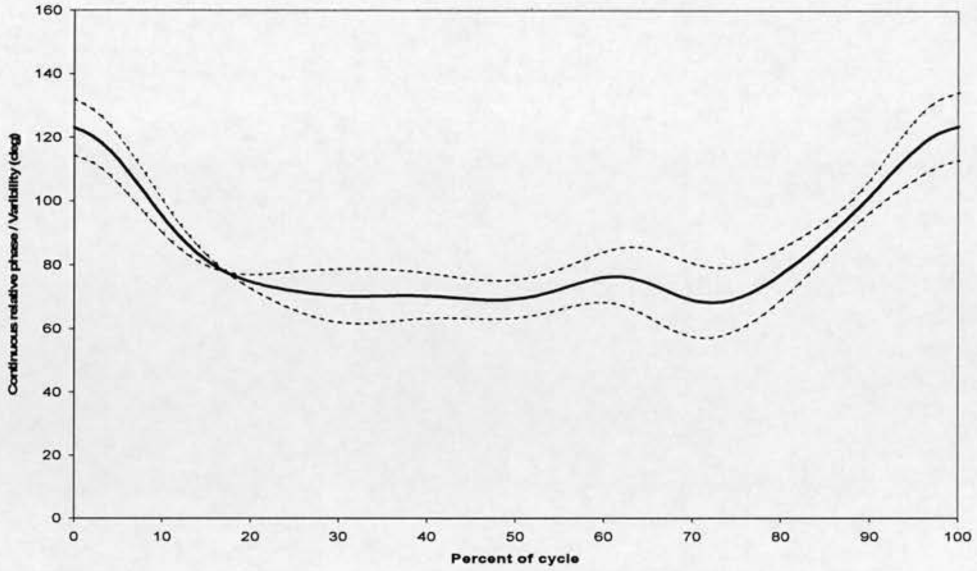


Figure 4.4.31 Mean CRP (normalized) with SD ensemble curves hip - knee joint over a complete cycle of flutter kicking (0 to 100%).

Data showing the hip-knee joint CRP variability for the LF, FF and control groups are presented in Table 4.4.4. When kicking with flippers, the average CRP of the swimmers in the LF group was smaller than that of barefoot kicking. The decrease in magnitude of CRP for the LF group was (30.79 %). Over the training sessions, the average CRP for the FF group were very similar to those of the pre training session (Table 4.4.5).

These results indicated that the coordination of the lower extremities of the LF group was affected considerably when the task constraints changed from barefoot kicking to flipper kicking and the FF group's coordination wasn't affected by this change. During training sessions, the average variability of the LF group was higher than that of barefoot kicking in the pre training sessions while the variability of the FF group was lower than that of pre training session.

Table 4.4.4 Mean continuous relative phase (CRP), standard deviations (SD), and effect size (E.S.) over the complete kicking cycle for LF, FF and CO groups.

	LF			FF			CO	
	Pre training	Pooled Training	Post training	Pre training	Pooled Training	Post training	Pre training	Post training
Mean	87.08	60.27	75.38	81.75	80.06	73.78	72.45	68.87
SD	7.41	10.85	11.36	14.68	11.70	10.51	7.03	11.40
E.S.		-3.62	-1.58		-0.12	-0.54		-0.51

The results indicate that the FF group maintained similar phase relationships between hip and knee angular motion across all sessions. The effect size of -0.54 for the post training relative to the pre training is modest, especially considering that the control group had an equivalent change from pre to post training.

The change in CRP from pre training to the training sessions of the LF group was very large (E.S. -3.62). Also, the CRP did not return completely to pre training values in the post training session (E.S. -1.58).

The small effect on the CRP of the hip and knee of the FF group is not surprising given that the system adjusted rapidly to maintain the vertical undulations to maintain performance (results from Section 1). That is, the kinematics were retained with a similar relationship because this was suited to task achievement. The adjustment would have required a change in joint torques so that the kinematics could be maintained despite the additional load imposed by the foot flippers. However, it appears that the adjustment in joint torques was achieved rapidly and readily.

In contrast, adjustment to the leg flippers required a change in kinematics so that the body wave velocity index was maintained despite a change in anthropometrics of the system. That is, a change from a three segment system to a two segment system in which the second segment had increased in length. Thus, a change in kinematics, including the phase relationship between hip and knee joints was required in order to achieve the relationships between the vertical undulations 'known' by the system to be desirable for performance. Importantly, the results presented in Section 1 for %power and body wave velocity index indicate that this adjustment was made rapidly and appropriately.

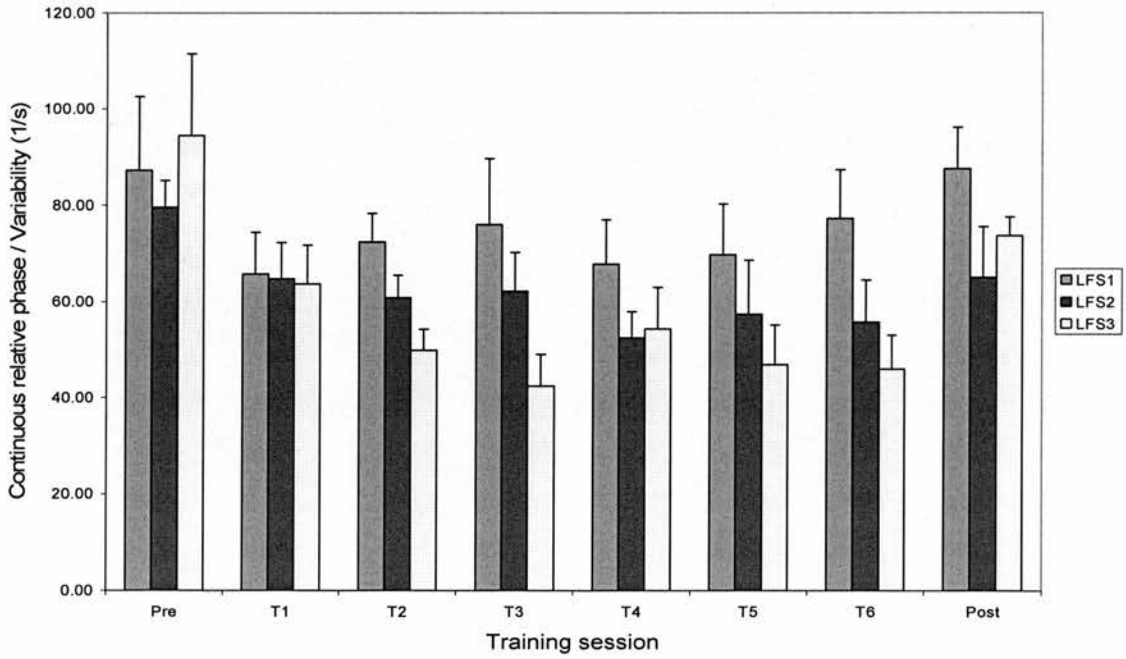
Table 4.4.5 Mean values, variability (SD) and effect size (E.S., mean values relative to the one in pre training session) of CRP over all experiment sessions for LF and FF groups.

		Pre	T1	T2	T3	T4	T5	T6	Post
LF	Mean	87.08	64.72	61.00	60.15	58.16	57.97	59.62	75.38
	SD	7.41	1.05	11.28	16.89	8.37	11.45	16.04	11.36
	E.S.		-3.02	-3.52	-3.64	-3.90	-3.93	-3.71	-1.58
FF	Mean	81.75	84.07	75.80	77.96	78.13	85.00	79.38	73.78
	SD	14.68	15.48	6.39	14.20	5.04	16.05	13.04	10.51
	E.S.		0.16	-0.41	-0.26	-0.25	0.22	-0.16	-0.54

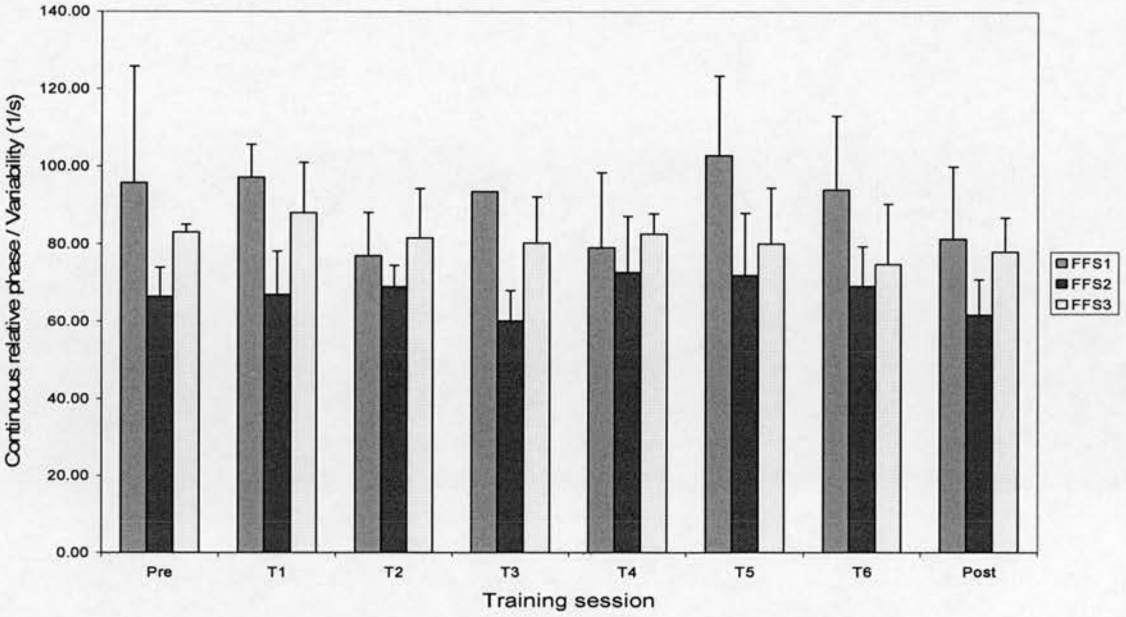
Note: Pre/Post: pre or post training session (kicking without flippers); Ti: the ith training session (kicking with flippers).

Table 4.4.5 shows that the mean effect size for both LF and FF groups not much different in T1 from other training sessions. That is, almost all of the adjustment in the coupling relationship of the hip and knee required to be appropriate for task achievement occurred rapidly, that is in T1.

Mean CRPs across all sessions of each swimmer are shown for the LF and FF groups in Figure 4.4.32. All three swimmers in the LF group provided evidence that there was rapid change in mean CRP when changing from barefoot to a flipper kicking constraint environment. When returning to the barefoot condition there was a rapid change back towards the mean CRP pattern of the pre training session. However, there was evidence that the post training pattern was influenced by the previous constraint environment associated with wearing the leg flippers. That is complete readjustment to the original re-training condition did not occur in the first five trials post training. Swimmers in the FF group retained a pattern similar to that of the barefoot condition despite the change in constraint environment prior to changing the pattern during the training sessions. Unlike some of the other measures, there was no consistent evidence that swimmers reduced the variability of the CRP from pre training to T1.



(a)



(b)

Figure 4.4.32 Mean continuous relative phase (CRP) and variability for the LF group (a) and FF group (b) for all measurement sessions.

4.4.4 Summary

When changing from the barefoot constraint environment to the flipper constraint environment there was rapid change in kinematics for both the LF and FF groups. This was indicated by changes in patterns of hip and knee angle-angle, phase planes of the hip joint, phase planes of the knee joint. The CRP patterns did not change markedly for the FF group but did change markedly for the LF group.

For both the LF and FF groups initial adjustment was followed by considerable exploration of movement possibilities indicated by the variability in knee-hip angle relationships, and knee and hip phase planes. This variability tended to be greater in training sessions beyond T1 than in T1.

Adjustment of kinematics when returning to the barefoot constraint environment was also rapid for both LF and FF groups. However, there was evidence that the immediate post training pattern was influenced, to varying degrees among swimmers, by the preceding flipper constraint environment.

The change in CRP from pre training to the training sessions of the LF group was very large (E.S. -3.62). Also, the CRP did not return completely to pre training values in the post training session (E.S. -1.58). This implied that, due to the change in the effective length of the second segment, change in kinematics was required to maintain the body wave velocity index appropriate for efficient achievement of the task. The small effect on the CRP of the hip and knee of the FF group indicated that the kinematics were retained with a similar relationship because these kinematics were already suited to task achievement. However, retaining those appropriate kinematics would have required a large change in joint torques.

CHAPTER 5

CONCLUSION

The purpose of this study was to investigate the process of adaptation to change in task constraints, in particular the presence or absence of flippers in swimming. Two general hypothesizes were addressed:

(i) The adaptation of skilled swimmers from a familiar task constraint environment (kicking without flippers) to a second familiar task constraint environment (foot flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

(ii) The adaptation of skilled swimmers from a familiar task with a familiar constraint environment (kicking without flippers) to the same familiar task with an unfamiliar task constraint environment (leg flippers) and back to kicking without flippers occurs in the first 10 trials following the change in task constraints.

The hypotheses were both supported with respect to the movement pattern remaining appropriate for task achievement as indicated by the fundamental criteria, that is, a high percentage of power in the fundamental Fourier harmonic of the vertical oscillations of the hip, knee, and ankle; and appropriate phase relationships between hip, knee, and ankle undulations indicated by a velocity index close to 1.0. For both the LF and FF groups the necessary adjustments in kinematics were made to satisfy those criteria even in the first session under the new constraint conditions. This applied to both changing from the constraint environment from barefoot to flipper and from flipper to barefoot.

However, while the hypotheses were supported with respect to the fundamental criteria, the optimal performance with respect to swimming speed and stroke index was greater in T2 for the LF group. This meant that the system still needed to 'explore' to find the optimal movement pattern to optimize performance under the new conditions. This involved changing parameters such as amplitude and frequency of the kicking motion to suit the fluid environment in which the task was being performed, while retaining the predominantly sinusoidal undulations with appropriate phase relationships between the undulations. The quicker optimization by the FF group than the LF group is logically attributable to the fact that the constraint environment was familiar in the case of the foot flipper condition but unfamiliar in the case of the leg flipper condition.

Small variability in normalized angle-angle of knee-hip joint and normalized phase planes of knee and hip joints during the first training session with both foot flippers and leg flippers indicated a tendency for the system to seek stability in movement pattern when first adjusting to a changed constraint environment. In subsequent sessions the system introduced freedom to 'explore'. All three LF participants also had small variability in kicking frequency in T1.

The number of trials required to develop an appropriate movement pattern for performance of a swimming kicking task with unfamiliar constraints was much less than that required to develop an appropriate movement pattern for the jumping task with unfamiliar constraints in the study by Sanders and Wilson (1992). In that study the system had to find an appropriate movement pattern whereas in the kicking task the system 'knew' the basic characteristics of the movement pattern required. This provided evidence for the idea that human neuromuscular systems can adjust rapidly to task constraints if the movement pattern appropriate for task achievement is familiar to the system.

It would appear that if the required movement pattern is familiar to the system can adjust to changes in task constraint environment even if that constraint environment is considerably different from the range of previous experiences. In the case of swimming with leg fins, the task required a major change in hip and knee joint coupling as indicated by a major change in CRP across barefoot and leg flipper conditions. The system made the change successfully even in the first trials with the leg flippers. Furthermore, the low variability in the first training session indicated that a stable solution was found virtually immediately in keeping with dynamical systems theory for self organizing systems.

Although the systems adjusted within the first 10 trials to the changed constraint environment in terms of the fundamental criteria of appropriate movement pattern, there was evidence that some kinematic features were influenced by the preceding constraint environment. However, this remains inconclusive for four main reasons. First, there were an insufficient number of trials in the post training session to assess whether, with time, the kinematics would return completely to the pre training pattern. Second, the performance declined and the associated kinematics changed over the period of the experiment due to what appeared to be a decrease in motivation or an increase in fatigue. Third, the observed effects were not consistent across participants. Fourth, there was considerable natural variability within and between participants. The first and second of these are clearly limitations of the study that have become evident in the light of the results. Design of future experiments will benefit from that experience.

The study also provided information that reinforced knowledge and ideas relating to human swimming. A 'whip-like' undulation pattern comprising sinusoidal undulations with appropriate phasing relative to each other such that a body wave travels caudally was evident and supports the work of Sanders, Cappaert and Devlin, (1995) and Sanders (2006) with respect to human kicking without flippers and the studies of Li (1989; 1990), Luk, Hong, Chu and Li (1999), Rejman et al., (2002), Gautier et al. (2004), and Luersen et al. (2004) with respect to human kicking with flippers.

Meeting the basic criteria for aquatic kicking movements, that is, a high %power in the fundamental Fourier harmonic with phasing such that the velocity index was close to 1.0, did not, in isolation, optimize performance. This emphasizes the importance of adjusting amplitude and frequency of kicking to optimise the interaction of the system with the reversed Kármán vortex street (Lighthill, 1975) to maximize propulsion (Triantafyllou, Triantafyllou and Yue, 2000; Colgate and Lynch, 2004; Beal et al., 2006).

From this work it can be suggested that human systems can adjust rapidly to unfamiliar task constraints in the task of kicking in swimming when the required movement pattern is familiar to the system from skilled performance of swimming kicking. However, rapid adaptation to produce an appropriate movement response does not preclude continued improvement through further 'exploration' to 'fine tune' to a changed environment. Further work is required to establish whether the hypotheses supported in this study for the task of kicking in swimming are supported for other tasks in which the fundamental movement characteristics of skilled performance are familiar to the system.

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APPENDIX A PROJECT DESCRIPTION AND SAMPLE OF CONSENT FORM

care

Centre for Aquatics Research & Education

Director: Professor Ross Sanders r.sanders@ed.ac.uk

05 Feb. 2005

THE UNIVERSITY OF EDINBURGH
CENTER FOR AQUATIC RESEARCH AND EDUCATION

Effects of lower limb co-ordination with leg fins, foot fins and bare foot swimming

PARENTAL LETTER OF CONSENT FOR MINORS

Dear Parent or Guardian:

I am a PhD student in the Department of Physical Education, Sport and Leisure Studies at The University of Edinburgh. I am conducting research to understand effects of lower limb co-ordination with leg fins, foot fins and bare foot swimming. Therefore, I am seeking 10 male volunteers as the subjects. The leg fins are a new design of fins to assist in developing a strong and effective kick (please see the Appendix B). I hope that you will find this project interesting and your child will be willing to participate in this study.

Your child's participation in this study is voluntary if you choose not to have your child participate or to withdraw your child from the study at any time. The results of the research study may be published, but your child's name will not be used.

What's in it for you?

During the period of the study we will arrange for you to see your own swimming from the underwater camera views. This may help you to improve your technique.

Location:

St Leonard's Land Swimming Pool, Holyrood Road.

Description:

The study is very simple and will require your child's participation for approximately half an hour for two times per week for 5 consecutive weeks. According to the design, there are three subjects each in the leg fin and foot flipper groups, and four subjects in the control group (no training group). In the training groups, your child will wear a pair of leg fins or foot fins to swim during the training session. The training sessions are two times per weeks - the same dates of your child's normal swimming training (please see the Table 1 for detail).

Table 1. Schedule

	Tursday (Session 1) (19.00-19.300pm)	Saturday (Session 2) (14.30-15.00pm)	Sunday (Session 3) (17.15-17.45pm)
Week 1 (From 14th Feb)	Test 1 (17th Feb) *Swimming/Kicking test (bare foot, pre training) Familiarization of fin All groups		Training 1 (20th Feb) *Kicking with fin Fin groups
Week 2 (From 21st Feb)	Training 1 (24th Feb) *Kicking with fin Fin groups		Training 1 (27th Feb) *Kicking with fin Fin groups
Week 3 (From 28th Feb)	Training 1 (3rd Mar) *Kicking with fin Fin groups	Training 1 (5th Mar) *Kicking with fin Fin groups	
Week 4 (From 07th Mar)	Training 1 (10th Mar) *Kicking with fin Fin groups		
Week 5 (From 14th Mar)	Training 2 (17th Mar) *Kicking bare foot Fin groups		Test 2 (20th Mar) *Swimming/Kicking te (bare foot, post trainii All groups

*: Video recording
Trainings: 10 trials of kicking, video record: 5 (odd number kickings)
Tests: 5 trials of kicking, video record: 3 (odd number kickings)

The research include four parts:

1. Test 1 (pre training test):
   a) Time and video recording of 25m freestyle sprint.
   b) 5 trials 10m no arm front crawl kicking with maximum effort. Time and video

Recording: 3 trials, odd trials.

2. Training 1:

Following the pre-training test you will be assigned to the leg fin group, the foot flipper group, or the control (no training) group. You will have six sessions training 1 of 30 minutes duration. These will be organized beginning of the usual club training. There will be no video recording for the subjects of the control group during training session (but you can still have the chance to view your swimming from the underwater camera views).

Training sessions comprise 10 trials of 10 meters maximum effort mid pool underwater kicking.

3. Training 2:
One session only, bare foot kicking only. Same trials as training 1.

4. Test 2 (post training test):
Similar to the pre training test:
a) Time and video recording of 25m freestyle sprint.
b) 10 trials 10m no arm front crawl kicking with maximum effort. Time and video

Recording: 5 trials, odd trials.

If you have any questions concerning the research study or your child's participation in this study, please call me at 0131 650 9790 or you can contacted to the Prof. Ross Sanders, head of CENTER FOR AQUATIC RESEARCH AND EDUCATION at 0131 651 6580.
Thank you very much for your co-operation.

Sincerely,

Shuping Li

Department of Physical Education, Sport and Leisure Studies
The University of Edinburgh
Holyrood Road
Edinburgh EH8 8AQ

Tel: +44 (0) 131 650 9790
Email: Shuping_Li@education.ed.ac.uk

PLEASE KEEP THESE PAGES FOR YOUR INFORMATION AND RECORDS.

PLEASE RETURN THE SIGNED CONSENT FORM ON THE NEXT PAGE TO SWIMMING COACH.

THE UNIVERSITY OF EDINBURGH
CENETR FOR AQUATIC RESEARCH AND EDUCATION

Effects of lower limb co-ordination with leg fins, foot fins and bare foot swimming

PARENTAL LETTER OF CONSENT FOR MINORS

Yes, my child would like to be involved in this study. I understand that my child may withdraw at any time. The unique aspects of the pool and the risks associated with them have been explained to me.

I give consent for my child (Name: please print) ____________________________ to participate in the study described on the previous page.

____________________________ ______________________________
Parent's Signature Date

Tel / Mobile:

Email:

PLEASE RETURN THIS SIGNED CONSENT FORM TO YOUR COACH.

APPENDIX B EFFECT SIZE AND EFFECT SIZE MEASURES

Here is a synthetic descriptive on the Cohen's effect sized (Cohen's d) from the publications from Cohen (1988), Dunlap, Cortina, Vaslow, and Burke (1996), Rosnow & Rosenthal (1996), Becker (2000), Coe (2000), Thalheimer & Cook (2002).

1. Standardized difference between two independent groups

$d = \dfrac{M_1 - M_2}{S}$ where $S = \sqrt{\dfrac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$ where x_i is the raw score, $\bar{x}$ is the mean, and n is the number of cases.	Cohen (1988) defined *d* as the difference between the means, M_1 - M_2, divided by standard deviation, S, of either group. Cohen argued that the standard deviation of either group could be used when the variances of the two groups are homogeneous. In meta-analysis the two groups are considered to be the experimental and control groups. By convention the subtraction, M_1 - M_2, is done so that the difference is positive if it is in the direction of *improvement* or in the predicted direction and negative if in the direction of *deterioration* or opposite to the predicted direction. *d* is a descriptive measure.
$d = \dfrac{M_1 - M_2}{S_{pooled}}$ $S_{pooled} =$ $\sqrt{\dfrac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 - 1) + (n_2 - 1)}}$	In practice, the pooled standard deviation, S_{pooled}, is commonly used (Coe 2000). The pooled standard deviation is found as the root mean square of the two standard deviations (Cohen 1988). That is, the pooled standard deviation is the square root of the average of the squared standard deviations. When the two standard deviations are similar the root mean square will be not differ much from the simple average of the two variances.

2. The interpretation of Cohen's *d*

Cohen's Standard	Effect Size	Percentile Standing	Percent of Nonoverlap
	2.0	97.7	81.1%
	1.9	97.1	79.4%
	1.8	96.4	77.4%
	1.7	95.5	75.4%
	1.6	94.5	73.1%
	1.5	93.3	70.7%
	1.4	91.9	68.1%

Cohen (1988) hesitantly defined effect sizes as "small, $d = .2$," "medium, $d = .5$," and "large, $d = .8$".

Effect sizes can also be thought of as the average percentile standing of the average treated (or experimental) participant relative to the average untreated (or control) participant. An ES of 0.0 indicates that the mean of the

	1.3	90	65.3%
	1.2	88	62.2%
	1.1	86	58.9%
	1.0	84	55.4%
	0.9	82	51.6%
LARGE	0.8	79	47.4%
	0.7	76	43.0%
	0.6	73	38.2%
MEDIUM	0.5	69	33.0%
	0.4	66	27.4%
	0.3	62	21.3%
SMALL	0.2	58	14.7%
	0.1	54	7.7%
	0.0	50	0%

treated group is at the 50th percentile of the untreated group. An ES of 0.8 indicates that the mean of the treated group is at the 79th percentile of the untreated group. An effect size of 1.7 indicates that the mean of the treated group is at the 95.5 percentile of the untreated group.

Effect sizes can also be interpreted in terms of the percent of nonoverlap of the treated group's scores with those of the untreated group. An ES of 0.0 indicates that the distribution of scores for the treated group overlaps completely with the distribution of scores for the untreated group, there is 0% of nonoverlap. An ES of 0.8 indicates a nonoverlap of 47.4% in the two distributions. An ES of 1.7 indicates a nonoverlap of 75.4% in the two distributions.

3. Effect size measures for two dependent groups

There is some controversy about how to compute effect sizes when the two groups are dependent, e.g., when you have matched groups or repeated measures. These designs are also called *correlated designs.* Let's look at a typical repeated measures design.

A Correlated (or Repeated Measures) Design

O_{C1} O_{C2}

O_{E1} x O_{E2}

Participants are randomly assigned to one of two conditions, experimental (E.) or control (C.). A pretest is given to all participants at time 1 ($O_{.1.}$). The treatment is administered at "X". Measurement at time 2 (O_{E2}) is post treatment for the experimental group. The control group is measured a second time at (O_{C2}) without an intervening treatment.. The time period between $O_{.1}$ and $O_{.2}$ is the same for both groups.

This research design can be analyzed in a number of ways including by gain scores, a 2 x 2 ANOVA with measurement time as a repeated measure, or by an ANCOVA using the pretest scores as the covariate. All three of these analyses make use of the fact that the pretest scores are correlated with the posttest scores, thus making the significance tests more sensitive to any differences that might occur (relative to an analysis that did not make use of the correlation between the pretest and posttest scores).

An effect size analysis compares the mean of the experimental group with the mean of the control group. The experimental group mean will be the post treatment scores, O_{E2}. But any of the other three means might be used as the control group mean. You could look at the ES by comparing O_{E2} with its own pretreatment score, O_{E1}, with the pretreatment score of the control group, O_{C1}, or with the second testing of the untreated control group, O_{C2}.

APPENDIX C ANGLE-ANGLE PLOTS OF INDIVIDUAL SWIMMERS

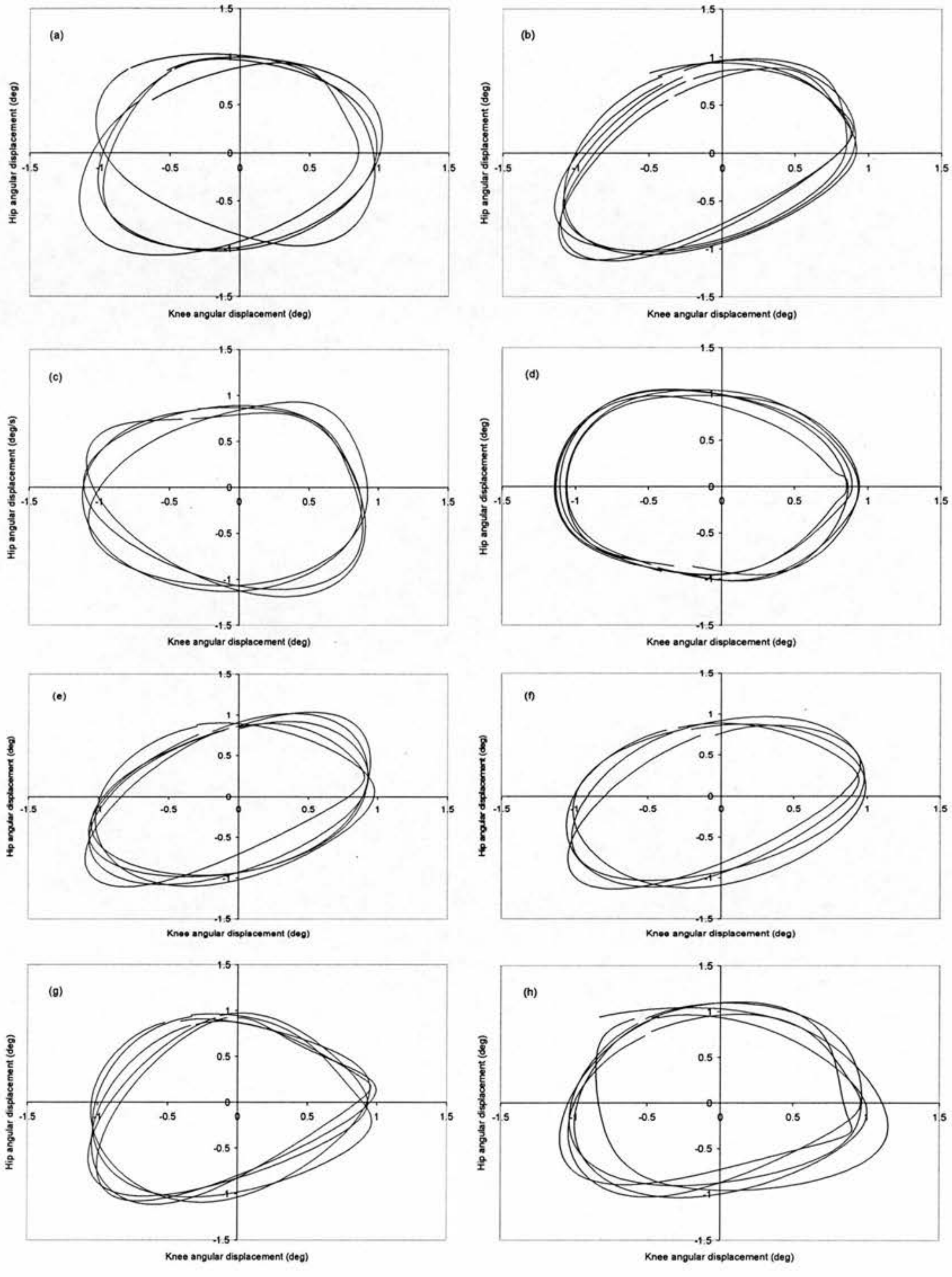

Figure 1 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer LFS1.

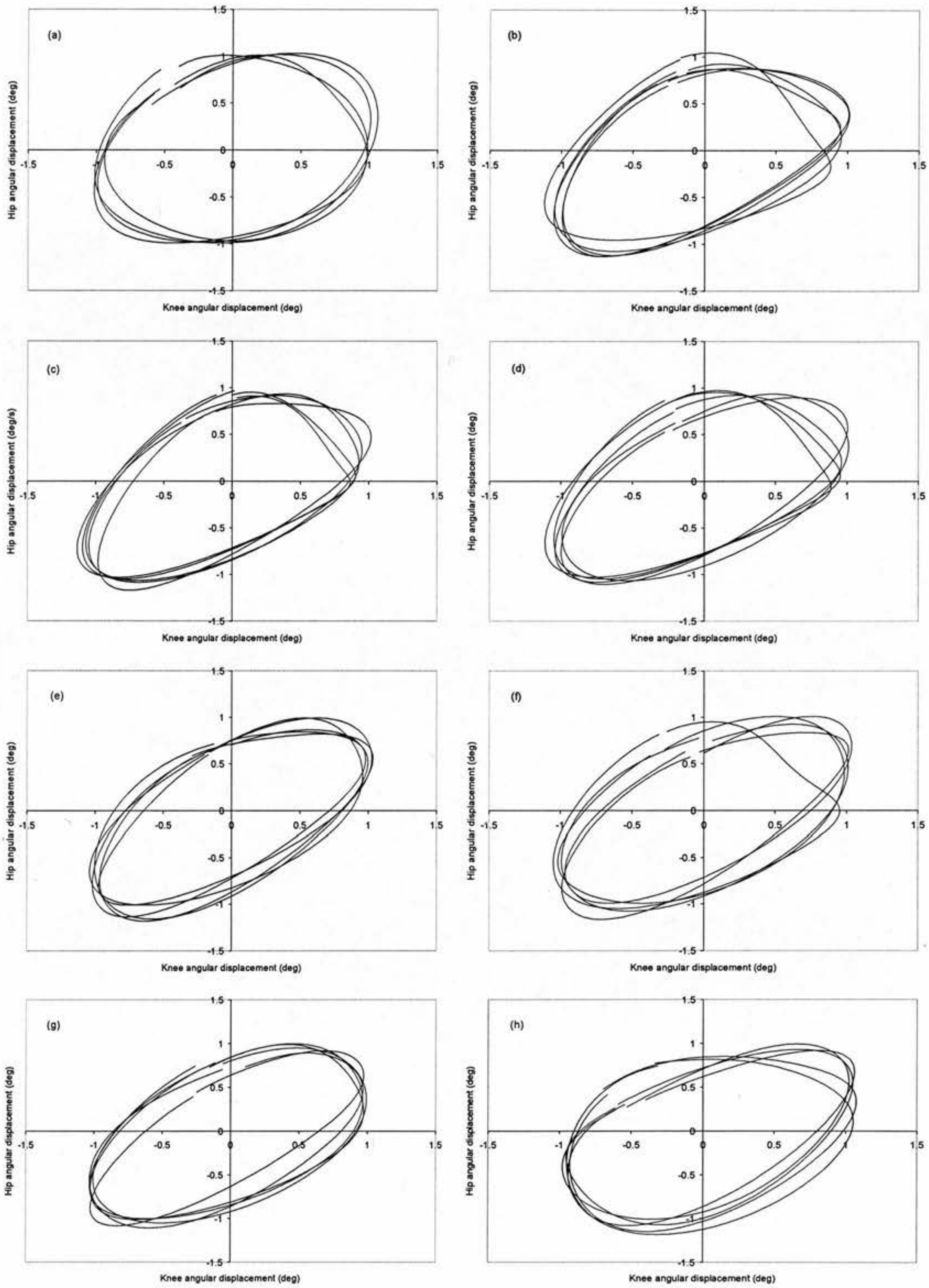

Figure 2 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer LFS2.

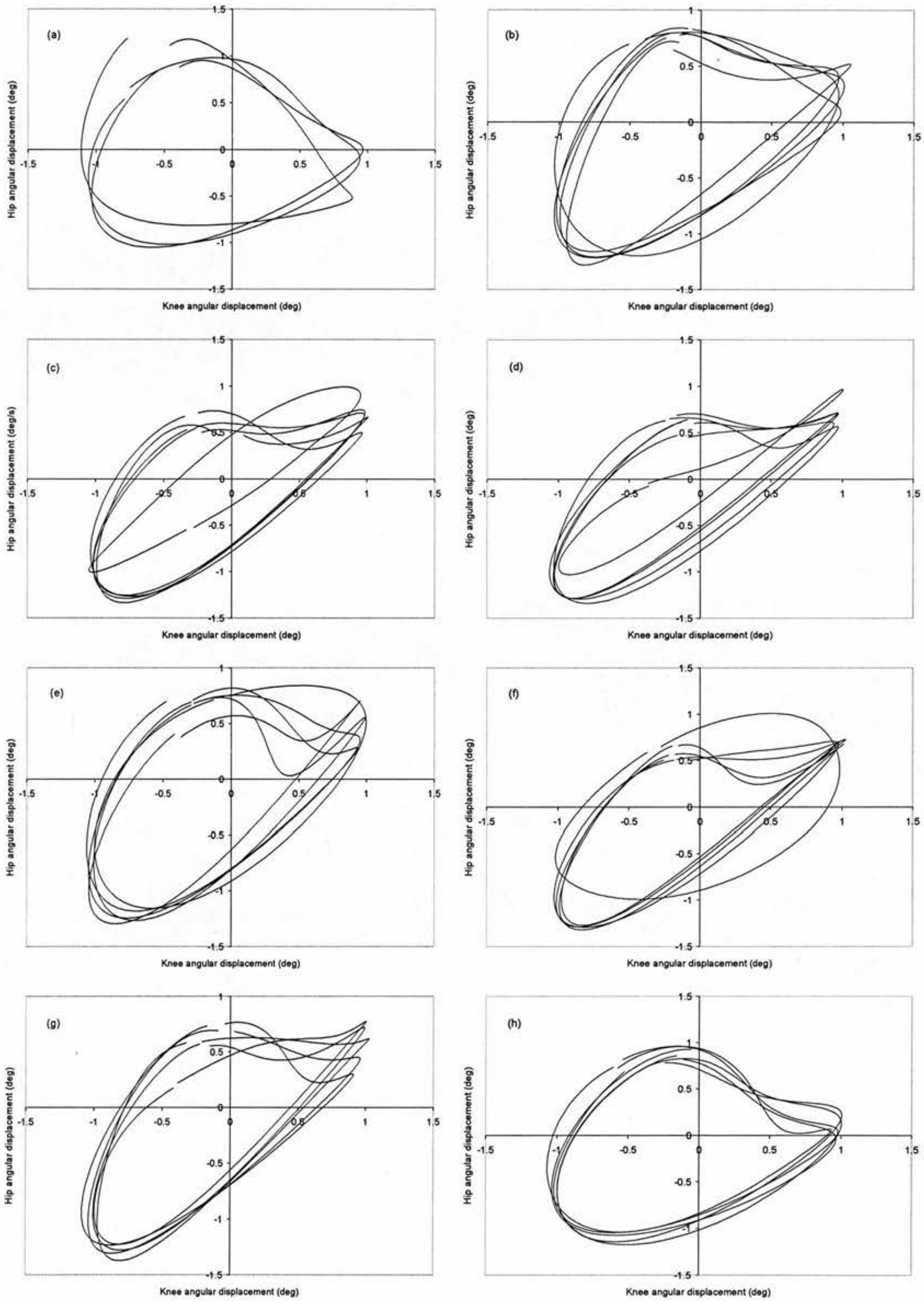

Figure 3 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer LFS3.

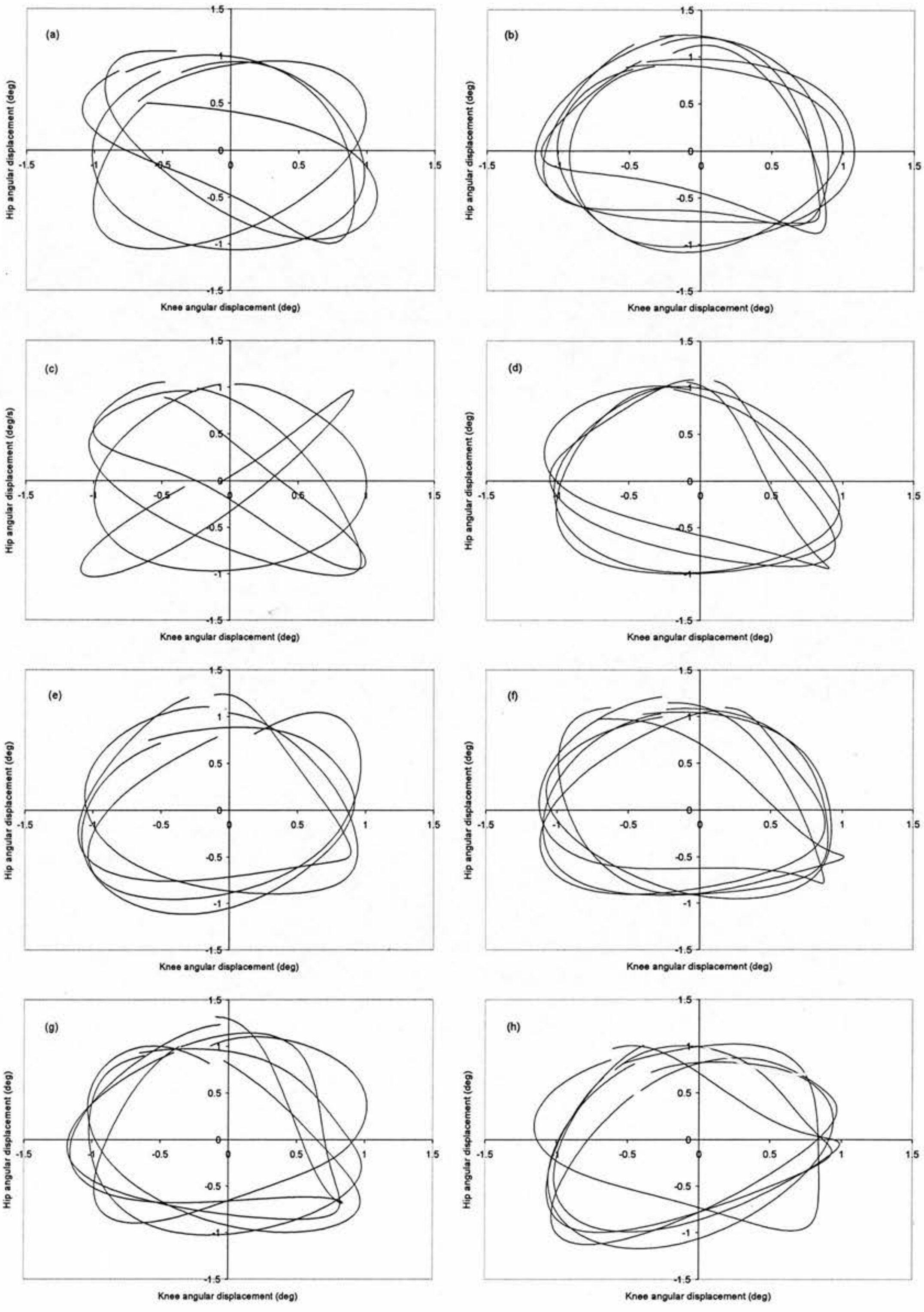

Figure 4 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer FFS1.

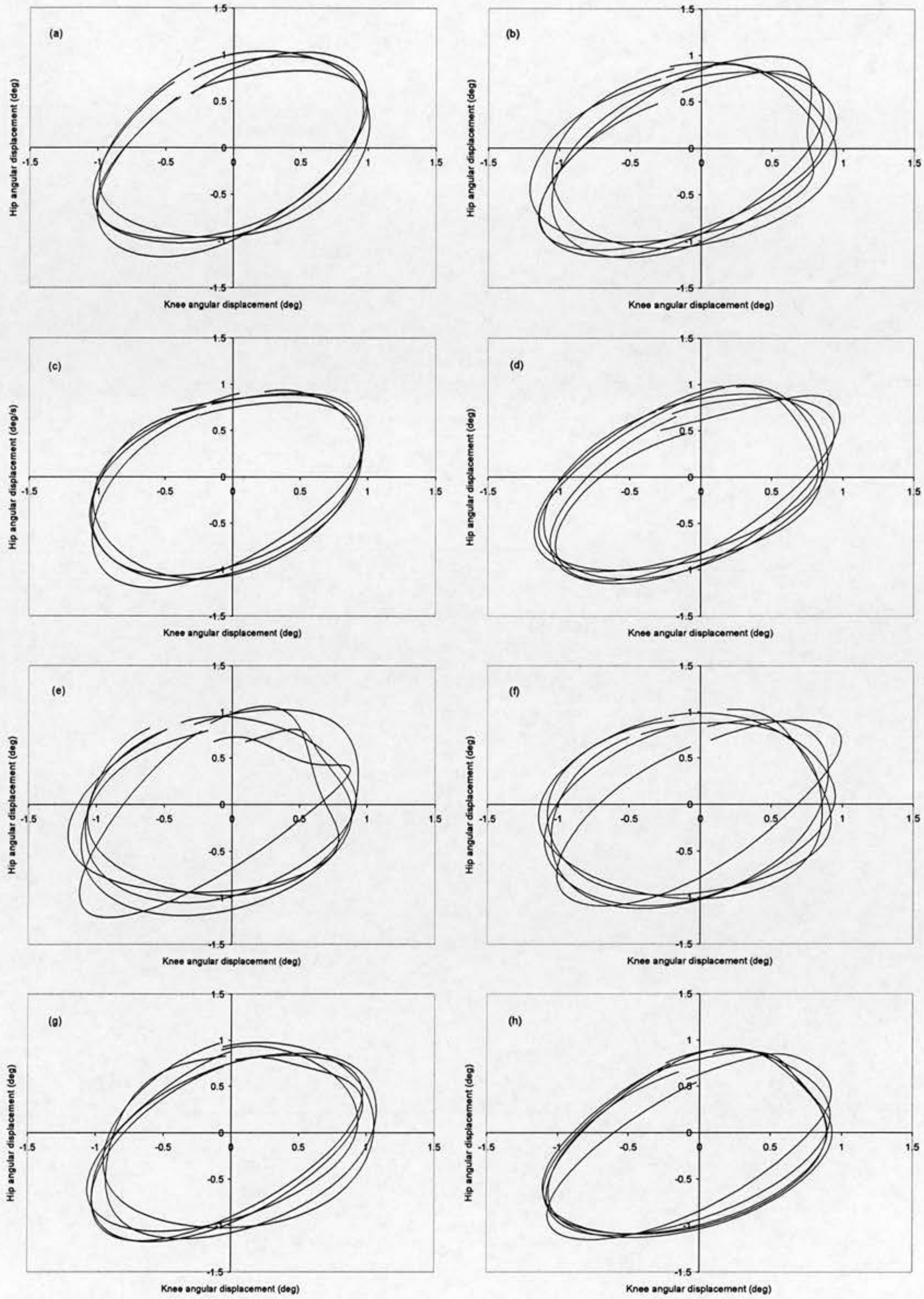

Figure 5 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer FFS2.

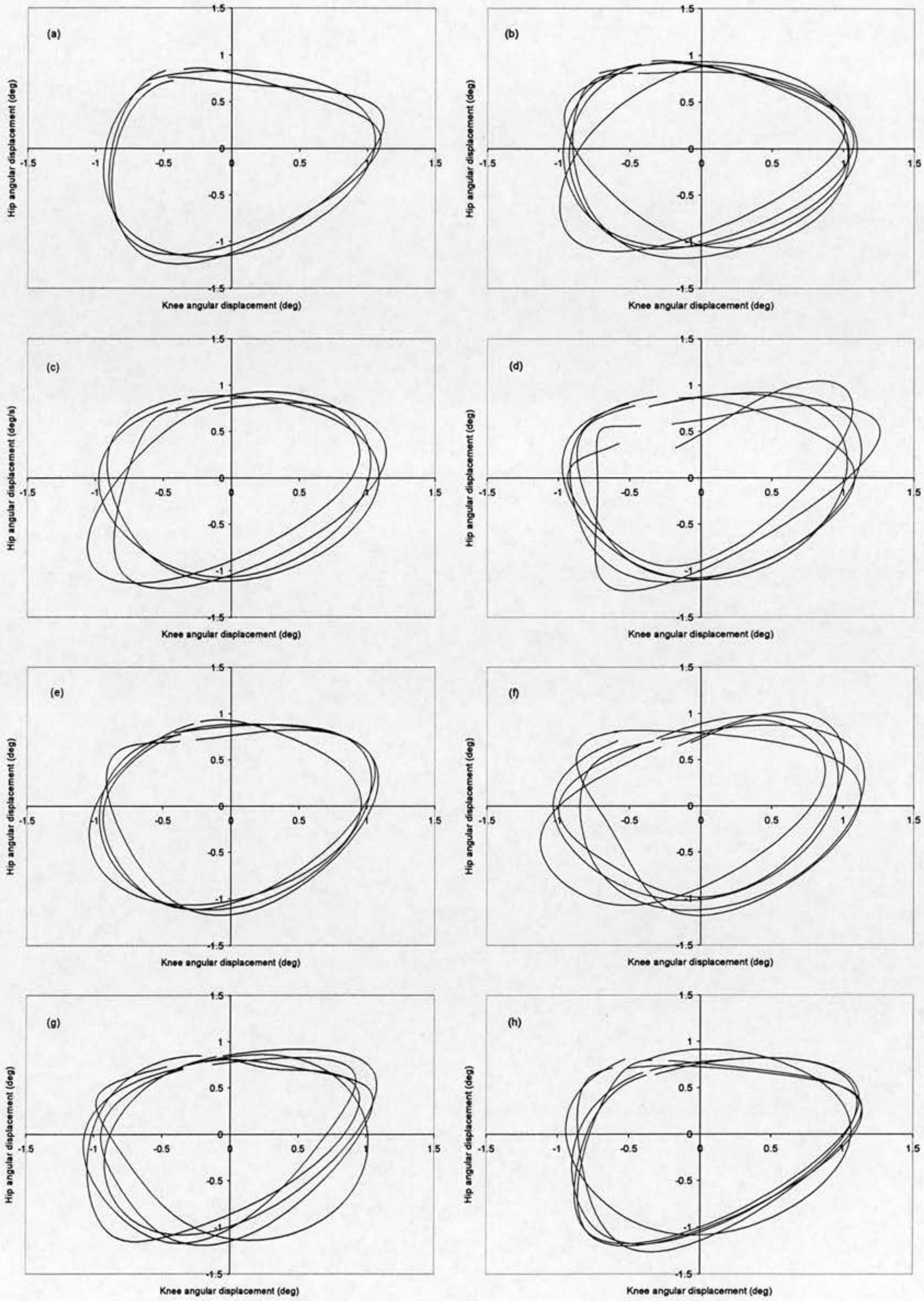

Figure 6 Knee-hip angular displacement plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer FFS3.

APPENDIX D KNEE JOINT PHASE PLANE OF INDIVIDUAL SWIMMERS

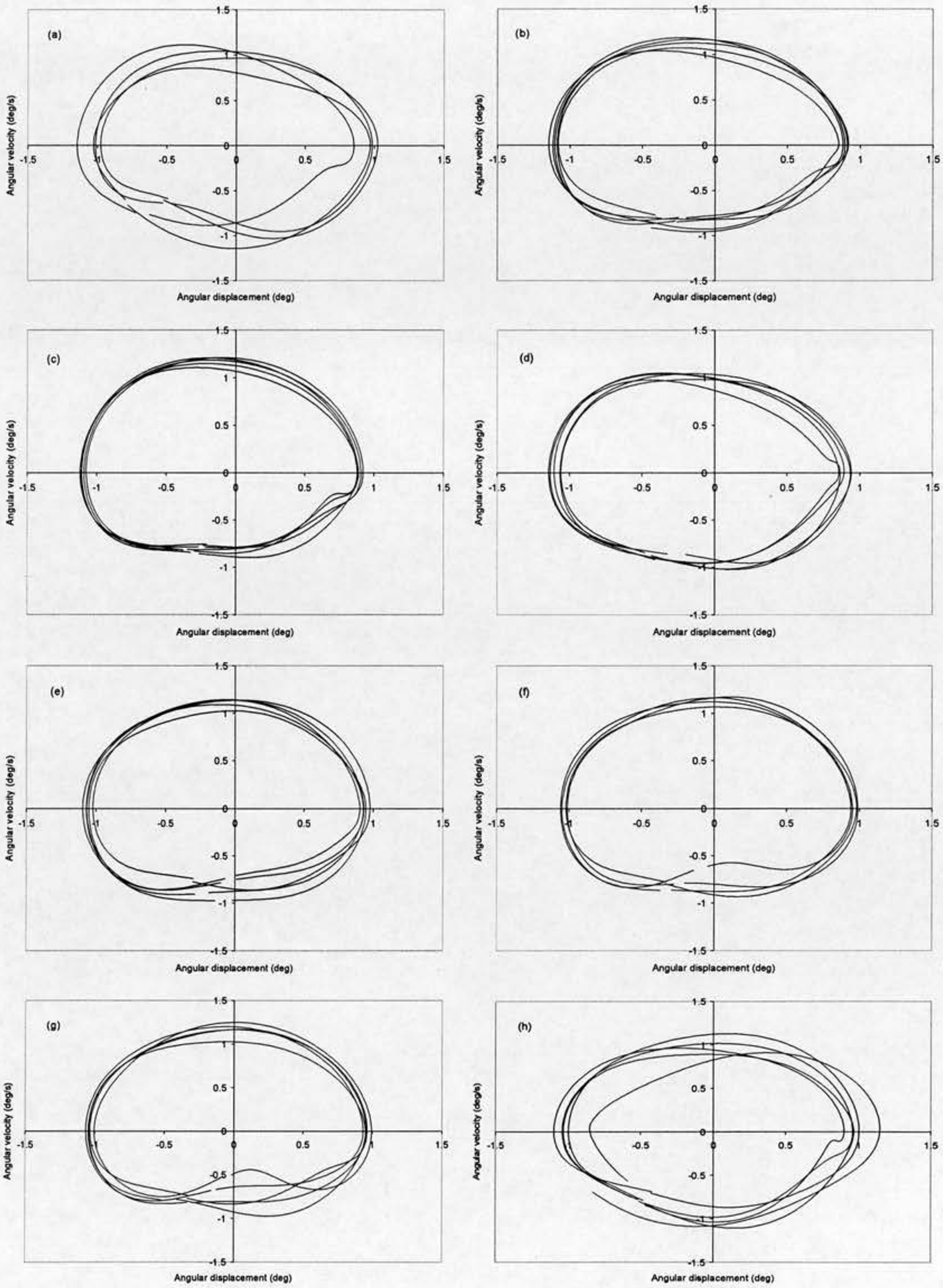

Figure 1 Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer LFS1.

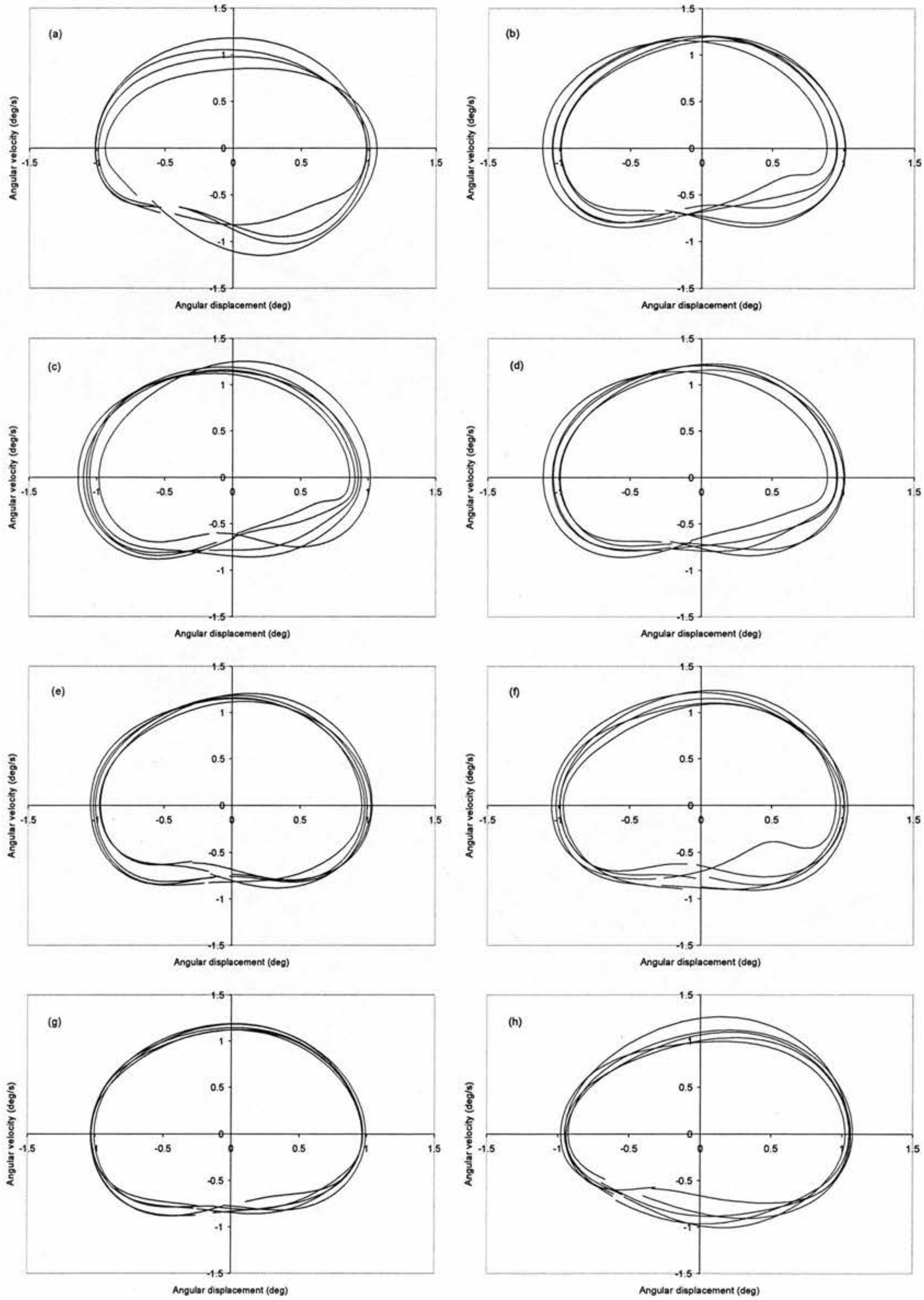

Figure 2 Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer LFS2.

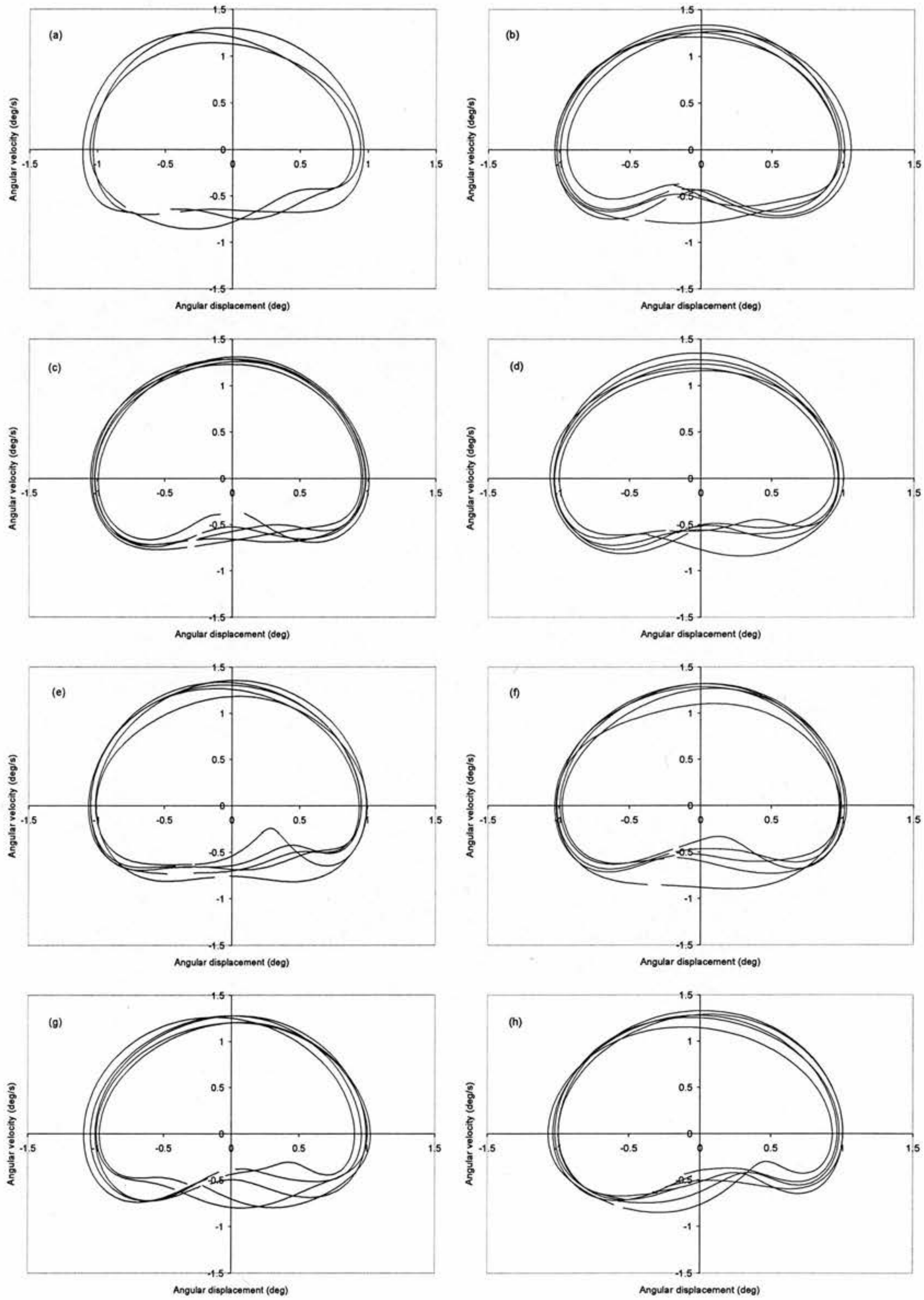

Figure 3 Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and the post training sessions for swimmer LFS3.

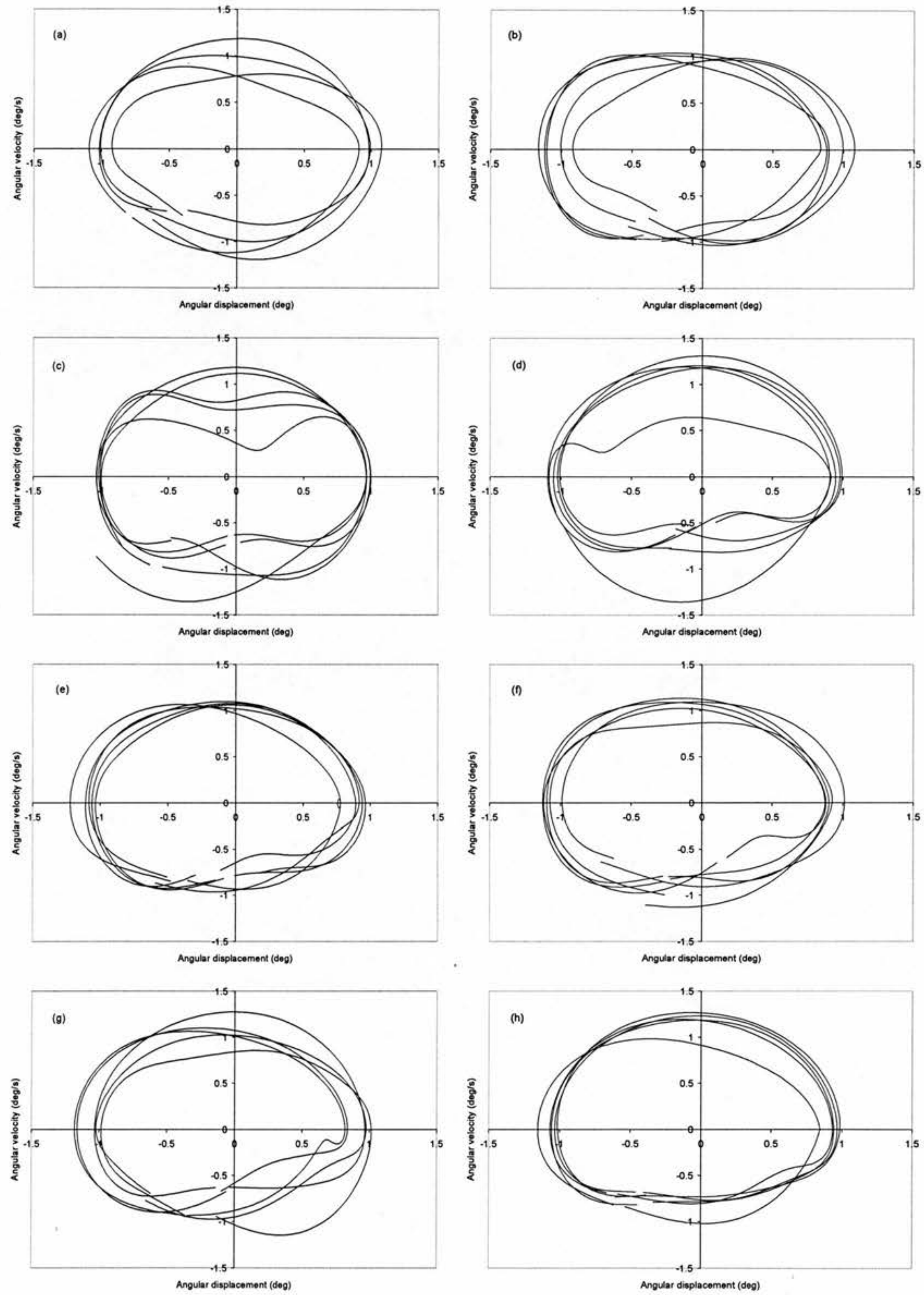

Figure 4. Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS1.

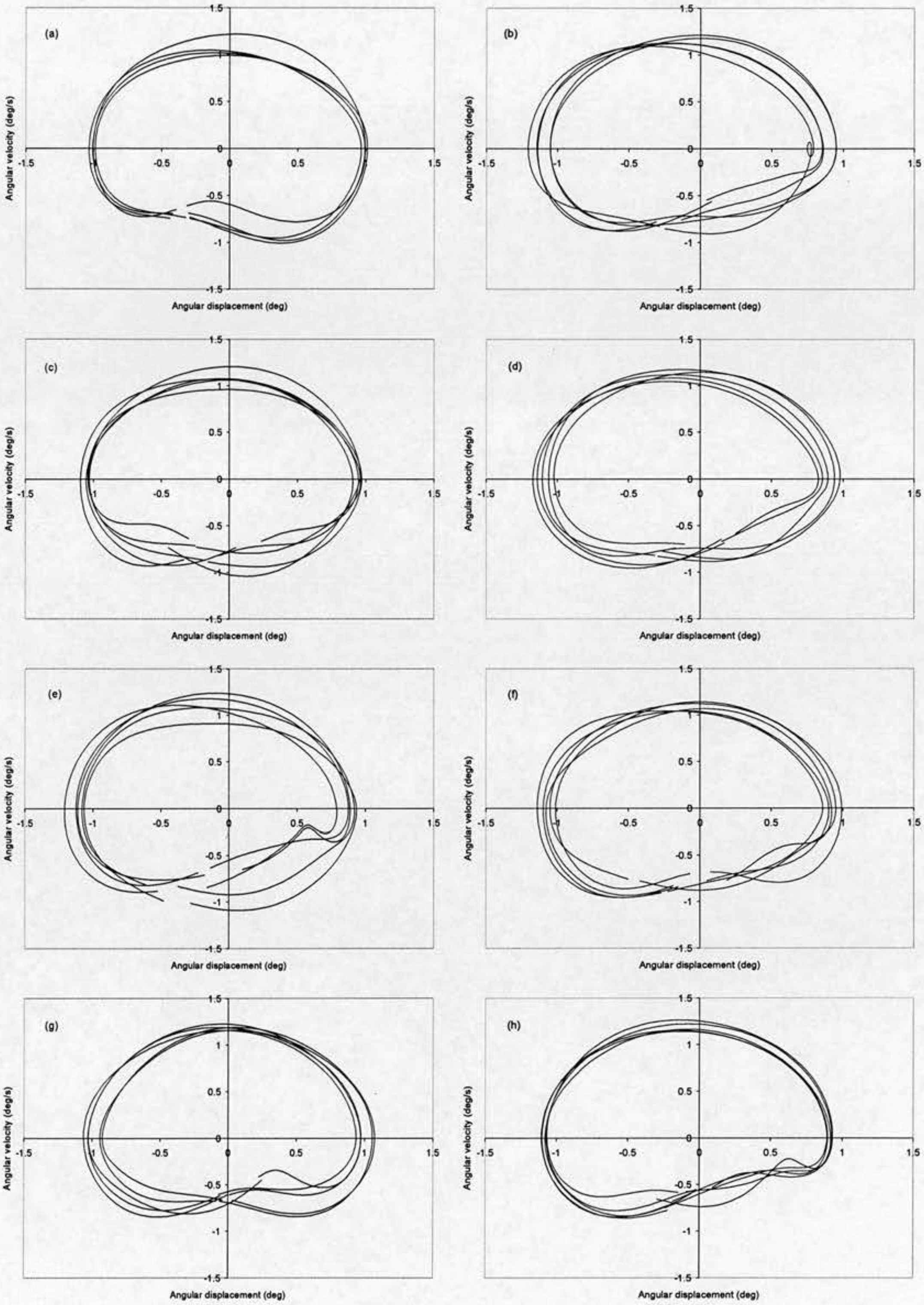

Figure 5 Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS2.

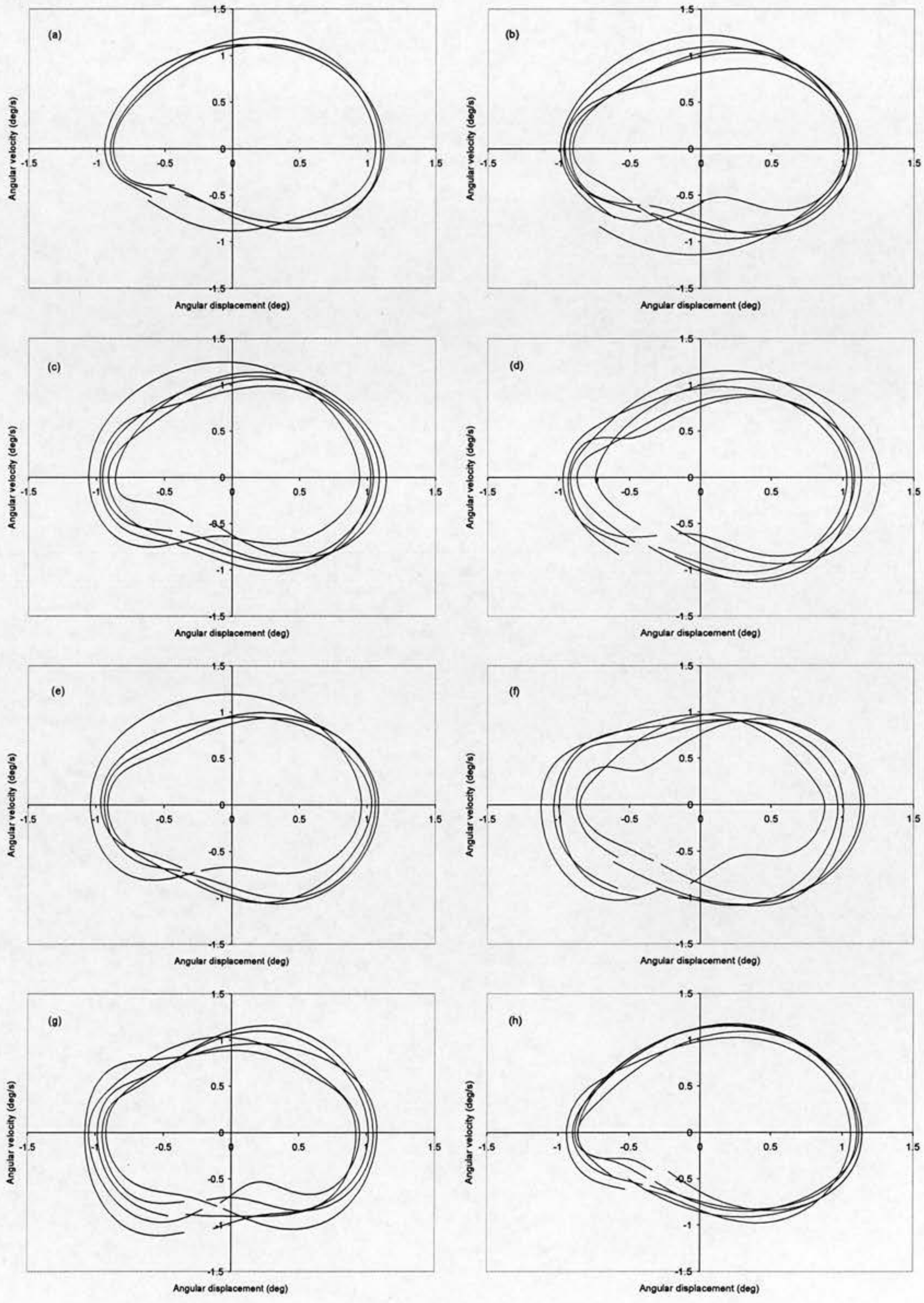

Figure 6 Knee joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS3.

APPENDIX E HIP JOINT PHASE PLANE OF INDIVIDUAL SWIMMERS

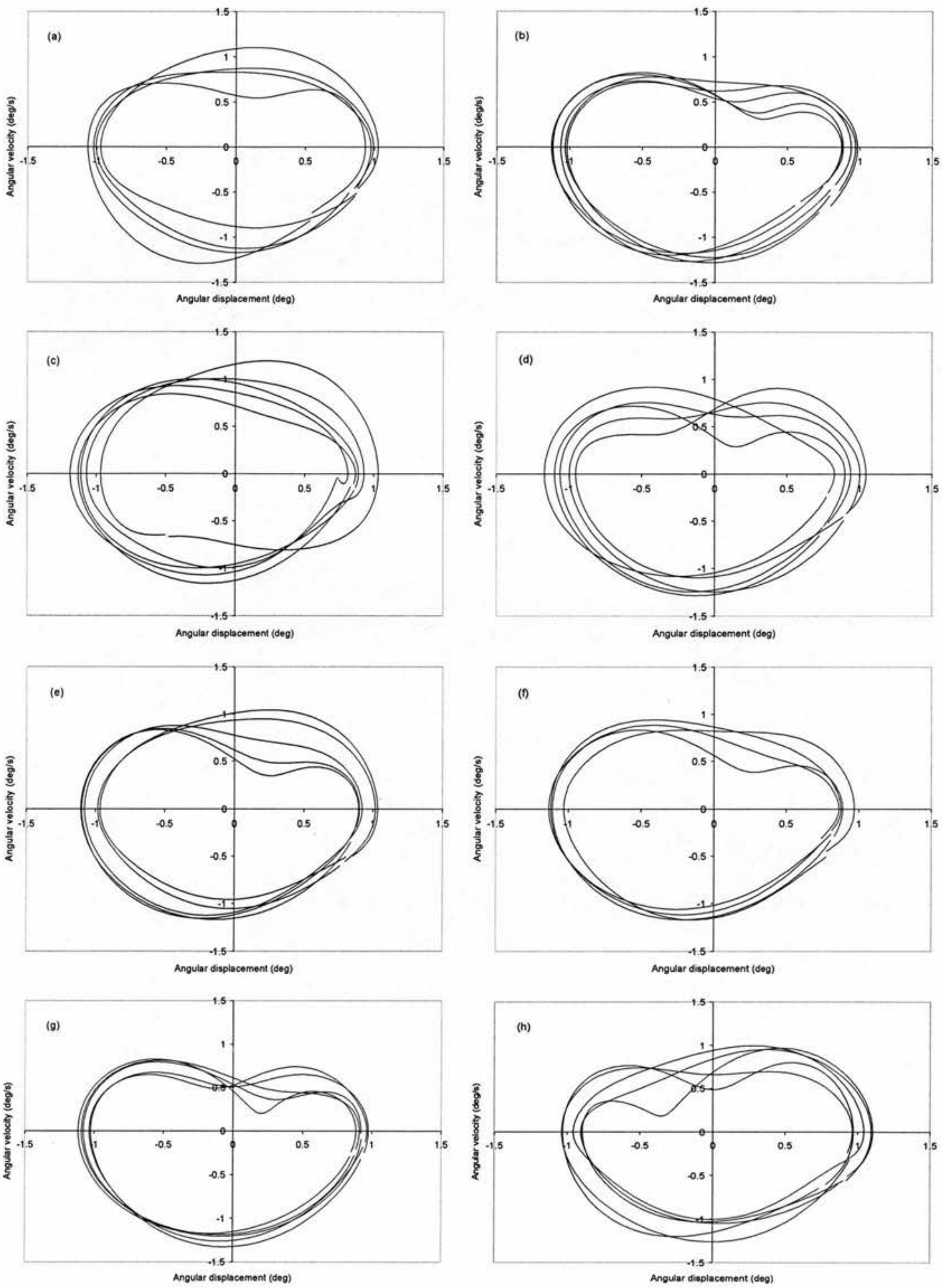

Figure 1 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer LFS1.

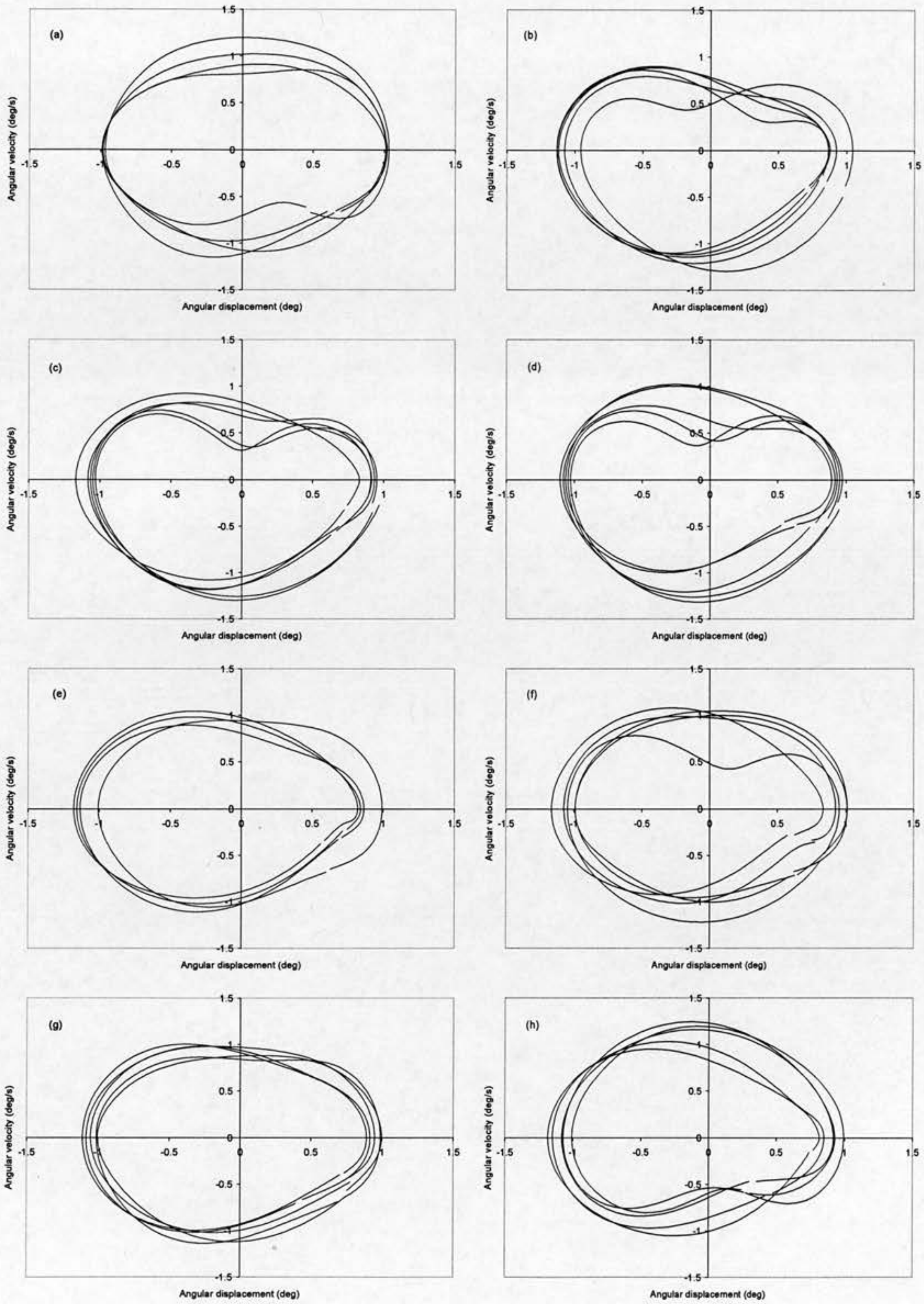

Figure 2 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer LFS2.

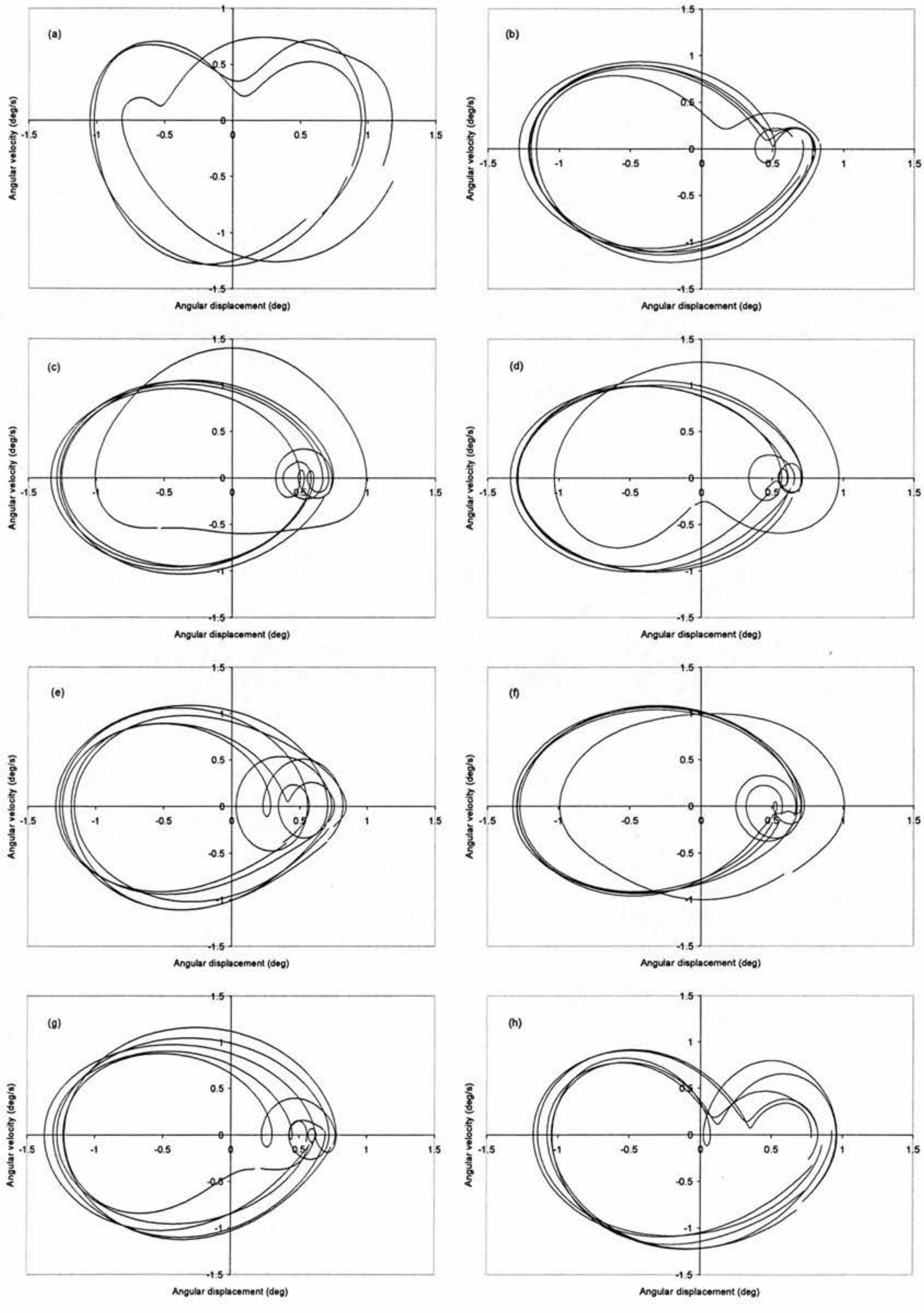

Figure 3 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer LFS3.

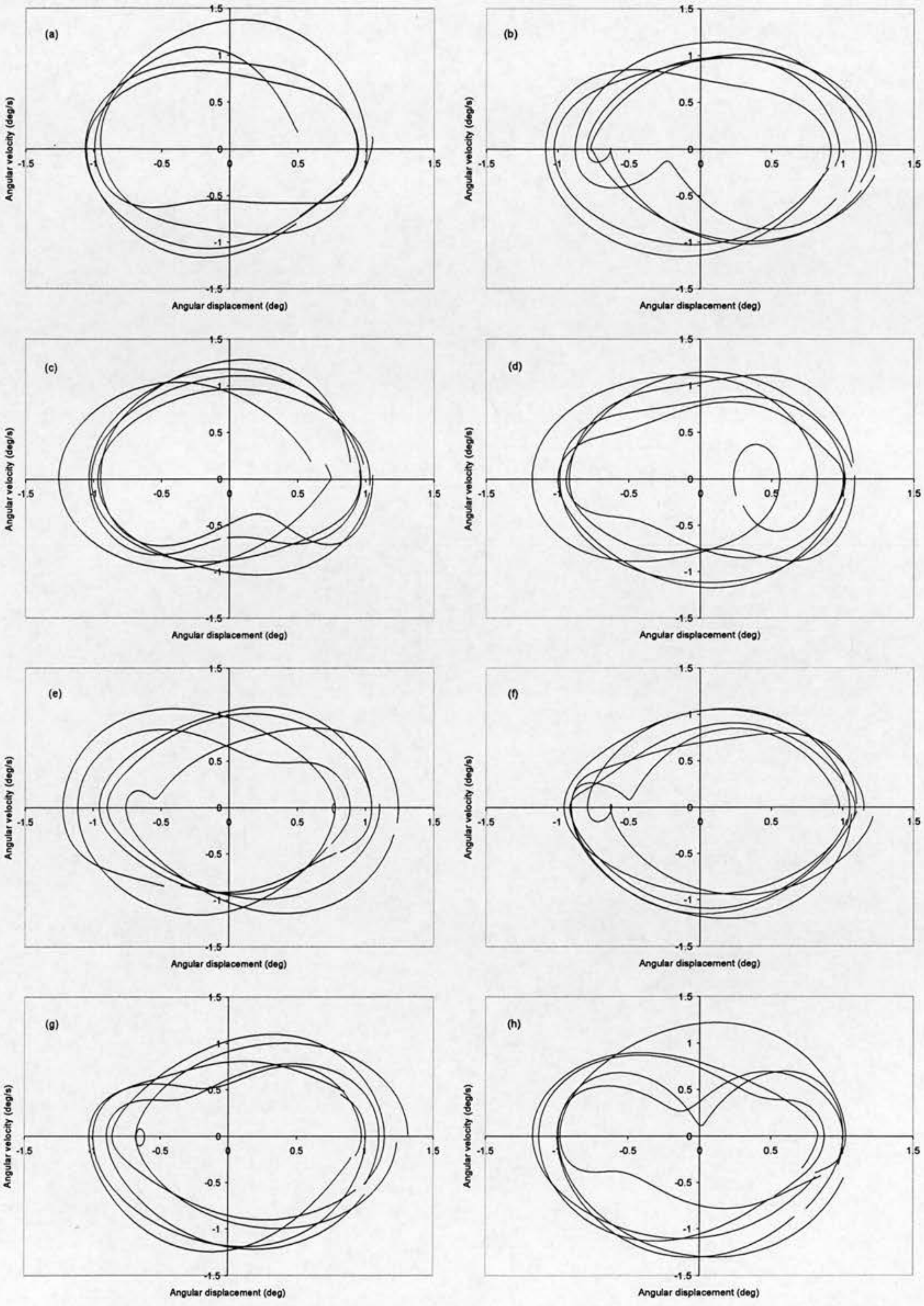

Figure 4 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS1.

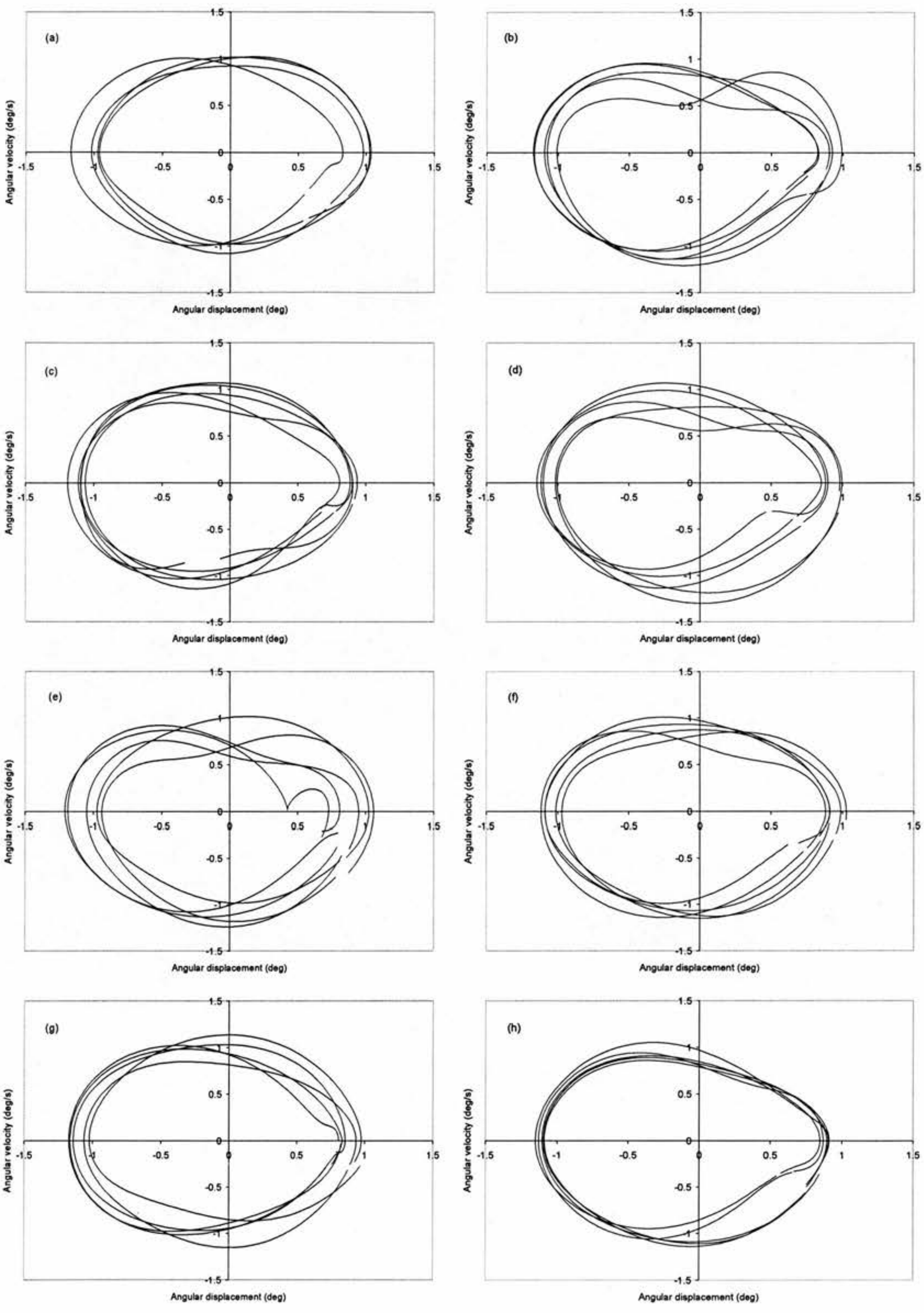

Figure 5 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS2.

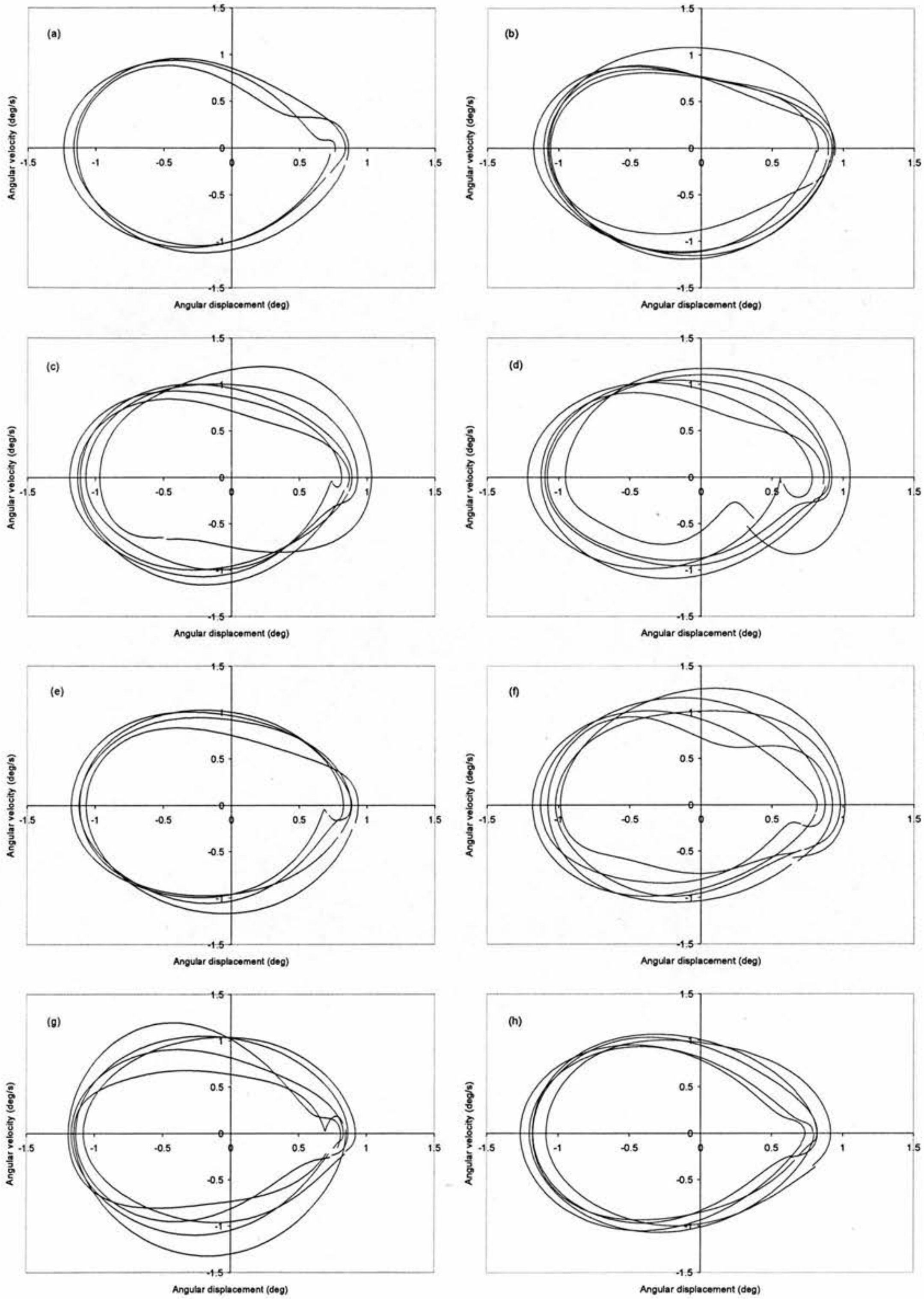

Figure 6 Hip joint angular displacement-velocity plots of (a) the pre, (b) the first (T1), (c) the second (T2), (d) the third (T3), (e) the fourth (T4), (f) the fifth (T5), (g) the sixth (T6) and (h) the post training sessions for swimmer FFS3.