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EXPERTISE AND TRAINING EFFECTS ON CO-ORDINATION DYNAMICS IN A WHOLE BODY RHYTHMICAL TASK

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USE OF THESIS

DECLARATION

I certify that this thesis does not to the best of my knowledge and belief:

(I) Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(ii) Contain any material previously published or written by another person except where due reference is made in the text; or

(iii) Contain any defamatory material.

[redacted]

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EXPERTISE AND TRAINING EFFECTS ON CO-ORDINATION DYNAMICS IN A WHOLE BODY RHYTHMICAL TASK

Abstract

This research consists of two studies. The purpose was to investigate the effects of slow and fast music tempo on interjoint co-ordination variability in an aerobic stepping task. The 'step knee-up' task is a cyclical whole body movement performed on the step platform. The exercise consisted of a few repetitive cycles. A cycle was defined by eight counts, four counts for the left leg pattern and four for the right leg as follows:

The first half of the cycle was counted: 1. Step up with the left foot onto the 20-cm step platform, 2. Flex the right hip to bring the right knee up;
3. Step down to the floor with the right foot and, 4.Tap once with the left foot on the floor near the right foot.

The second half of the cycle consisted of the following four counts:

1. Step up onto the platform with the right foot; 2. Flex the left hip to bring the left knee up. 3. Step down to the floor with the left foot and,
4. Tap once with the right foot on the floor near the right foot.

The participants were instructed to move both arms simultaneously forward and backward so that the limbs would perform in-phase movement, which is opposite to the natural anti-phase arm movements that accompanies walking and stepping activities. This pattern of the arm movements has been defined as a proposed pattern or the 'to-be-learned' pattern.

In particular, the research examined to what extent unskilled and skilled participants would adjust their movement co-ordination to cope with changes in performance conditions in attempting to achieve the criterion task. In the first study, these effects were observed in novices and experts, while the effects of the fast tempo training on intrinsic dynamics (self-paced condition) were considered in the second study. Both studies were based on the Dynamic Systems Theory. The environmental factor, which was considered as the control parameter affecting performance in both studies, was the music tempo.

In the first study interjoint co-ordination responses were analysed in terms of a version of the Haken, Kelso and Bunz's (HKB) model that considers detuning or frequency competition terms. Six novice and six expert females participated in the experiment performing a 'step-knee-up', a whole body rhythmical task, under different music tempos. They were tested at a slow tempo at 48 beat/min and at a fast tempo of 144 beat/min. Two hypotheses were proposed. Firstly, it was hypothesised that discrete relative phase variability of inter-joints co-ordination would be higher at the fast tempo then at the slow tempo in both, novices and experts.

It was further hypothesised that, in order to cope with changes in performance conditions and still achieve the criterion task, novices would demonstrate higher variability than experts at both the slow and fast tempo.

Results showed that interjoint co-ordination in experts was more consistent (less variable) at both the slow and fast tempo compared to novices, in all couplings expect in the left leg. Furthermore, follow-up tests revealed that Tempo and Side effects in novices were not significant.

In experts, however significant Side effect was found in shoulder joint coupling and hip-knee joint coupling. Higher variability was found in left leg interjoint coupling between hip and knee joints at both tempos, compared to the right leg. In shoulders joint coupling, however, higher variability was found only at the slow tempo for the right side observation of the L Shoulder-R Shoulder movement.

Finally, it was observed that the initially specified arm movement direction (iso directional or in-phase movement) changed to anti-phase direction at fast tempo in novices. Therefore, in novices, in-phase arm movements were more sensitive to fast tempo perturbations compared to anti-phase. While these results may be in contrast to Haken, Kelso and Bunz's model predictions they are partly supported by Whittal, Forester and Song's (1999) findings.

In the second study, whether practising the task under the fast music tempo would affect the interjoint co-ordination stability at the preferred tempo performance (without the music) was investigated.

It was hypothesised that, after the training under the fast music tempo interjoint coupling variability at the preferred tempo would decrese.

The hypothesis was partly accepted as variability decreased in the self-paced condition after training only in shoulder-shoulder interjoint couplings compared to the self-paced condition before training.

Results in the second study were discussed in relation to Shoner and Kelso's (1988) dynamical theory of environmental function and motor learning transfer principles.

It was found that training under the fast tempo did not significantly affect overall performance at self-paced and fast tempos. However, different changes in interjoint co-ordination strength were observed in different couplings before and after training as the function of (the left or right) body side.

It was concluded that interjoint co-ordination flexibility is highly specific to the interaction between the task, body side, performance condition and skill level. Finally it was suggested that an individual approach to the analysis of variability in co-ordination dynamics in skilled and unskilled performance and learning be considered.

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CHAPTER1

INTRODUCTION

Research of skilled and unskilled performance has been very popular in studies of motor learning and performance. The performance outcomes at novice and expert levels have been compared and defined as unskilled or skilled behaviour respectively. However, the effect of environmental factors on performance at different skill levels, as well as the process of skill acquisition from novice to expert level is still not well examined.

In motor learning research the general basis for assessing skilled behaviour is the observation of the overt performance of some task. The process of skill acquisition may be affected by different factors, which could either facilitate or constrain the performance outcome. Some factors, such as the amount of practice, learning conditions, and the amount and quality of control parameters can be adjusted according to the level of expertise. However, there are other distracting effects from the environment, such as, light and noise that are less controllable. These factors may constantly change in a non-linear way that cannot be predicted by the performer. Performance at any level of skill, when affected by such factors will be adjusted to the stress conditions.

Dynamic systems approaches to the study of motor behaviour can be based on two theoretical frameworks. The first, Dynamic Systems Theory (DST), has been used as a theoretical framework for studying co-ordination since 1980 and beyond (Kelso, 1981, 1982, 1984; Reed, 1982; Turvey,1990; Kugler and Turvey, 1987; and others). The second approach is Dynamic Pattern Theory, developed by Kelso (1982) considering Haken's (1977) synergetics and phase transition methodology. The current research is based on the Dynamic Systems Theory framework

Movements can be defined as dynamic changes in posture with respect to the frame of reference. The frame of reference can be internal (the performer's body) or external (the environment in which the action occurs) (Kelso, 1991). Different internal (individual characteristics) and external (environmental conditions) factors may affect dynamic changes in posture. When the motor behaviour of organisms is guided by the external and/or internal information, qualitative changes in movement patterns behaviour may be observed.

Traditional theories in cognitive science have explained these qualitative changes in terms of *a priori* cognitive or neural structures imposed upon behaviour, considered as pre-existing 'motor programs'. In Dynamic Systems Theory, changes in movement patterns are understood as consequences of interactions between organism-environment systems, with the behaviour or movement being guided by external information and/or by intentional dynamics. These changes have been explained by non-linearity, self-organising or chaotic system principles (Haken, 1983). The Dynamic Systems Theory framework to motor skill learning is based on Bernstein's (1967) view of the action system and on the perceptual theories of Gibson (1979). Ecological psychologists, who argue that movements are controlled by direct links between perceptual and action systems without the involvement of any cognition, support Dynamic System Theory (Reed, 1982; Turvey & Kugler, 1984). Whiting and Zernicke (1982) however, argue that the Dynamic System Theory does not deny the existence of cognition, but simply attempts to explain as much as possible without recourse to cognition. In recent years, research based on the Dynamic System Theory has contributed to better assessment and prediction of changes in co-ordination pattern behaviour and motor skill learning.

In the current research, the Dynamic System Theory was applied to examine differences in skilled and unskilled performance at slow and fast tempos and the effects of training on inter-limb co-ordination in a whole body rhythmical task known as 'the step aerobic task'. Detail description of the task is provided in the Methods section.

This task has been selected, as a relevant example in observing inter-limb co-ordination applied in maintaining the body balance while stepping up and down. The step aerobic task is a popular exercise practised in gyms and fitness centres to improve stability and general fitness. Furthermore, this exercise is also common to everyday stepping task.

Rhythmical movements constitute a major class of human motor behaviour as evidenced in cyclic locomotion actions such as walking, running, stepping and other everyday tasks. One of the main characteristics of those actions is the regularity in the timing of joint motions that is organised into co-ordinated patterns. In recent years, there have been major advances in the theories of motor co-ordination in the area of applying the concept of non-linear dynamical systems (Kelso, 1995; Turvey, 1990). One of the most cited models is the Haken-Kelso-Bunz (HKB) model in which the dynamics of the coupling term capture the degree of stability in a system by analysing the system's pattern of co-ordination (Haken, Kelso & Bunz, 1985; Schoner, Haken & Kelso, 1986). The HKB model predicts the existence of two stable co-ordination modes, in-phase and anti-phase, depending on the coupling strength between the oscillating units. The strength of coupling, in the HKB model, is the function of oscillation frequency. At low frequencies the strength of coupling is sufficient to make both in-phase and anti-phase solutions. However, as the frequency rises, the coupling weakens and the anti-phase pattern loses stability and, beyond that critical frequency, the in-phase solution prevails. Although this research is not based on phase transition methodology, the HKB model predictions can be used in discussion of variability in inter-joint co-ordination at different tempos, other than self-paced tempo. Thus, the HKB model has been used in Study 1 of the current research to discuss variability in inter-joint co-ordination at slow and fast tempos.

The current research consisted of two studies. Both studies were framed within the Dynamical Systems Theory in which the variability of the discrete relative phase, was the focus. In Study 1, the perturbing effects of slow and fast music tempos on limb joint variability were examined in expert and novice performance. In Study 2, the effect on intrinsic pattern behaviour of practising an aerobic step task at fast tempo was investigated when performing the task without the music. The self-paced condition was considered to reflect the intrinsic dynamics in task performance. The results were then discussed considering the transfer of motor learning principle according to the Dynamic System Theory.

Background to Study 1

Tempo and Skill Effects on Co-ordination Dynamics in a Whole Body Rhythmical Task

In Study 1, the variability of the discrete relative phase (DRP) in inter-joint co-ordination at slow and fast tempos was tested with experts and novices in an aerobic stepping task. The Dynamic System Theory was used for the quantitative analysis of inter-joint co-ordination.

A dynamic system is characterised by continuous changes of the system behaviour in space over time. The central question is how complex systems, such as human behaviour systems, produce these movement patterns over the time? When an action begins the spatial and temporal characteristics of the behaviour pattern are defined. During performance, a sequence of patterns emerges according to the principles of pattern formation in a dynamic system. Over time and with practice, the patterned behaviour evolves from a less stable form to a more consistent form. However, this process may also produce multiple stable patterns through principles of discontinuity and from perturbations in external conditions interacting with the system's characteristics (Kelso, 1991). External conditions in Study 1 were simulated by changes in music tempo that might have a different effect on novice and expert system characteristics.

Statement of the Problem

Over the past hundred[1] years studying the motor performance has been mainly assessed within a cognitive system framework. However, theories of motor learning and skill acquisition based on the cognitive system framework have had difficulty when used to identify the characteristics of an expert and a novice performing the task.

When the performance is affected by environmental factors, perceptual information generated by these environmental factors affect the extent of perturbations in both, expert and novice pattern behaviour. Therefore, the level of variability in expert and novice performances would be different. This issue has been analysed from the Dynamic System Theory in this thesis.

According to the Dynamic System Theory, the movement system is flexible and can adjust to changing conditions by adopting new co-ordination patterns. Less understood is how the interaction of the task and skill level affects these pattern changes (Broderick & Newell, 1999). The issue of co-ordination pattern formation and pattern stability, or variability, as a function of skill, task and environmental constraints has been considered in research. (see Newell & McDonald, 1994). However, less well understood is temporal variability in interjoint co-ordination patterns and how the interaction of task environmental constraints and the skill level of the performer influence these patterns. In this first study, the following research questions were addressed:

1. How is the interjoint co-ordination pattern stability affected by different performance tempos in novices and in experts?
2. To what extent do unskilled and skilled participants adjust their movement

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[1] Bryan and Harter (1897), Weiner (1948) and Bartlett (1947) may be considered among the other earliest information processing theorists in the cognitive understanding of skilled performance.

co-ordination to cope with changes in performance conditions in attempting to achieve the criterion task?

Hypotheses

Movement variability in novices can be seen as either a lack of experience with the task under the particular condition (the music tempo), or simply as an individual inability to adjust movement behaviour to the particular rhythm (music tempo) regardless of the amount of practise. It may also be expected that novices, in their attempts to adapt to the music tempo, would be successful in demonstrating more consistent performance in a few cycles, but would not be able to demonstrate it throughout the trial. This will contribute to overall trial variability.

Similarly, movement variability in experts may be a result of the participant's experience with the task under different conditions. This experience enables the expert to adapt to the task constraints by experimenting with a variety of movement patterns thus, demonstrating flexible movement behaviour, particularly under faster movement frequencies.

Considering conclusions by Latash's (1994) and Newell and McDonald (1994) that movement flexibility can be observed from beginner to expert levels of performance within and between different trials of the same task, it was hypothesised that:

1. The discrete relative phase variability in inter- joint co-ordination will be higher at a fast tempo than at a slow tempo in both, novices and experts.

2. Novices will demonstrate a higher variability than experts at both slow and fast tempos in attempting to achieve the performance task.

Background to Study 2

Training Effects on Co-ordination Dynamics in a Whole Body Rhythmical Task

In Study 2, the effect of practice on discrete relative phase variability in inter-joint co-ordination was observed in a motor learning transfer paradigm. In particular, the effect of practice was observed on changes in intrinsic dynamics. The co-ordination patterns that the learner has and brings to a given motor task are called the intrinsic dynamics (Zelaznik, 1996).

Intrinsic dynamics can be more specifically defined as the dynamics of the order parameter when environmental information is absent. Environmental information corresponds to information that defines the task to be learned. The required behavioural pattern is primarily dependent upon the performers' intrinsic dynamics (Schoner & Kelso, 1988). Thus, as Annett (1969) suggests, individual training methods and different coaching techniques might be required to produce optimal results even when participants practise under the same conditions. Changes in the movement behaviour may be expected when environmental information, such as a fast music tempo, is imposed onto the learner's intrinsic dynamics. These changes are the result of co-operation and competition between the intrinsic dynamic state and the environmental information. Practising and learning the task under defined conditions can affect the pattern behaviour to different degrees.

Statement of the Problem

Although research in motor learning has been conducted for many years, it is not yet clearly defined what individuals learn, how they learn, and how the learning is transferred into performance. Transfer of learning is a concept that involves the influence of previous experience on the learning of a new task or on performing a known task in a new context. Positive transfer occurs when experience with a previous skill facilitates or aids the learning of a new skill. The greater the component similarity between new and old skills or between new and old performance conditions, the greater the positive transfer from one skill to another. Similarity between the cognitive processing demands of the two conditions accounts for positive transfer between the two performance contexts. Negative transfer effects occur when experience with a previous skill restrains or interferes with the performance of a new skill or the same skill under a new condition. Changes in the spatial location and the timing characteristics of the response to the same stimuli may also be observed with the negative (Magill, 1993).

A major issue in motor learning research considers whether learning involves acquiring a specific pattern or a more general pattern. Stelmach (1996) points that the learned or acquired representation permits the participant to transfer the learned motor control pattern to a new movement pattern.

From the Dynamic Systems Theory, the acquisition of motor skill may be considered in terms of both quantitative and qualitative changes (Zanone & Kelso, 1992). Inherently stable states are defined as states of preferred co-ordination patterns to which the motor system is attracted during performance. Identification of these so-called ‘attractors’ through analyses of pattern consistency can provide a basis upon which to interpret changes in co-ordination patterns as a result of practice.

Zanone and Kelso (1992) have found that a newly learned pattern can become part of the intrinsic dynamic pattern. Such a conclusion provides a strong theoretical basis to describe how learning evolves, regardless of the initial level of learning experience, and how expertise can be developed. As a result the following questions were considered:

Does practising a task under a fast music tempo affect the co-ordination pattern when the task is performed without the music? In other words, how does practice under the fast tempo affect the stability of the former intrinsic dynamics (self-paced tempo) of the co-ordination pattern?

Hypothesis

Firstly, it should be assumed that the self-paced condition might not be of the same movement frequency for each participant thus, a hypothesis would have limitations. However, in the current study the participants demonstrated similar stepping cycle frequency at self-paced tempo) which enabled the comparison of the performance at two conditions (see 'Calculations of Frequencies' section. It was therefore hypothesised that:

1. The variability in interjoint co-ordination in self-paced performance after training will decrease when compared to the self-paced condition before training.

Overall Purpose

Expert and novice performance was analysed in Study 1 of the research. The initial purpose was to compare the temporal variability in inter-joint co-ordination in expert and novice performance at slow and fast tempos. The second purpose of Study 1 was to identify how novices and experts adjusted to the perturbation afforded by music tempo, that is whether the skilled performance was more or less resistant to tempo changes than unskilled performance and, how these changes could be explained from the Dynamic System Theory.

Study 2 was designed to find out how training under a fast tempo may affect the inter-joint co-ordination pattern behaviour at a preferred tempo (self-paced condition). The principle of motor learning transfer was explored by determining whether training under a fast tempo affected the intrinsic dynamics of self-paced performance.

Significance of the Studies

To date little research has been conducted to investigate movement patterns variability in expert and novice whole body rhythmical task performances applying the Dynamic System Theory. While Broderick and Newell (1999) have recently contributed to research in skill acquisition considering the Dynamic System Theory, the issue of pattern variability in whole body co-ordinated movements at different skill levels needs more research.

By observing variability in performance, it may be possible to measure a performer's adjustment to environmental conditions. Therefore, by examining the variability in the movement pattern behaviour at different skill levels and under different conditions, this research can contribute to a better understanding of the ways in which the individual co-ordination can be adjusted to environmental conditions. Finally, this research can contribute to motor learning research that uses the transfer design to analyse changes in inter-limb co-ordination and pattern variability.

Delimitations

1. Only women, 17- 45 years old, participated in the experiment.
2. All testing was conducted in the Biomechanic Laboratory at the School of Biomedical and Sport Science, Edith Cowan University.
3. The testing of each individual in the first study was conducted in single session
4. Testing in the second study was carried out over a period of two weeks as follows: pre-testing was conducted a day before the experiment started while post-testing was conducted the day after the twelve training sessions were completed.

Limitations

1. Analysis of a stepping task was performed under the selection of two different music tempo conditions. Nor all participants may have felt the particular tempo (fast or slow) and therefore they may have not have followed the rhythm the music meter attempted imposed upon them

2. Participants defined as 'experts' were selected on the basis of their previous experience with the step-aerobic task which required a minimum of five years involvement in regular training (at least three training sessions per week) training. Whilst some experts had more than five years experience in step aerobics and participated in dance training as well, it was assumed that not all experts would be skilled to the same level of expertise when performing at the fast tempo.

3. Due to technical problems with the hardware/software system used for data collection and calculation in the first study, there was a need for considering a different system in the second study. However, the shift to the new equipment did not affect the methodology and data analysis.

Ethical Consideration

Edith Cowan University Ethics Committee provided the Ethical approval for this research at the meeting on 01/05/98.

CHAPTER 2

REVIEW OF RELATED LITERATURE

This chapter provides an overview of the literature, which considers how the Dynamic Systems Theory is applied to motor learning and movement co-ordination. The Dynamic Systems Theory is presented in the first section followed by a presentation of learning of co-ordination patterns and concepts of variability in pattern formation and motor learning transfer. Finally, in the last section, the relevant method for the quantification of interjoint co-ordination is presented.

Dynamic Systems Theory

The term dynamic systems has been attributed to the work of the mathematical topologist Stephen Smale in the 1960s-70s (Stewart, 1989). However, this approach has its roots in the work of Poincare, who at the turn of the century applied a geometrical approach to the study of continuity (Garfinkel, 1983). The problem addressed by Poincare was whether or not the solar system is stable. Poincare applied topological techniques to calculate the stability of three or more point masses ("the three body problem"). An example of such a technique is the portrait called the "Poincare section", which presents the state of a periodic system at a given point of successive cycles. This technique allows one to determine whether a system exhibits stable, periodic behaviour, by analysing a cross section of trajectories. The Dynamic Systems Theory in fact refers to an interdisciplinary approach based on classical mechanics (the study of statics and dynamics: kinematics, kinetics), Poincare's techniques and non-linear dynamics. A cyclic behaviour found in nature can be interpreted as the limit cycle attractor of a non-linear system with synchronisation among rhythms acknowledged as the fundamental characteristics of non-linear coupled oscillations. The parallels between fundamental phenomena of biological systems and properties of non-linear dynamics motivated researchers in movement behaviour to study co-ordination from the Dynamical Systems Theory perspective.

To date, most of the tasks used in early research into movement co-ordination and motor learning have been single limb movements and positioning tasks. Complex movements, involving whole body activity are rarely examined rigorously (Swinnen, 1994). During the last decade new empirical methods and analytical tools originating in the fields of mathematics and physics have been specifically developed for studying non-linear, complex movements based on the Dynamic Systems Theory.

The Dynamic Systems Theory dates back to the early work of the Russian psychophysiologist Nikolai A. Bernstein. Bernstein (1967) filmed children and adults' writing and running patterns, the labour movements of both skilled and unskilled factory workers and people's movements in everyday situations. He concluded that regardless of the degree of similarity of the situations where movements happened and the level of the participant's skill, movements never followed exactly the same trajectory. This constant change in the movement trajectories of limbs was the result of the movement space that is multidimensional. Bernstein contrasted the subtle variations of human limb movements to fixed trajectories of machines, which move with a single degree of freedom in up and down or to and from trajectories. Bernstein assumed that the underlying organisation of human movements is flexible both across and within tasks and could not be of a mechanical nature. When there are changes in the task, in the performer's intention or in the environment, the performer's nervous system is able to form temporarily assembled units and to reorganise the degrees of freedom of the body. Bernstein called these units of organisation synergies and described the process of developing and learning skills as the process in which synergies are created and destroyed.

Bernstein's insight that the central control of all unnecessary (redundant) degrees of freedom of the human body is impossible, was recognised through the later work of scientists such as Turvey, Kugler and Kelso (Kelso, 1982). They combined this insight with Gibson's perception and action premise. Gibson (1979) stated that the general principles of movement behaviour had to be found, not just in the characteristics of an organism alone but in the relationship between an organism and its environment.

Dynamic System Theory as a conceptual alternative to the central executive theories of motor programs, provides a means to study the behaviour of complex systems. Complex systems have many non-linearly interacting components. The theory describes principles of pattern formation and evolution that are applicable to any complex system. For example, under the influence of energy, a system's component interactions become spontaneous collective effects that appear as self-organised patterns of behaviour (Vereijken & Bongaardt, 1999).

The similar behaviour of biological systems and non-linear dynamic systems has motivated researchers in human movement sciences to interpret motor co-ordination as pattern formation in a dynamic system. Kelso (1988) proposed the Dynamic Systems Theory as a new paradigm for understanding behavioural changes. The Dynamic System Theory assumes that movement patterns are self organised within a system and emerge from under a 'bottomup' control strategy. This strategy involves identifying order parameters, which describe the behavioural patterning in complex systems. By analysing how these variables change over time, it is possible according to Kelso (1988) to predict the future behaviour of a system.

A dynamic system can be modelled as a discrete system by an interactive process or mapping or as a continuous system described by a system of differential equations (Crutchfield, Framer, Packard & Shaw, 1986). The topological description of behaviour is generally conveyed in the 'state space' of the system framework. This space is a 'geometric model for the set of all idealised states' of the system (Abraham & Shaw, 1982, p.13). Idealised states are based on a few variables that represent observable behaviour. The framework where the motor behaviour would be observed can be defined by 'collective variables' (the order parameters) which consistently capture critical aspects of the behaviour (Schoner & Kelso, 1988). Importantly, the changes in co-ordination within some system variables do not typically refer only to the state of the central nervous system but also to environmental factors.

Pattern formation has been extensively studied in physical and biological systems. In the theoretical concept of pattern formation, it has been stated that when systems reach critical points at which the structure is formed spontaneously, a reduction of the observed numbers of degrees of freedom can be observed (Kelso, 1988). This means that the large number of degrees of freedom is reduced to only a few, when a movement is smooth, consistent and co-ordinated. Schoner and Kelso (1988) suggest that besides the physical aspects of pattern formation such as range of movement, characteristics of living creatures such as the biological features of co-ordination in pattern formation, should be also considered in movement pattern analysis.

The current research considers changes in the particular, or discrete point in co-ordinated patterns under changeable environmental conditions and therefore is based on the Dynamic System Theory modelled as a discrete system by an interactive process or mapping. The following characteristics of co-ordination patterns were considered:

- when movement is sustained, because of various perturbations and environmental conditions, the pattern's stability is changed and
- biological systems are open to environmental information and therefore they may be flexible in adjusting movement behaviour to environmental conditions.

These patterns may change according to environmental demands in such a way that the change persists. Demands such as pattern flexibility and adjustment to control parameter can explain these changes.

In a generalised motor program, control parameters are defined as certain parameters specified prior to movement output, and determine how the movement behaviour would be carried out. This feature of movement behaviour allows us to understand how movements can be adjusted to environmental demands when compared to an already learned movement pattern (the generalised motor program) as the basis for the action (Schmidt, 1991).

According to Dynamic Systems Theory an emergent behaviour arises from the collective behaviour of all contributing subsystems, including both the central nervous and musculosceletal systems (Diedrich and Warren, 1995). Other constraints, such as environmental factors (i.e., gravitational forces, walking surfaces) and the task itself (i.e., running or walking at different velocity and/or different stride frequency) also contribute to the behaviour of the system. In Dynamic Systems Theory different phase and frequency relationships between body segments or limbs typify order parameters. Changes in the order parameter occur when a specific control parameter (i.e., movement speed and frequency) is changed. According to Dynamic Systems Theory a high dimensional system is described in terms of a low dimensional representation. For example, relative phase can be used as an order parameter to describe co-ordination changes between segments with the change of performance tempo (control parameter).

Furthermore, the spontaneous formation of pattern-self organisation-can be rooted in the notion of instability of motion. Instabilities offer a way to identify candidate control parameters that are responsible for a system's behaviour. Instabilities allow a clear distinction between one pattern of behaviour and another, enabling us to identify the dimension on which pattern change occurs. Observed patterns can be mapped onto attractors of the collective variable (the order parameter). This is presented by non-linear limit cycle behaviour. Finally, it is also possible that we may not be aware of the control parameter unless its variation causes qualitative changes to order parameters (collective variables).

Fowler and Turvey (1978) propose that, for each degree of freedom of the co-ordinative structure left unconstrained by muscle linkages, there is a variable of the organism-environment system specified by perceptual information that affects the performance. The above authors conclude that acquiring a new movement pattern means that an actor has to become perceptually attuned to the consequences of different configurations by the scaling of a control structure component. The optimal organisation arises when the following factors are implemented within the action system:

- the reactive forces of the limbs and their interaction with the environment are used so that they can be largely responsible for producing a desired trajectory (Bernstein, 1967), and when

- the additional degrees of freedom can be controlled so that the movements can be performed more fluidly (Bernstein, 1967; Newell & Van Emerik, 1989).

Furthermore, Turvey (1990) argues that the rhythmic motions of a simple system are dependent upon the mechanical characteristics of the system's length, the relation of mass to length and the dynamics of its gravitational and elastic forces and, the neural elements supplying periodicity and motor impulse.

For a complex motor system to operate in a co-ordinated fashion, however, a co-ordinative structure for each operational motor system and the particular task constraints needs to be created to have its own characteristic periodicity. The Dynamic Systems Theory de-emphasises the role of the cognitive control of action and places emphasis on the role of information arising from the environment and the motion of limbs and joints. From the Dynamic Systems Theory, bifurcation processes, or phase shifts, explain the development of movement pattern diversity and complexity. When a control parameter (for example, movement speed) is scaled up, the relative stability of the system is disrupted. If these fluctuations are large enough in the scaling of the control parameter, the system is driven to a new, more stable solution. By such repeated bifurcation, movement patterns achieve multi stability. The different control parameters, which emerge to drive phase shifts, do not themselves specify the nature of the change. These changes can be the result either of the previous experience in the task or the perceptual information input. The most widely used variable to characterise the overall order and pattern dynamics of behaviour is the relative timing or relative phase (Kelso

& Jeka, 1992).

The original research that described co-ordination in terms of physical self-organisation is the dynamical modelling of rhythmic hand and finger movements (Kelso, 1981, 1984; Haken 1985). In these experiments subjects were instructed to move rhythmically both hands and index fingers in either symmetric, in-phase mode (the simultaneous activation of homologous muscle groups) or anti-symmetric, anti-phase mode (the simultaneous activity of non-homologous muscle groups). When the subjects started in anti-phase and the cycling frequency was gradually increased, at a 'critical' frequency, a sudden involuntary transition to in-phase movements occurred. No phase transition occurred if subjects decreased movement frequency after first having switched from anti-phase to in-phase (the latter system behaviour is known as the hysteresis phenomenon). The observed changes in a movement pattern are evidence of spontaneous self-organisation in movement co-ordination. In the above experiment, the order parameter was defined by phase angle differences between the moving limbs (a relative phase). The control parameter was the cycling frequency of oscillation (a period). In the HKB model the cycling frequency relates to the scaling (or coupling) terms (a, b) in the equation (1):

$$V(\phi) = -a\cos(\phi) - b\cos(2\phi), \qquad (1)$$

where (ϕ) is relative phase between the fingers derived in their respective phase space and V is the potential.

Equation (1) is a potential function that can account for the observed transition in co-ordination. V (ϕ) results in minima for $\phi = 0°$ and $\phi = 180°$, assuming that these values of the parameter (ϕ) can be performed in a stable fashion. To account for the transition from anti-phase to in-phase co-ordination the control parameter (the movement frequency) was changed. These changes affected the potential function in such a way that an increase in movement frequency resulted in the annihilation of the anti-phase co-ordination while the in-phase pattern remained stable. In the HKB model this is related to the ratio between the two coefficients a and b in the equation (1). In the original experiment by Kelso (1981, 1984) and Haken (1985) with increasing movement frequency the ratio b/a decreased, resulting in a differential decrease in stability of the two co-ordination modes at the observed transition at $b/a = 0.25$.

In order to understand why this ratio changes as a function of the control parameter (the movement frequency), the phase transition was also modelled at the level of the equations of motion describing the kinematics of the two rhythmically moving fingers. The moving fingers were modelled as self-sustaining (a limit-cycle) oscillators influencing each other on the basis of their kinematics. The resulting model is an autonomous system of coupled differential equations in which the co-ordinated behaviour is sustained on the basis of the system's state variables such as position and velocity. This model implied that no additional, explicitly time-dependent, forcing function would be required to account for the ongoing rhythmic activity.

The transition from anti-phase to in-phase has been observed in different systems. For example, the HKB model was generalised to the co-ordination between different effector systems such as arm and leg (Jeka & Kelso, 1995), single limb movements (Wimmers, Beek & van Wieringen, 1992), and between the rhythmically swinging legs of two different persons (Schmidt, Carello & Turvey, 1990).

To model the kinematics of the movements in coupling limbs and/or limb segments, the HKB model was extended to the level of coupled differential equations (Haken et al., 1985). The coupling function, through which the two component oscillators interact, implied that the collective dynamics of the resulting system were adequately modelled by the potential function defined by the equation (1). A differential equation (2) expresses the dynamics of the relative phase (ϕ) that is derived for the system of coupled oscillators. This equation is directly related to the potential function defined by the equation (1).

$$d(\phi) / dt = - dV(\phi) / d\phi \qquad (2)$$

On the basis of the equations (1) and (2), the dynamics of the relative phase (ϕ) were expressed by the equation (3):

$$d(\phi) / dt = -a \sin \phi - 2b \sin (2\phi) \qquad (3)$$

At the level of coupled differential equations, the strength of coupling between the oscillators varies as a function of the amplitude at which the limbs oscillate. With increasing frequency, peak velocity increases due to the Van der Pol damping term, whereas amplitude decreases due to the Rayleigh term. Coupling strength and, thus, pattern stability decrease with decreasing amplitude. This explains why the transition from anti-phase to in-phase co-ordination occurs. The coefficients a and b in the equation (1) depend in different ways on the amplitude of movement. At some crucial amplitude the anti-phase pattern loses stability while the in-phase pattern remains stable.

Other changes in movement amplitude and the accompanying changes of the control parameter movement frequency have been considered with further versions of the HKB model (see Haken et al., 1985; Peper & Beek, 1988). The coupling between the oscillators has been modelled using time derivatives and the resulting relative phase dynamics is expressed by the equation (4):

$$d(\phi) / dt = (\alpha + 2\beta r^2) \sin \phi - \beta r^2 \sin (2\phi), \qquad (4)$$

where r is the real amplitude of the oscillation and α and β are two adjustable but then fixed parameters.

The transition from anti-phase to in-phase co-ordination occurs at $2\beta r^2 = - \alpha - 2\beta r^2$, at the critical amplitude $r = (- \alpha / 4\beta)^{1/2}$, $\alpha < 0$. This implies that movement frequency has only an indirect effect on the stability of co-ordination, mediated by the associated changes in amplitude.

A further version of the HKB model has been derived by incorporating a time delay function in the coupling between the two oscillators as presented by the equation (5):

$$d\phi /dt = - 1 / \omega^2 r \, [(\alpha r + 6\beta r^3) \sin \phi - 3 \beta r^3 \sin (2\phi)], \qquad (5)$$

where ω is the frequency of the oscillator. In this version of the HKB model pattern stability not only depends on the parameters α and β and movement amplitude r, but also on the movement frequency ω itself. As a result, an increase in movement frequency leads to an overall decrease in pattern stability. The transition from anti-phase to in-phase co-ordination occurs at the critical amplitude $r = (- \alpha / 12\beta)^{1/2}$, $\alpha < 0$.

In summary, at the level of coupled oscillators the HKB model predicts that at the frequency-induced transition from anti-phase to in-phase the inverse relation between movement frequency and amplitude mediates co-ordination. The main difference between the two versions of the HKB model is based on the absence or presence of an explicit dependence of the pattern stability on movement frequency per se. However, in both versions (the time derivatives and the time delay model), increase in movement frequency results in a transition from anti-phase to in-phase co-ordination. In the time delay version, the degree of coupling depends rather strongly on the tempo and to a smaller extent on the movement amplitude, whereas in the time derivative version it varies purely as a function of movement amplitude.

In addition, the version of the HKB equation which includes detuning or the frequency competition term $\Delta\omega \neq 0$ (frequency difference between oscillating components: segments, limbs) should not be neglected in general conclusions on interjoint co-ordination. This issue will be considered in the discussion of the current results.

The general outcomes from the HKB versions have two important implications. Firstly, it is indicated that movement behaviour may self-organise, in other words, it can emerge without having been prescribed by the control parameter. That is, frequency (the control parameter) does not specify the emerging orders in any way. Secondly, it is demonstrated that the behaviour of a system with many degrees of freedom at its micro-level may be successfully described at its macro-level by means of a single order parameter (the relative phase) with only a few degrees of freedom.

However, one might still not be satisfied with this dynamic account of the transition phenomena. Beek (1990), for example, has emphasised the fact that the potential function presented by Haken et. al. (1985), has a strictly operationally defined nature and that these mathematical description of hand movements might not in itself explain why one state (the relative phase) is more stable than the other. Furthermore, the potential function itself does not make it clear which processes might underlie the phase transition.

Schmidt, Carello and Turvey (1990) have considered the above problem in their experiment of between-person co-ordination. Their subjects formed pairs and were instructed to watch each other's oscillating lower leg. They were instructed to maintain a common frequency, co-ordinating their leg movements either anti-phase or in-phase while increasing movement frequency. In the above experiment by Schmidt et al. (1990) the two oscillators, the limbs, were equivalent and the coupling between them was bilateral (each limb can change its movement characteristics as a function of the other). A similar phenomenon, relating to transitions from anti-phase to in-phase movements at critical frequencies, was also observed as in Kelso's 1981 and 1984 experiments.

Findings from the above experiments revealed that the dynamic principles governing within-person transitions also govern between person transitions, suggesting that the transitions are independent of the neural instating components (two nervous systems versus one nervous system) and independent of the nature of the informational coupling (visual versus haptic). Since the coupling between the two oscillators is only visual, it may be the case that the anti-phase organisation collapses when the perceptual limit to resolve the information specifying the anti-phase motion is reached (Schmidt et al.1990; Turvey 1990). If this is so, phase transitions should also be expected if one biological oscillator (a limb) is driven by an externally paced, non-biological oscillator (a metronome or the music tempo) because the informational resolution threshold still exists in one of the subsystems (the human).

Wimmers, Beek & Van Wieringen (1992) tested the above hypothesis in their experiment of rhythmic tracking movements. The subjects were required to track a rhythmically moving visual target spot (a driving oscillator) with their lower arm (a driven oscillator). As the formers (the visual target) drove the later oscillator (the lower arm) and not vice versa, the coupling was unilateral. Wimmers et al., thus investigated whether phase transitions also occur in the case of unilateral coupling. Their findings demonstrate that the shift from anti-phase to in-phase movement occurs when frequency increases in case of unilateral coupling as well as in case of the bilateral coupling of two oscillating units.

Phase transitions can occur over a large interval and under different values of control parameter (Haken, 1977). By defining order and control parameters, researchers who apply a Dynamic Systems Theory, can identify quantitative and qualitative changes in movement behaviour.

In summary, the Dynamic Systems Theory assumes that control is autonomous implying time-independent control that is, human movement evolves as a function of current state rather than as a result of a pre-organised time series. It is assumed that time is not a parameter of movement that is directly controlled. In addition, the role of cognition in motor control and learning should not be assumed *a priori.* In other words, employing the Dynamic Systems Theory to describe motor behaviour (or components of behaviour) does not necessarily preclude invoking cognitive mechanisms to explain motor behaviour. The tools provided by the Dynamic Systems Theory have been useful in studying complex systems behaviour, individual system components and their linear interactions as well as attributing to the effect of learning. The next section will include research in applying Dynamic Systems Theory to motor learning.

Dynamic Systems Theory and Learning

The concept of learning is characterised by a diversity of definitions, approaches and experimental methods in different disciplines. In psychology, for example, learning has been studied as verbal, perceptual and motor skill learning. Schmidt and Lee (1998) provide some of the common characteristics found in definitions of motor learning. The authors definition of motor learning requires that:

> (1)..."the learner acquire a specific capability for producing skilled behaviour; (2) learning occurs as a result of practice; (3) learning cannot be observed directly, just from tests of retention and transfer; and (4) learning involves a relatively permanent change in behaviour " (p.334).

The majority of motor control and learning research from the Dynamic Systems Theory considers the issue of learning a motor co-ordination pattern. Walter, Swinnen, Corcos, Pollaton and Pan (1997), defined motor co-ordination as the generation of appropriate spatial and temporal relations among movement-related events in a way that the goal of an action can be successfully achieved. According to Webster's Dictionary definition (1988, p.288), co-ordination is "the harmonious functioning of parts for most effective results".

From a Dynamic Systems Theory, multilimb co-ordination is considered as the interaction or coupling of co-ordinate structures. During the learning process, the variability in the co-ordination dynamics may be observed. According to Schoner, Zanone and Kelso (1992),"...learning is the change of the co-ordination dynamics..." (p.36), so the dynamic properties of co-ordination patterns, particularly their temporal stability, must be considered in the learning process. Schoner et al., modelled the co-ordination pattern dynamics by equations of motion of a collective variable (X) as defined below:

$$d X / dt = F_{intr} (X), \qquad (1)$$

where F_{intr} is modelled by internal system dynamics, called intrinsic dynamics. The right-hand side of the equation (1) is called the 'vector field'. Biological boundary conditions, such as task constraints, environmental context, or psychological properties, are parameters of the intrinsic dynamics. If these constraints do not specify a particular pattern, the co-ordination dynamics are called intrinsic dynamics. Intrinsic dynamics are contrasted with constraints with influences that specify a particular set of co-ordination patterns and which are captured instead by the behavioural information. This is the case in rhythmic movement tasks involving several components driven by a metronome (or by music tempo) where the metronome (or music tempo) frequency is non-specific to the relative timing of the different limbs. Intrinsic dynamics can change through the process of learning, and the learning of one task may affect the intrinsic dynamics for another task (Schoner, Zanone & Kelso, 1992).

In the Dynamic Systems Theory of co-ordination, learning is the change of the co-ordination dynamics. For example, the memorised behavioural information change that occurs when corresponding to a pattern which is to be learned. The pattern 'to-be-learned' may be determined on the basis of the final skill performance after learning, by assessing the corresponding behavioural information. If memorised behavioural information is assessed at different points during the learning process, the pattern 'to-be-learned' can be reconstructed from the asymptotic value of that information. The pattern 'to-be- learned' must be characterised in the same space of variables to which both the performed pattern and behavioural informations occur.

To actually model learning dynamics, initial tendencies of learning should be defined more specifically as some patterns are easier/faster to learn then others. Unfortunately, such information is not available yet, partly because no direct assessment of how co-ordination dynamics evolves during learning is possible (Schoner, Zanone & Kelso, 1992).

The dynamic properties of co-ordination patterns, in particular their temporal stability, must be monitored to assess learning. Inversely, any change of stability may be an indication of learning even when no change of the average performance can be detected. Assuming that learning takes place in the presence of environmental, or perceptually defined, behavioural information through feedback, then the co-ordination dynamics contain three components: intrinsic dynamics, environmental behavioural information and the current memorised behavioural information. This is formulated mathematically in the equation (2).

$$dX/dt = F_{intr}(X) + c_{env}\, F_{env}\,(X, t, Y_{env}) + c_{mem}\, F_{mem}\,(X, Y_{mem}) \quad ...(2)$$

In the above equation, F_{intr} represents the intrinsic dynamics, F_{env} is attracted to perceptually defined required patterns, and Y_{env} and F_{mem} are attracted to the patterns presently required by memory Y_{mem}, at any time t, during the learning of these patterns. The variable 'c_{env}' is the strength of the environmental perturbation F_{env}, while 'c_{mem}' is the strength of the memorised perturbation F_{env}.

To better understand what happens during the learning of co-ordination patterns, Schoner, Zanone and Kelso (1992) suggest that random influences might be analysed and modelled as noise process-stochastic forces that are not captured by collective variables. These influences determine the level of pattern fluctuations and they are considered to be measures of stability. In the presence of noise, the multi stable system may switch randomly among its various attractors.

According to Zanone and Kelso (1992), learning is the result of co-operation and competition between the intrinsic dynamic state and environmental information. Co-operation exists when a new pattern of co-ordination is adjusting to the nature of an attractor, an intrinsically stable state, by increasing its stability. Competition arises when the new pattern of co-ordination does not conform to an existing attractor. However, as the learned co-ordination pattern occasionally regresses back to an attractor's stable state, the pattern's consistency is decreased. This may be observed in the pattern's qualitative changes.

The ability to rapidly acquire and reproduce novel movement skills and how this learning takes place has been the feature of various theoretical models and experimental investigations. The study of interlimb co-ordination has proved to be a suitable framework in which to examine the process of learning new motor skills. Central to this approach is the view that learning can be expressed as the evolving stability of the to-be-learned co-ordination pattern. The stability of co-ordination is characterised by the relative phase relationship between two limbs as they perform continuous rhythmic oscillation in time with an external stimulus (e.g., an auditory signal) or self-paced by the participant. Usually there are only two patterns of co-ordination (in-phase 0° and anti-phase 180°) that can be performed without practice As learning occurs a tendency to perform pre-existing patterns is diminished and is replaced by increased attraction to the to-be-learned pattern (Kelso, 1984).

Understanding the dynamic stability of co-ordination is one of the central themes of dynamic approach. Dynamic stability may be conceived of as the maintenance of the essential features of a co-ordination pattern when facing the changed task demands such as an increase in the movement frequency. The extent to which learning affects the dynamic stability of a to-be-learned pattern of co-ordination has not yet been treated explicitly. Smethurst and Carson (2001) examined how practice affects the maintenance of a co-ordinated pattern as the movement frequency is scaled. Eleven volunteers performed a bimanual pronation-supination task. Their ability to maintain the target task -90° out-of-phase and the transfer task - 270° anti-phase were examined before and after the five practice sessions. Each session consisted of 15 trials of only the 90° out-of-phase pattern. Time to transition onset was used as the index of subject's ability to maintain two symmetrically opposite patterns. The results suggest that the practice does improve the stability of the 90° out-of-phase pattern and that such performance is transferable to the performance of the unpractised 270° anti-phase patterns. In addition, the anti-phase pattern remained more stable than the practised in-phase pattern throughout. These findings support the notion forwarded by Lee et al. (1995) who advocates that during learning the natural co-ordination tendencies of the system are, contrary to the theoretical predictions, suppressed, but not completely destabilised (Smethurst & Carson, 2001).

Swinnen, Walter and Shapiro (1988) argue that the problem of learning consists of searching in the perceptual motor workspace for a stable solution to the motor problem. This can be achieved by changing the potential workspace or changing both solutions to the problem and the workspace. The potential to perform the desired movement is present at the beginning of learning. The extent to which a learner is trying to perform a given action may depend on the degree of similarity between the new desired movement pattern and the performer's intrinsically 'preferred' pattern. In such cases, the problem of learning is to adjust the movement to the extent of context-specific demands. Once the initial success is achieved in performing a new task, more trials may be required to stabilise behaviour.

Bernstein (1967) identifies three phases of co-ordination during the acquisition of a new skill. The first phase is described as the performers' search for a solution that solves new motor task requirements. When learning a new skill the participant is concerned firstly about maintaining balance by staying in control over reactive forces. These demands can be met by reducing the total number of degrees of freedom that should be co-ordinated. This can be achieved by keeping degrees of freedom 'rigidly, spastically fixed' (Bernstein, 1967, p. 108), or by applying rigid couplings (the cross correlation) between multiple degrees of freedom or distal linkages.

Several studies have supported these processes. Newell and van Emmerik (1989) in handwriting research and McDonald, van Emmerik and Newell (1989) in dart throwing research have reported that the unpractised arm shows higher cross correlation in the distal linkages compared with the dominant arm. Considering the unpractised arm as an unskilled system and the dominant arm as a skilled system, these findings supported Bernstein's statement of movement control during the early stages of learning by applying rigid couplings between multiple degrees of freedom.

Vereijken, van Emmerik, Whiting, and Newell's (1992) research supports both strategies of reducing degrees of freedom in the early phase of skill learning. The authors observed ankle, knee and hip joint movements in novices during the early phase of learning to slalom on a ski apparatus. Rigidly fixated joints indicated that couplings were formed between joints to reduce the control problem facing the novice. Findings of the above studies indicated that novices were not able to control their degrees of freedom in a flexible way but adjusted them as rigid unit. During the second stage of the acquisition of co-ordination, the participant's progress in flexibility was illustrated by including in the performance additional degrees of freedom.

Verejiken and Bogardt (1999) found that during the process of skill acquisition, individual differences exist in both the amount of practice needed before advancing to the next level of co-ordination and in the exact direction that one takes to achieve the highest co-ordination level. When learning a new task and when advancing from an earlier to a later stage, it may happen that temporary relapses to an earlier stage can occur. However, the authors argued that differences also exist between tasks. At the early stage of acquisition, more risky tasks such as skating and cycling require a higher level of constraint of degrees of freedom, while less risky tasks allow more relaxed performance (Vereijken & Bogaardt, 1999).

Shaw and Alley (1985) note that, to acquire a new movement pattern one learns the laws that govern a dynamic control structure. To learn the laws of this control structure formation, the participant has to become perceptually attuned to the consequences of different configurations of the components of the control structure. According to Fowler and Turvey (1978, p.6):

> "A movement pattern has structure, and discovering an optimal organisation arises when an actor has configured his or her action system so that the following two principles are involved: a) the reactive forces of the limbs and their interaction with the environment are used so that they can be "largely responsible" for producing a desired trajectory, and b) additional degrees of freedom are used, thereby increasing the number of controllable parameters within the control structure so that the movements may be performed more fluidly".

According to Gibson (1966) the most powerful constraints result from the interaction between performers' perceptions and actions. In other words, perceptions guide choices of actions, and actions structure perceptions. This premise emphasises the fact that becoming skilled involves learning how to use the relevant information from the environment that guides actions.

Other research (for example, Proteau, 1992) has indicated that motor learning results in the formation of a sensory motor representation within the central nervous system (CNS) that is specific with regard to the sensory information experienced in practice and could also be specific to the motor output. By contrast, Turvey (1977) and Shaw and Alley (1985), argue that motor learning itself is the perceptual-motor act of learning to co-ordinate, or map, the perceptual invariant with the action invariant. It has been suggested that to acquire a new movement pattern an actor perceptually explores the dynamic workspace of the control structure (Fowler & Turvey, 1978; Kugler

& Turvey, 1987; Newell, Kugler, van Emmerik & McDonald, 1989). In some parts of the system, the initial state of the control structure assembled to produce a recently learned movement pattern is not very stable. To maintain the system balance, these parts have to be constantly rearranged. The stability of the system in these parts changes because the parameters of the control structures are manipulated by changes in performance conditions. Changes in performance can be considered in the feedback in order to manipulate the control parameters over the time, to obtain the final optimal equilibrium state (Kugler & Turvey, 1987).

According to Reed (1982), learning an action is the process of learning how to use available information to modulate actions. The feedback from an action-perception cycle can be used to modify further actions.

Information feedback has been used in research based on cognitive theory. Although the current research is based on the Dynamic Systems Theory, it is worthwhile to mention the relevant issues in cognitive theory as indicated by Starkes, Caicco, Boutilier and Servsek (1990) in their dance research. The authors showed that:

a) experts recall domain specific information more accurately than less skilled dancers;
b) in the classical ballet, structured sequences are recalled with greater precision by experts than unstructured sequences, although not for creative modern dance sequences, and
c) coding strategies appear to vary with expertise and with the demands of the particular recall task such as verbal description on dance performance.

Considering the above findings it can be assumed that experts, while being consistent and accurate, are also able to adapt to the demands of the task which may result in performance variability.

Motor Learning and Variability

Motor learning is the process of acquiring a new skill and involves a change of behaviour through practice or experience. A popular methodology in the study of changes in performance, which occur during skill acquisition, is the comparison of expert and novice performance on a given task. Imitation of an expert can assist learning, however this effect may depend upon the learner's ability to abstract higher-order information such as movement fluency (Annett, 1969).

In the Dynamic Systems Theory, the concept of stability is the crucial factor to acquiring a new movement pattern (Shaw & Alley, 1985). Zanone and Kelso (1992, 1994, and 1997) have considered the concept of stability based on the knowledge that bimanual co-ordination has certain preferred states that are stable. These authors conclude that cyclical movements in different upper limb tasks can be accurately and consistently performed in 0° or 180° relative phases without practice, which refers to intrinsic pattern behaviour. These two patterns may interfere in the process of new pattern formation and also serve as reference markers for assessing the relative capability to perform a new pattern. However, the initial attempts to learn a different pattern of co-ordination usually result in the performance of either one of these two co-ordination patterns (Zanone & Kelso, 1992; Lee, Swinnen, & Verschueren, 1995). A relative permanency in behaviour is characterised by the strength of a new co-ordination pattern in terms of its capability to remain stable and attract other co-ordination patterns. In addition, it is important to consider the movement variability because, although there may be an improvement in a pattern's consistency and accuracy, learning also involves perturbations to more stable behaviour (Lee, Swinnen & Verschueren, 1995).

Inherently stable states of movements are the preferred modes of co-ordination to which the motor system is attracted during performance. New co-ordination patterns are not developed from 'scratch.' They emerge with respect to these basic attractors as qualitatively different modes of co-ordination from the old patterns

Consistency in movement patterns is a function of skill level, the task and the environmental conditions (Newell & McDonald, 1994). Learning a new task is initially constrained by pre-existing modes of co-ordination. With practice the performance becomes less constrained, movement invariance may develop and consistency can be promoted. This however does not exclude the development of movement adaptability in order to cope with environmental changes. Newell and McDonald (1994) conclude that both movement consistency and movement flexibility could be observed throughout skill development from beginner to expert levels of the performance. This means, if one looks only at variability without also considering what the co-ordination pattern is, then the difference between experts and novices will be unclear. Beginners can show high variability when trying to perform a criterion task, but if they change from the complex task to simple movements and alternate phase state, they may show high stability instead.

The distinction between novices and experts is usually based upon differences in their ability to sustain co-ordination under changed environmental information (Ackerman, Schneider & Wickers, 1984). According to Deakin and Allard (1991, p. 49), "Expertise in dance has been characterised by an ability to produce a consistent, accurate, physical performance that matches a conceptual ideal". This means that less variability may be expected in experts' compared to novices' dance performance. However, considering Latash's (1994) conclusions, movement flexibility may be expected in both experts' and novices' performance within and between different trials of the same task.

Recently, Broderick and Newell (1999) observed the stability of co-ordination patterns in people of different age and skill levels in bouncing a basketball. The dominant arm movement patterns in the less skilled subjects were more variable than in the more skilled subjects. The co-ordination patterns revealed that "the movement patterns of less skilled subjects and the motion of the articulators showed directional changes as a function of skill level that began both proximally and distally and moved towards the centre of the effector chain with practice" (Broderick & Newell, 1999, p.165). This means that the interaction of the task and the skill level of the performer influence the patterns of change in co-ordination and that in ball bouncing, novices were less constrained in their overall movements. It seems that the process of skill acquisition is the one of showing more constraint over the possible degrees of freedom, as Bernstein (1967) argues, since the control of the ball bouncing was restricted from proximal and distal directions to be controlled in vertical direction. Broderick and Newell (1999) conclude that

> "... the nature of the task dynamics as constraints on changes in patterns of movement with skill acquisition leaves wide open the question of the way the co-ordination organises with respect to various types of tasks (p.187)."

In a step-aerobic task, the music tempo and the height of the step platform are considered as constraints that may affect the individual's co-ordination differently. Therefore, it can be expected that in the step-knee-up performance, pattern variability may be found within and between subjects. Furthermore, Broderick and Newell (1999) argue that:

> "... relatively consistent patterns to the organisation of co-ordination identified by correlation and phase relation variability, on this and other tasks in beginners and experts, may also exist in terms of invariant structures of co-ordination that persist throughout skill progress (p. 187)."

If this is so, then variability is inevitable in so far as it is assumed that invariant structures in the form of intrinsic dynamics exist within each individual.

The issue of variability has recently been discussed in research by Large (2000). Large investigated how people adjusted movement patterns to music. In his research, Large (2000) simulated human performance by developing a proposed model that included meter perception, and beat induction to which the input was a musical stimulus and the output was a pattern–forming dynamical system. The rhythmic stimulation effects on the system resulted in bifurcation, which was related to temporarily formed patterns of oscillations. Large found that observed patterns of finger tapping to music were stable as they persisted in the absence of an input and when influenced by a different beat input which interfered with the previous one. Nevertheless, these patterns can re-organise under a new temporal structure. Large concluded that when people listen to different musical rhythms a stable initial pattern is formed. This pattern is multi-periodical and is the initial pattern that allows synchronisation of more complex movement patterns such as in dance.

Large points out that the complexity of the environmental stimuli in the real world must be considered in understanding the perception–action process. In a similar way, to better understand co-ordinated movements the individual's perception of stimulus structure should not be underestimated. According to Latash (1994, p.295),

> "The task and conditions of its execution (to the extent that we are able to control them) do not ambiguously define the movement. If one accepts the idea of the non-equilibrium nature of the motor control system, external movement patterns are going to be unique even if the task and conditions are reproduced ideally. As a result, repetition of a motor task leads in different trials to different movement trajectories."

This means that from trial to trial, variability in movement behaviour is expected because a correspondence between conditions, task and movement patterns cannot be maintained even for the simplest movements.

The key concepts that describes the system's co-ordination dynamics are a collective variable, or order parameter, and a control parameter, the factor perturbing the stability of the system (Kelso, 1991).

Schöner, Jiang and Kelso (1990) emphasise progression velocity and stride frequency as especially relevant parameters from the perspective of Dynamic Systems Theory. This theory views a specific gait pattern to be an emergent behaviour that arises from the collective behaviour of all contributing sub-systems, including both the central nervous and musculoskeletal systems (Diedrich & Warren, 1995). Constraints, such as those found in the environment (walking surfaces, gravitational forces) and task itself (walking or running at different velocity) also contribute to specifying the behaviour of the system.

Factors such as locomotor speed and stride frequency can affect various aspects of human locomotion. Winter (1983) has reported an 18% increase in knee velocity and a 21% increase in hip velocity accompanied an increase in natural walking cadence of 17% .

Hreljac (1995) has demonstrated the influence on hip angle of changing both speed and gait pattern. Hreljac illustrates this with interactions produced by manipulating both, speed and gait mode factors. In walking, the range of hip motion increased as the progression speed increased. However, as the gait pattern changed to running at the preferred transition speed, the hip motion range decreased. The author found it difficult to determine whether the change in certain kinematics variables, such as the hip joint angle range of movement, were due to the change of the gait pattern or due to the change in locomotion speed.

Recently, Li Li, van den Bogert, Caldwell, van Emmerik and Hamill (1999) have found similarity in thigh and leg co-ordination patterns when walking and running under controlled speed and stride frequency conditions. In this case, by stabilising the control parameters of speed or frequency, it was possible to isolate the effects of different gait patterns on co-ordination and variability. The variability of relative phase demonstrated that walking and running had similar amounts of variation between gait conditions at the control stride frequency at the testing speed of 2.24 m/s (close to the walk to run transition speed). These authors suggest the similar variability characteristics may exist at other locomotion speeds and may also be affected by stride frequency.

The role of neuromuscular constraints in the co-ordination has been observed in research considering spontaneous transitions between different patterns of co-ordinated movement. While such transitions were observed in cyclic movements of peripheral limbs and limb segments (fingers, hand, gait) whole body movements have not been similarly addressed.

Burgess-Limerick, Shemmell, Barry, Carson and Abernethy (2001) explored spontaneous transitions between different patterns of lower limb co-ordination in a whole body task, as a function of lift height during repetitive lifting and lowering. Manual lifting, whether performed discretely or repetitively, involves cycles of flexion and extension movements of limbs and trunk. This research provides an experimental paradigm that has a potential, which may provide a considerable insight into the role of musculo-skeletal constraints in determining inter-joint co-ordination.

The authors investigated the characteristics of spontaneous transitions in a whole body movement involving repetitive manual lifting and lowering the load. However, transitions between different modes were not observed because in these experiments lifting was performed as discrete trials and the experimental manipulation involved separate trials in different height conditions. The phenomenon of spontaneous transitions between qualitatively different co-ordination patterns was observed as abrupt transitions from stoop to squat techniques were observed during descending trials and from squat to stoop during ascending trials. The authors ascribed observed transitions as a consequence of trade-off between biomechanical advantages of different techniques and the influence of the lift height on this trade-off (Burgess-Limerick et al., 2001).

The question remain what variable, or combination of variables, is the lifter sensitive to and how does this coalition of constraints influence the pattern of co-ordination adopted?

In summary, the distinction between In order and control parameters enables researchers who apply the Dynamic Systems Theory to identify the nature of different co-ordination patterns that may occur due to a small change in a control parameter (Haken, 1977). As such changes may occur during the process of learning either the specific pattern or a more general pattern, this issue can be considered within the concept of the motor learning transfer.

Motor Learning and Transfer

This section considers the issues of transfer in motor learning research. Motor learning transfer has been used in research to investigate whether learning involves acquiring a specific pattern or a more general pattern, and whether the acquired representation is abstract in nature and is permitting subjects to transfer the learned motor control pattern to a new movement pattern, or whether it is based on examples (Stelmach, 1996).

One area of motor learning considers how the learning is transferred between and within new tasks. Transfer tests have been applied to answer this question (Schmidt, 1982). Transfer tests allow one to examine which parts of a task can be transferred to a different task or to the same task performed under different conditions. The transfer phenomenon is defined as negative or positive transfer. Positive transfer occurs when fundamental parts are not changed when the same task is performed under different conditions so, the invariant characteristics of the task are common to pattern behaviour in all conditions. Negative transfer may be seen as changes or degradation in some skill because of practice or experience in another.

Annett and Sparrow (1985) state that non-specific elements in skill learning make it possible to transfer experience from one situation to others that are similar. That is, acquiring some specific skills may enhance the acquisition of other related skills. In the traditional theory of transfer it was thought that practising any task would develop various abilities and then the transfer tasks will benefit from the particular ability. An alternative view is that transfer occurs only when the original learning task and the transfer task share some common elements that may be understood as stimuli and responses. Transfer that occurs when previous experience interferes with the learning or performance of a new skill, which is similar in all but a few important respects, is called negative transfer.

A problem can arise when near-identical stimuli must be linked to different responses. For positive transfer to occur it is important that the two tasks should have common stimuli and responses as well as common stimuli-response connections.

The essential factor in transfer is an awareness of elements or features common to the old and the new task. This awareness is important in coaching and teaching and in choosing training techniques that are likely to enhance useful transfer (Annett & Sparrow, 1985).

Many studies in the field of motor behaviour have used transfer design to assess learning (Adams, 1987). It is assumed that learning not only affects the specific task to be learned but may also affect behaviours other than the one being practised (Zanone & Kelso, 1994). In their model of bimanual co-ordination, Zanone and Kelso (1994) consider motor learning transfer to explain why intrinsic dynamic behaviour is invariant when observing the transformation from the positive to the negative phase angle (+Ø to -Ø).

The co-ordination dynamics were equal or symmetrical in the prescribed left-right hand performance. This symmetry may be broken when behavioural information specifies a required pattern, which is different from the initial pattern. This may happen if a different hand is defined as the leading one, for example, the right hand if the left hand was used before. The symmetry pattern stabilised with learning, although it was not practised. The fact that the proposed pattern and its symmetrical pattern are both learned, suggests that transfer of learning occurs automatically. Zanone and Kelso (1994, p.478), conclude in their transfer study that:

> " ...what was learned was an abstract phase relationship between the rhythmically moving components, where learning a phase relationship was independent of the bodily segments actually recruited in the movement. Such generalised abstract learning enables an individual to achieve the same outcome regardless of the effectors used. The learned pattern becomes the part of the intrinsic dynamics as a new stable attractive state of the co-ordination dynamics in the absence of specific task requirements".

The notion that the general workspace of the intrinsic dynamics changes with practice refers to the loss of stability in the original preferred pattern while a new pattern becomes more stable. However, the effect of negative transfer (see p. 41) suggests that behaviour of the intrinsic dynamics behaviour may remain unchanged when new tasks are learned (Schmidt & Young, 1987).

Zanone and Kelso (1992) have studied a relative timing task in which five subjects cycled their index fingers; each paced by two metronomes, at 90° relative phase. The co-ordination dynamics defined by the stability of relative timing changed with learning. The stability of relative timing increased with learning as the proposed pattern was more closely achieved. The task and the expected performance outcome defined the proposed pattern. If memorised behavioural information was assessed at different points during the learning process, the proposed pattern could be approximated from the new pattern performed at the particular point of the learning process. The increase in the stability of 'relative timing' in the above study indicated that the skilled subjects were more likely to recover quickly from a perturbation of their co-ordination pattern than less skilled subjects.

Observation revealed that the movement pattern variability decreased in learned conditions as well as in patterns performed under conditions other than the learning condition. Zanone and Kelso (1992) pointed out that such observation provided further evidence of the following dynamic system features:

- Learning involves a change of co-ordination dynamics, and at each point during the learning process a system will have a well-defined learning dynamics;
- The deviation of performance towards a newly learned pattern is a direct measure of memorised behavioural information and;
- The increasing influence of the learned condition on nearby phasing conditions is consistent with the increase in the relative strength of the memorised pattern.

Zanone and Kelso applied the relative timing task test to establish the intrinsic co-ordination tendencies of different effector systems (for example, fingers) and the co-ordination dynamics under a different condition. Then a particular relative timing task was learned by one effector system (for example fingers). The transfer was analysed both for the learned task and for its dynamic environment (scanning task). Therefore, in the above study the authors observed the transfer of motor co-ordination skills among different effectors or different patterns of movement at a) the particular level of co-ordination (for example, the skill level of the participant: novice or expert), b) the particular performance condition, and c) the behaviour of the proposed pattern at different stages of the learning process. Such an approach may contribute to understanding the changes in the co-ordination dynamics due to learning conditions.

Changes of stability can be observed even in cases where the mean performance changes little in the entire learning process. If changes in the co-ordination dynamics can be observed also under conditions other than those learned, when similar patterns are required perceptually, then a systematic deviation towards the learned pattern may be observed. By observing the effects of learned conditions on neighbouring conditions, Zanone and Kelso concluded that a learned pattern could become a part of the intrinsic dynamic. The memorised behavioural information influenced performance under conditions in which environmental information was not identical to the learning conditions.

In summary, it is suggested that transfer effect can also be interpreted and observed within the Dynamic Systems Theory in gross motor task performance. Changes in the variability of intrinsic pattern behaviour due to the learning process and/or changes in the performance under the learned condition may be ascribed to either negative or positive transfer effect.

Quantification of Interjoint Co-ordination

Burgess-Limerick and Abernethy (1993) state that relative phase angle may be used as a measure sensitive to the effects of environmental changes, learning, or other factors which may affect movement conditions. For example, with gait co-ordination variations of relative phase angles for each subject and each condition, running and walking, can be calculated as the mean of the standard deviation observed on the ensemble curve which represents the number of observed gait cycles in a trial. The results of these calculations are an indication of cycle to cycle variability and can be used to compare system stability characteristics across gait patterns (van Emmerik & Wagenaar, 1996). The above method was used in the present study to analyse the differences in the angular displacement amplitude of joints observed at the point of co-ordination (step-knee-up) in five cycles.

Corcos, Gottlieb, Jaric, Cromwell and Agarwal (1990) point out that most research that considers the effects of practice in single joint movements has been based on the framework of independent central control of the levels of muscle activity which are usually directly associated with the EMG levels and patterns.

Because there was no comparable framework to the above mentioned in research by Corcos et al. (1990), their analysis of the effects of practice in multi joint movements was usually based on segment by segment description. However, multi-joint models have also been proposed as solutions to problems in the analysis of multi-joint movements. For example, Berkinblit, Gelfand and Feldman (1986 a, b) have suggested a kinematic solution. This type of control is considered as kinematic because movements in each individual joint depend not only on the position of the joint and target, but also on the integrated influence of movements in all other joints on the working point trajectory. In the analysis of the variability of movement patterns in a whole body rhythmical task, as proposed in this study, the kinematic approach may be used to explain the integrated influence of joint movements on multi limb co-ordination.

Overall Chapter Summary

Behavioural patterns adjust continuously to the environment (for example, catching, tracking, and synchronisation of a rhythmic movement with a metronome and so on). In order for the physical environment to become meaningful to the biological system, it is necessary that a dynamic relationship exist between the system and its environment. This may be conceived as the information of the perception-action pattern for a dynamic model that addresses how a part of the physical environment becomes meaningful to a system.

Co-ordinative structures or 'synergies' between muscles, as named by Bernstein (1967), specify basic properties of the movement system from the Dynamic Systems Theory. The function of these co-ordinative structures depends on physical constraints given by a range of movement and the environmental forces and objects with which they co-ordinate.

Behavioural patterns naturally performed in the absence of information that may specify behaviour are considered as intrinsic dynamics. The presence of intrinsic dynamics is evidenced by a systematic deviation of the required behavioural pattern from the actual behavioural pattern, in the direction of the stable states of the intrinsic dynamics. The qualitative effects of environmental information can be seen when the corresponding perturbation breaks the symmetry of the intrinsic dynamics. Schoner and Kelso (1988) propose the following assumptions regarding environmental information based on the Dynamic Systems Theory:

- Dynamics of the order parameter in the absence of environmental information (so called intrinsic dynamics) are not changed when such information is present.
- In the absence of intrinsic dynamics, environmental information affects the order parameter dynamics in a way that they are attracted to the required behavioural patterns. This is described in the following expression:

$d\,x_t/dt = f_{intr} + c_{env}\,f_{env}\ (x_t, t)$, where the variable '$c_{env}$' is the strength of the environmental perturbation f_{env}, f_{intr} indicates internal perturbation (intrinsic dynamics) of the organism and x_t presents the collective variable.

Another important qualitative effect of environmental information is the possibility of phase transitions in the order parameter dynamics (dependent variables). Such phase transitions exist if the intrinsic dynamics are qualitatively different from the dynamics specified by the environment (Kelso & Tuller, 1985).

The above assumptions are considered in the discussion of the results from Study 2 of this research. The findings of the current research in general are discussed within the assumption of a time delay version of the HKB model as presented by the equation (5):

$$d\phi/dt = -1/\omega^2 r\,[(\alpha r + 6\beta r^3)\sin\phi - 3\beta r^3 \sin(2\phi)], \qquad (5)$$

In this version of the HKB model, pattern stability depends on the parameters

α and β, on the movement amplitude r and also on the movement frequency ω itself. As a result, an increase in movement frequency (and similarly an increase in music tempo), which causes a decrease of the cycling period, will lead to an overall decrease in pattern stability.

In summary, although the experiments conducted in the current research could fit equally well within a motor programming perspective, the Dynamic Systems Theory has been preferred for the current research. Finally, the review of relevant methods used in quantification of interjoint co-ordination, has provided the rationale for the use of kinematic parameters and phase plane variables in the analysis of the learning effects on co-ordination dynamics in a whole body rhythmical task.

CHAPTER 3

METHODS AND PROCEDURES

This chapter includes procedures for the participants' selection, experimental procedures, apparatus employed, variables, research design and analyses applied in Study 1 and Study 2.

Study 1

Sample

Twelve healthy volunteer females between the age of 18 and 45 participated in this study. Prior to testing, a letter of consent was signed by participants. Based on their experience with step aerobic exercise, participants were assigned to either the novice or expert group. The novices (n = 6; average age = 34 years: two women aged 18, two aged 45 and two 40 years old) were defined as those who had no prior experience in step aerobic exercise. The expert group (n = 6; average age = 33 years: two women aged 21, two of 37 and two 43 years old) was selected from current aerobic instructors with experience in teaching step aerobic classes (at least two sessions per week over the last three years or more). All participants reported that they were right hand and right leg preferred. The experiment was carried out according to the ethical guidelines laid down by the Edith Cowan University Committee for the Conduct of Ethical Research.

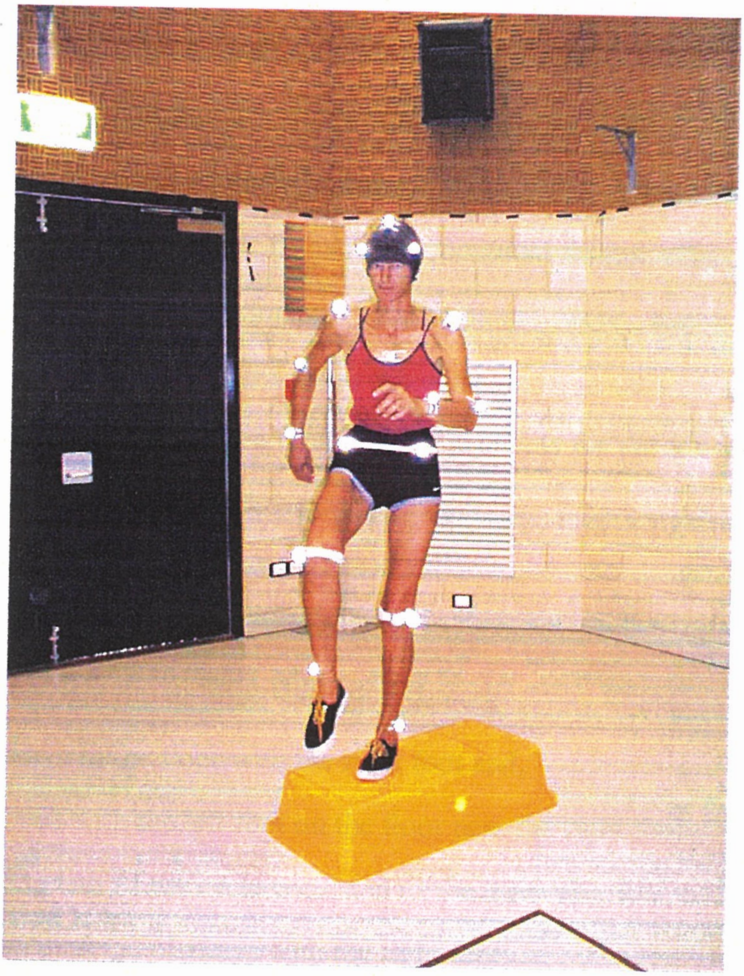


Figure 1. The task, 'step-knee-up'

Procedure

Participants initially performed an aerobic step-knee-up task onto a 20-cm high step aerobic platform under four tempo conditions. In the current study only performances under slow and fast tempos were analysed. The task performed under the fast tempo is presented in Figure 1.

The four conditions were: self-paced tempo (no music), slow tempo (48 beats per minute), a medium tempo (96 bpm.) and a fast tempo (144 bpm) administered in that order. To avoid the potential fatigue effect only one trial per condition was performed. Participants were tested individually, completing all four trials in a single session.

A cycle consisted of eight counts, four counts for the left leg pattern and four for the right leg as follows:

The first half of the cycle was counted as:

1. Step up with the left foot onto the 20-cm step platform,
2. Flex the right hip to bring the right knee up;
3. Step down to the floor with the right foot and,
4. Tap once with the left foot on the floor near the right foot.

The second half of the cycle consisted of the following four counts:

5. Step up onto the platform with the right foot;
6. Flex the left hip to bring the left knee up;
7. Step down onto the floor with the left foot and,
8. Tap once with the right foot on the floor near the left foot.

The participants were instructed to move both arms simultaneously forward and backward so that the limbs would perform in-phase movement, which is opposite to the natural anti–phase arm movements that accompanies walking and stepping activities. The arms performed a swinging motion in the sagittal plane, with elbow flexed to approximately 80° pushing both hands and elbows up front on stepping up and pulling elbows back on stepping down. This pattern of the arm movements has been defined as a proposed pattern or the 'to-be-learned' pattern.

A cycle was defined as the trajectory between the two consecutive hip joint maximum flexion observed at knee-up position in the same side limb. For example, a cycle for the left knee joint angle and a cycle for the left shoulder joint angle were defined with the reference to the cycle of the left hip joint angle. Figure 2 illustrates movements that occur at the shoulder, hip and knee joint during one cycle.

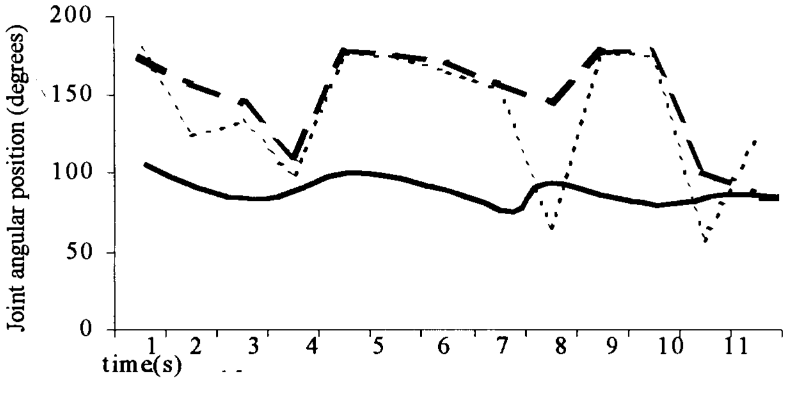


Figure 2. Angular position of left hip (— — —), left knee (...) and left shoulder joint (—) during one cycle at slow tempo for one novice participant.

The first maximum left hip flexion (115°) was observed in the third second when the right foot stepped on the platform and the left leg moved up. At that hip flexion position, the left knee angle was 110° and the left shoulder angle was 80°. The next maximum left hip flexion was observed in the twelfth second (90°) with the left knee angle of 115° and the left shoulder angle of 90°. The left hip flexion of 150°, noted in the ninth second, indicated the left foot stepping up on the platform. At this moment the beginning of a cycle was counted for the other (right) leg. Therefore, only two consecutive joint angles at 'knee-up' position of the same leg were relevant for the definition of a cycle.

The task was demonstrated prior to testing by the examiner under the self-paced condition only. Participants were not permitted to practice the task prior to testing trials. However, they were advised to warm up for 3-5 minutes with stepping and stretching exercises to ensure that markers were securely fixed.

Participants were instructed to follow the music tempo and to perform six right and six left cycles, or turns of six 'step-knee-up' with each leg, under each condition. As a cycle was counted to 8, and it was established that novices and experts would be able to perform 6 cycles in 60 seconds at slow tempo (48 b/min = 6 cycles x 8 counts per cycle), and 6 cycles in 20 seconds (as 18 cycles in 60 seconds) at fast tempo (144 b/min = 18 cycles x 8 counts per cycle).

Therefore, a trial time for six cycles was set at 60 seconds for the slow tempo condition and at 20 seconds for the fast tempo condition (18 cycles / 60 seconds = 6 cycles / 20 seconds). Video capture commenced with the participant's first step, when the examiner activated the 'collect' button, which enabled the starting signal. At slow tempo, data were collected for a 60 seconds trial, while the fast tempo trial was recorded over 20 seconds. A second signal was given when the time had elapsed to indicate the finish. Movements were performed between the starting and finishing signals initialised by the Motion Analysis System. The music was selected from professional aerobic dance tapes recorded at Music & Motion Studio (Victoria).

Prior to the trial, cube calibration data were collected with the smoothing procedure using an 8Hz Butterworth low-pass, second order filter. Data analyses were performed using Kintrak (version 5.6) software. Shoulders, knees and hips angles were calculated as absolute angles, while head angular displacements were observed in the frontal and sagittal plane with reference to the laboratory co-ordinate system (LCS), which is defined as a right-handed co-ordinate system. The LCS axes' orientation used for biomechanics analyses in Kintrak (Kintrak 5.6 manual, p.33) is defined by Z-axis vertical (positive-up), Y-axis anterior-posterior and, X-axis right-left.

Apparatus

The EVa/hires (Expert Vision advanced and a Hi-resolution, Hi-speed monitor) Motion Analysis System, (Motion Analysis Corporation producer, Santa Rose, Cal.US.) and the Kintrak (version 5.6) integrated hardware-software system were used for video data acquisition and data processing. Five Panasonic cameras were placed on tripods at a height of approximately 2 meters. They were arranged in a semi circle position, 3 meters from the step platform to acquire video data from the frontal and left and right sagittal planes (see Figure 3). The frame rate for the cube calibration and data collection in this study was 120 frames per second. Sixteen reflective ball markers of 3 cm diameter sizes were attached to the anatomical landmarks of each participant to define a 6-segment human body model consisting of head, left arm, right arm, left leg, right leg and trunk.

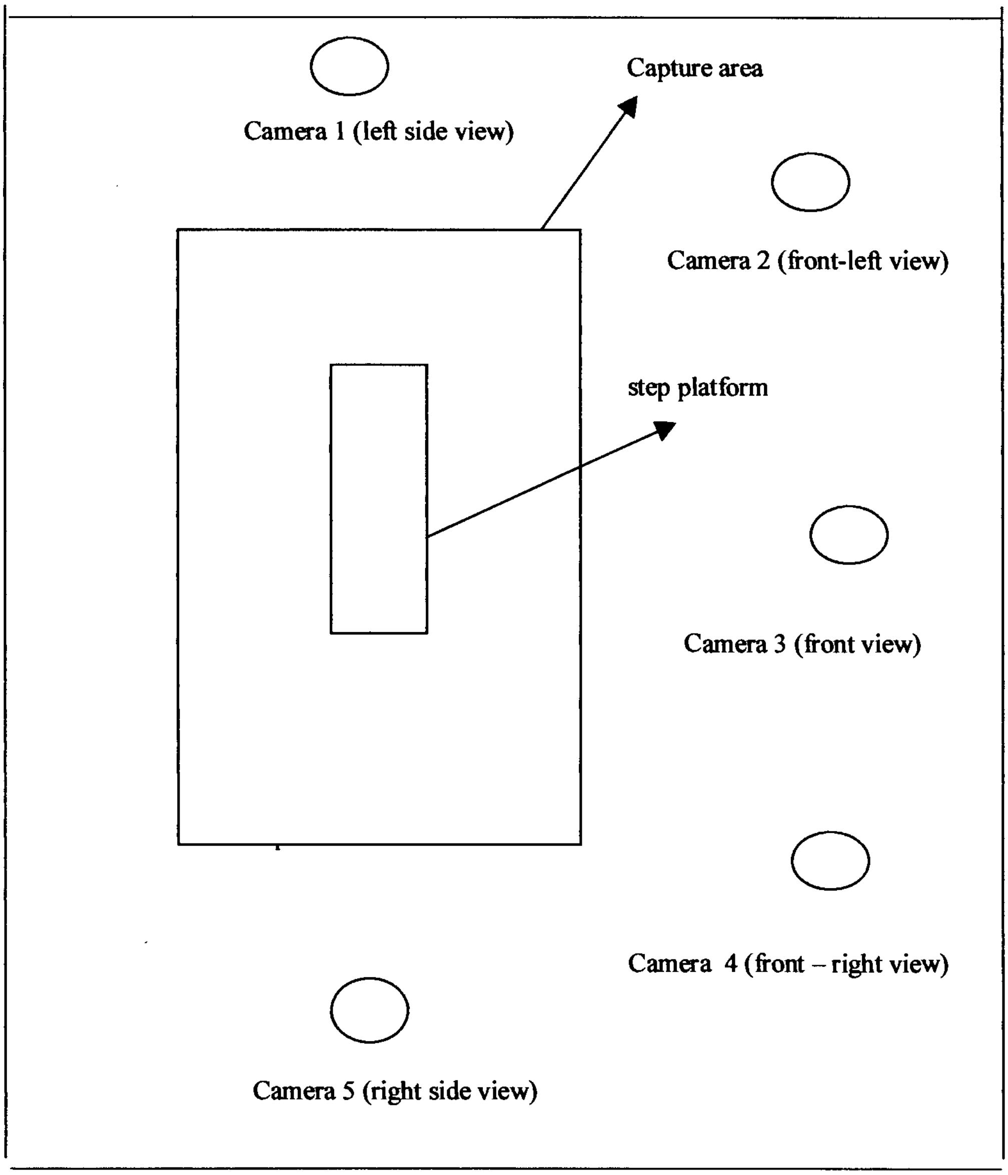


Figure 3. Camera set-up for Study 1

Three head markers were attached to a tight fitting skullcap: one marker on the vertex and one at 5 cm above each of the left and the right ears. The remaining thirteen markers were attached directly to the skin at: a) the acromia-clavicular joint on the left and right shoulder; b) the radial head of the left and right elbow joints; c) the lateral condyle of the left and right femur; d) the lateral sides of the shoes below the ankle joint; e) the left and right anterior-superior iliac spines (ASIS); f) on the sternum 10 cm distal to a sternal notch and, g) on the left and right hands at the middle of the wrist dorsum (see Figure 4).

Variables

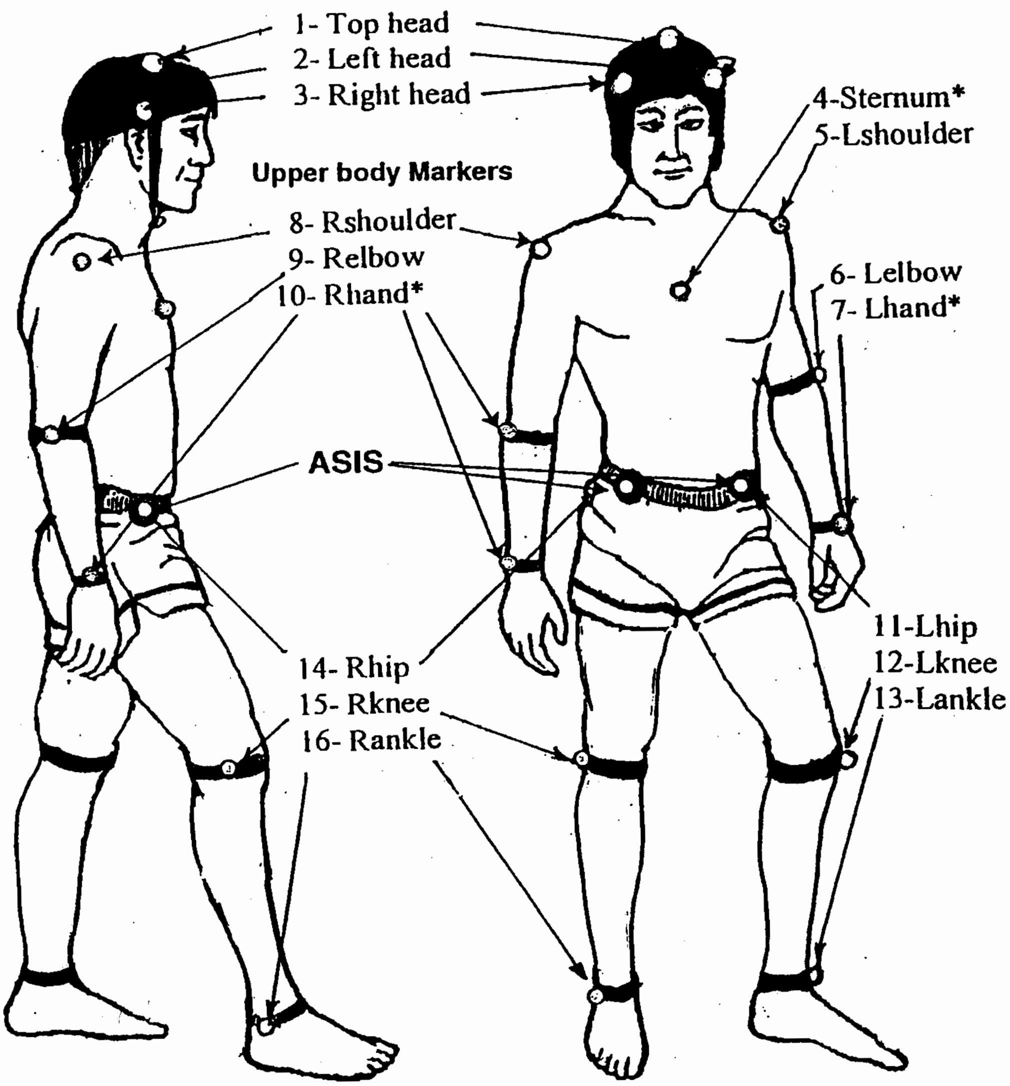
The independent variables were: 1. Skill level (1-novice; 2- experts) 2. Music tempo conditions (1-slow; 2-fast), and 3. Body sides (1-left; 2-right). Dependent variables were kinematic variables derived from the3-D (three-dimensional) video data input.

The following measures were calculated:

1) Knee angles (left and right leg), defined as the absolute angle between thigh and shanks that decrease when the knee joint flexes.

2) Hip angles (left and right), defined as the absolute angle between thighs and a trunk segment defined by the relevant side ASIS and shoulder markers. This angle decreases when the hip joint flexes.

3) Shoulder angles (left and right), defined as the absolute angle between the upper arm and the relevant side of the trunk defined by ASIS and shoulder markers. This angle increases in a positive direction when the arm is swinging forward, and increases in a negative direction when the arm is swinging backwards.



* Markers not digitised in Study 2

Figure 4. Simplified marker set for full body analysis

From these raw measures the following dependent variable was extracted for the quantitative analysis of the cycle behaviour and the further calculation of interlimb co-ordination:

1) Phase angle preference ($M\phi$) - mean phase angle at maximum hip flexion and knee-up position.

Quantification of interjoint co-ordination was calculated as the continuous relative phase angle (CRP) for the combination of hip and knee phase angles in: 1. Left leg (ϕ_{LH}-ϕ_{LK}), 2. Right leg (ϕ_{RH}-ϕ_{RK}) and, left and right shoulder phase angle in 3. Arms (ϕ_{LS}-ϕ_{RS}).

Variable Definition.

In two-point objects a proximal point plus a distal point creates an axis, with the proximal point at the origin and the distal point defining the axis. When two body segments define a variable, it is possible to calculate the angle between them. The type of angle can be absolute or projected. For the angular two point segments variables listed below, the angle type between these two segments was defined and calculated as the absolute angle.

Variable 1. Left shoulder angle

Markers placed on 2-2 point segments defined the Left shoulder angle. Segment one (the left upper arm) was defined by a proximal marker placed on the left shoulder joint (L Shoulder) and a distal marker placed on the elbow joint (L Elbow). A proximal marker placed on the left shoulder joint (L Shoulder) and a distal marker placed on the left ASIS (L Hip) defined segment two (torso).

The Left shoulder angle was observed as the left upper arm swings on the X-axis, with reference to the second segment (Z-axis) defined by L Shoulder and L Hip end points. These movements were observed in the sagittal plane.

Variable 2. Right shoulder angle

Markers placed on 2-2 point segments defined the Right shoulder angle. Segment one (the right upper arm) was defined by a proximal marker placed on the right shoulder joint (R Shoulder) and a distal marker placed on the elbow joint (R Elbow). For segment two, a proximal marker placed on the right shoulder joint (R Shoulder) and a distal marker placed on the right ASIS (R Hip) defined the torso.

Right shoulder angle was observed as the right upper arm swings on the X-axis, with reference to the second segment (Z-axis) that was defined by R Shoulder and R Hip end points. The movements were observed in the sagittal plane. Arm swings forward (in front of the body) were measured as positive angles while swings backward (behind the body) were defined as negative angles.

Variable 3. Left hip angle

Markers placed on 2-2 point segments defined the left hip angle. Segment one, the left thigh, was defined by a proximal marker placed on the left hip joint (L Hip) and a distal marker placed on the left knee joint (L Knee). For segment two, a proximal marker placed on the left shoulder joint (L Shoulder) and a distal marker placed on the ASIS (L Hip) defined the torso.

The left hip angle was defined by the left thigh swings, observed in the sagittal plane and about medio/lateral X-axis. Movements were calculated with reference to the torso or the second segment (Z-axis) defined by the L Shoulder and L Hip markers.

Variable 4. Right hip angle

Markers placed on 2-2 point segments defined the right hip angle. Segment one, the right thigh, was defined by a proximal marker placed on the right hip joint (R Hip) and a distal marker placed on the right knee joint (R Knee). For segment two, a proximal marker placed on the right shoulder joint (R Shoulder) and a distal marker placed on the right ASIS (R Hip) defined the torso.

The right hip angle was defined by the right thigh swings, observed in the sagittal plane and about medio/lateral X-axis. Movements were calculated with reference to the torso or the second segment (Z-axis) defined by the R Shoulder and R Hip markers.

Variable 5. Left knee angle

Markers placed on the 2-2 point segments defined the left knee angle. Segment one, the left thigh, was defined by a proximal marker placed on the left hip joint (L Hip) and a distal marker placed on the left knee joint (L Knee). Segment two, the left shank, was defined by a proximal marker placed on the left knee joint (L Knee) and a distal marker placed on the left ankle (L Ankle).

Variable 6. Right knee angle

Markers placed on the 2-2 point segments defined the right knee angle. Segment one, the right thigh, is defined by proximal marker placed on the right hip joint (R Hip) and a distal marker placed on the right knee joint (R Knee). Segment two, the right shank, was defined by a proximal marker placed on the right knee joint (R Knee) and a distal marker placed on the right ankle (R Ankle).

The left and right knee angles were observed in the sagittal plane as the absolute angle between thigh and shank.

Calculation of Absolute Angles

The following calculation is provided in the Kintrak Users Manual 5.6. Given two 2-point segments, A and B vectors, the absolute angle between them was calculated as follows:

$$e_a = (e_a x_i) + (e_a y_j) + (e_a z_k)$$

$$e_b = (e_b x\ I) + (e_b y\ j) + (e_b j\ z)$$

The unit vector 'e_a' was expressed as: $e_a\ x = A1\ x - A2\ x$;

$e_a\ y = A1 y - A2\ y$; and

$e_a\ z = A1\ z - A2\ z$ where,

$A = (A1\ x - A\ 2x) + (A1 y - A2\ y) + (A1\ z - A2\ z)$

Similarly the unit vector 'e_b' was defined as:

$e_b\ x = B1\ x - B2\ x$;

$e_b\ y = B1\ y - B2\ y$; and

$e_b\ z = B1\ z- B2\ z$, where

$B = (B1\ x - B2\ x) + (B1\ y - B2\ y) + (B1\ z - B2\ z)$

$$e_a * e_b = | e_a | * | e_b | * \cos \varnothing$$

$$\varnothing = a * \cos\ (e_a - e_b)$$

If one of the defined segments was an axis of the laboratory co-ordinate system, that segment was defined by selecting two arbitrary points along the axis. This is to be the end point of the other segment.

Co-ordinates given for the cube calibration control points determine the

LCS. The selection of the object-reference-frame is arbitrary. The calibration cube measurements have to be made in a right-handed co-ordinate system because the EVa hires software works only with a right-handed co-ordinate system. It has not been tested with a left-handed co-ordinate system. Cube calibration measures and calculation of linear joint displacements with reference to the LCS are expressed in millimetres. The LCS axes' orientation used for biomechanics analyses is defined as: "Z-up", having a person facing the +Y-axis; media lateral and, the +X-axis pointing from the person's right side to left side; anterior- posterior (for details see Kintrak 5.6 manual, p.33) The following measures were calculated in this study:

1) The angular position was calculated for hip, knee and shoulder joints as an absolute angle.
2) The angular velocity was calculated as the first derivative of displacement data applying Kintrak 5.6 tabular analysis. These data were calculated for further use in calculation of phase angles.

Calculation of Phase Angles

A limit cycle was adopted as a suitable attractor to describe the non-linear oscillatory motion of joints and segments during the stepping cycle. If each joint (or segment) motion is mapped onto a limit cycle attractor, and represented in a phase portrait, then it is possible to examine how the two limit cycle systems are co-ordinated. In other words it is be possible to analyse the system attractor dynamics.

Quantitative as well as qualitative analysis of interjoint co-ordination can be obtained by using a phase plane analysis (a plot of normalised joint angular velocity as a function of normalised joint angular position). The normalisation procedure scales the absolute maximum angular velocity to an absolute value of 1, leaving points of zero angular velocity unaltered. Points of zero normalised angular velocity correspond to points at which the joint is momentarily stationary. This procedure sets the minimum and maximum angular positions to -1 and +1 respectively. The zero normalised angular position corresponds to the midpoint of the range of the angular position adopted by the joint during the performed action. The positions of the joint at any time during the movement can be defined in terms of an angular displacement from the starting point (at $t = 0$) or phase angle, the inverse tangent of normalised angular velocity/normalised angular position (Burgess-Limerick, Abernethy and Neal; 1993).

In this study, in order to examine the attractor dynamics of shoulder, hip and knee joint motion, phase angles were calculated by transforming Cartesian co-ordinates of angular position and angular velocity variables (θ, $d\theta/dt$) to polar co-ordinates, with radius $R = \theta / \cos \phi$ and phase angle
$\phi = \tan^{-1} (\omega/\theta)$, where $\omega = d\theta/dt$.

Phase angle ϕi was defined from the normalised data for each stride cycle as the angle formed between the line (0, 0) to the current data point (θ_i, ω_i) and the right horizontal. Phase angle was calculated as:

$\phi = \tan^{-1} (\omega/\theta)$, where: θ = normalised angular displacement and,
ω = normalised angular velocity (see Figure 5.).

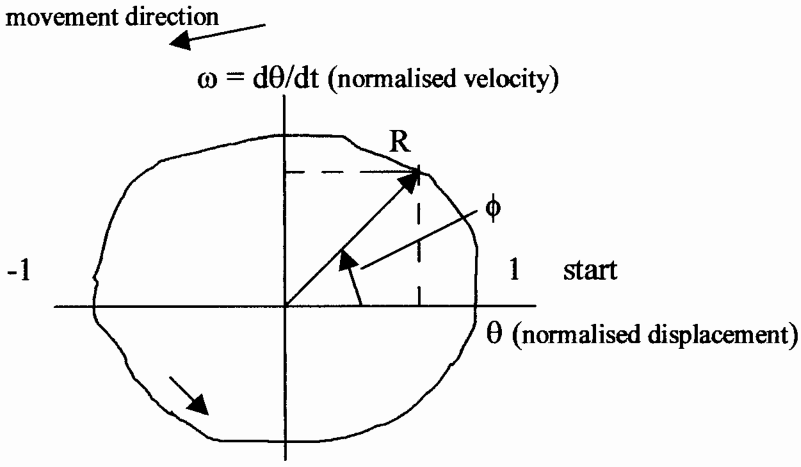


Figure 5. An example of phase plot with phase angle (φ) and radial amplitude (R). Time progress in anticlockwise direction around phase plot.

These data were derived from Kintrak 5.6 tabular analysis, stored in ASCII file format for processing with the customised program written in Unix/C^{++} languages. Joint angular position/displacement and velocity data were normalised and scaled to the interval (-1, 1) to calculate phase angles. Arctan function was applied to the tangens data (normalised velocity divided by normalised displacement) using Excel and Lotus Smart suite software phase angles were expressed in radians and converted into degrees.

Calculation of Relative Phase Angles

The extent of the phase lag between two joints at any point in time can be quantified as a 'relative phase' angle by subtracting the phase angle of one joint (proximal) from another (distal). The magnitude and temporal aspects of the proximal to distal co-ordination of pairs of limb joints within limb for example, left knee / left hip or bilaterally right shoulder / left shoulder, can be assessed by plotting a relative phase angle as a function of time. During the flexion phase of movement, the relative phase angles are positive, indicating that the proximal joints lead the distal joints, while in extension phase the relative phase angles are negative, quantifying the extent to which the proximal joints lag behind the distal during extension.

In this study, the relative phase angle was calculated to define changes in expert and novice interlimb co-ordination at different tempos. Continuous relative phases (CRP) were calculated at each point through the trial as the difference between the phase angle data of the observed pairs of joints. This calculation can be expressed by the equation: $\varnothing \text{ rel N} = \varnothing \text{jt1} - \varnothing \text{ jt2}$, where, for example, 'jt1', represents right hip joint, and 'jt2', refers to right knee joint.

Discrete relative phases (DRP) were observed in each cycle at the time of "knee-up" (i e, at maximum hip flexion) to obtain interjoint temporal co-ordination in the left and right limbs.

Relative phases angles were calculated as the difference between: 1) left hip and left knee phase angles; 2) right hip and right knee phase angles; and 3) left shoulder and right shoulder phase angles.

The continuous relative phase variable (CRP) for legs was calculated as the difference between hip and knee phase angles at each point throughout the observed stepping cycles. CRP_{legs} is therefore considered to be a measure of the co-ordination between the thigh and shank leg segments.

CRP for arms was calculated as the difference between left shoulder and right shoulder phase angles at each point throughout the cycles. CRP_{arms} is therefore a measure of the co-ordination between the left and right upper arm segments. Phase angles (ϕ) observed at the time of the 'knee-up' position (i e, maximum hip flexion) were considered in the relative phase calculation of the discrete relative phase (DRP).

Temporal variability within the pattern (VDRP) was obtained by calculating the standard deviation (SD) of DRP measures.

Calculation of Frequencies

Whilst the performance tempo was controlled and considered as the control parameter, the number of stepping cycles over the trial time (stepping cycle frequency) varied from subject to subject.

Stepping cycle frequency ($f = n/t$) was calculated as a ratio of the number of cycles within the trial (n) and the trial time (t). For the slow tempo condition the adopted stepping frequency was:

$$f = 6 \text{ cycles} / 60 \text{ seconds}$$

$$f = 1/10\ s^{-1}\ (\ .1\ \text{Hz})$$

Consequently a stepping cycle period ($T = 1/f$) would be 10 seconds.

For the fast tempo condition the adopted stepping cycle frequency was calculated as:

$$f = 6 \text{ cycles} / 20 \text{ seconds}$$

$$f = 3/10\ s^{-1}\ (\ .33\ \text{Hz})$$

$$T = 3.3 \text{ sec}$$

These measures were considered in calculation of phase angle:

$$\phi = \omega \times t$$

For one cycling period of time $t = T$, and $\phi = 360°$:

$$\omega = 360° / T \text{ (deg./ sec)}$$

Consequently, at any point of time (t_i) within the cycle for $0° \leq \phi_i \leq 360°$,

$$\omega_i = \phi_i / t_i.$$

When applying phase plane, ω is calculated as the projection of the radial amplitude 'R_i' on ω axis for the each point 'i' in the phase portrait $\omega_i = R_i \sin \phi_i$ (see Figure 5).

This calculation was performed as part of the normalisation procedure for phase angle calculation, applying the designed program (c.norm). In non-linear limit cycle behaviour 'ω' is considered as the measure of oscillating frequency.

Data Reduction

Slow and fast tempo trials only, were analysed because the first study was based on HKB model, which does not address preferred tempos. As the initial observation and video data showed no significant difference between medium and slow tempo, medium tempo was not considered for the analysis in this study. Thus, performance at fast and slow tempos will provide the distinction required making conclusions on tempo effects. The last five cycles in each trial of six cycles were analysed (five for each side of the body). These cycles were selected because it was believed that the movement pattern would be better adjusted to the performance rhythm by the end of the trial rather than at the first stepping cycle when adjustments to the step platform were being made. The time for the last five counted cycles in each trial was normalised and expressed in a percentage value, as 0-100.

Statistical Design

In order to compare variability in the kinematic parameters between skill level and conditions quantitatively, repeated measures ANOVA for Skill level (2) x Tempo (2) x Limb side (2) were performed on joint angular position of: hip (θH), knee (θK) and shoulder (θS) at the maximum hip flexion and knee-up position.

Within trial variability was calculated as discrete relative phase variability (VDRP) considering average relative phase standard deviation (SD) in the relevant joint angle position ('knee-up'). These values were observed on a continuous relative phase (CRP) curve, in each of five cycles, at the maximum hip flexion at 'knee-up' positions (discrete point). The pattern stability was analysed between skill level, condition and the body side (left or right) the applying repeated measures ANOVA on the relative phase average SD data for Skill level (2) x Tempo (2) x Side (2).

A follow-up test to control for the family wise TypeI error rate was performed on each independent variable (factor) separately applying one-way ANOVA. Where there was a non-significant interaction, a comparison of Marginal Means design was applied. For a significant interaction in repeated measures ANOVA design, Simple Effect and Simple Comparisons were tested as one-way ANOVA. In Simple Effect, per comparison alpha level was adjusted to the number of levels within the factor (for 2 levels: $\alpha_{PC} = 0.05/2$, that is, $\alpha_{PC} = 0.025$). If the simple effect was still significant after adjustments to the alpha level, the simple comparison was applied on $\alpha = 0.05$.

The next section provides the description of procedures and research design and analyses applied in Study 2.

Study 2

Sample

The participants for Study 2 included a further six female volunteers, novices from 17 to 43 years of age with the average age of 27 (two of 17, two of 21 and two 43 years old). These participants had no experience in the step aerobic task used in this experiment and did not participate in the first study.

Apparatus

The Ariel Performance Analysis System (APAS) was used to perform the three-dimensional analysis of kinematic. The digitising process of video images was performed automatically after the first two frames had been manually digitised. The last five cycles in a trial were digitised for the analysis. The beginning of the step-up onto the platform in the sixth cycle was the initial digitised frame. The last digitising frame was completed with the completion of the tenth cycle at the point when feet were on the ground in front of the step platform.

The computation stage of the analysis was performed after all camera views were digitised. The purpose of this stage was to compute the true three-dimensional image space co-ordinates of each participant's body joints from the relative two-dimensional digitised co-ordinates of each camera's view. Computation was performed using a 3D direct linear transformation algorithm. When the transformation was completed, a digital filter (4) smoothing function was performed on the image co-ordinates to remove small random digitising errors and to compute body joint positions / displacements and velocities. The display module was used to export and save calculated position/displacement and velocity data as a worksheet for further calculation. The normalisation procedure was performed on the above data applying a customised program, written specifically for this purpose.

Thirteen reflective ball markers of 3 cm diameter size were attached to the anatomical landmarks of each participant to define a 6-segment human body model consisting of head, left arm, right arm, left leg, right leg and torso. Three head markers were attached to a tight fitting skullcap: one marker on the vertex and one 5 cm above the left and the right ears. The remaining ten markers were attached directly to the skin at: a) the acromo-clavicular joints on the left and right shoulder; b) the radial head of the left and right elbow joints; c) the lateral condyle of the left and right femur; d) the lateral sides of the shoes below the lateral malleolus, and e) the left and right anterior-superior iliac spines (ASIS). As in Study 1, a 20-cm high step aerobic platform was used to perform the task. Kinematic variables were the same as in Study 1.

Procedure

Pre-test data were collected a day before participants began the task practice. Data were collected in a dance studio in the School of Biomedical and Sport Science, at Edith Cowan University, Joondalup Campus, in Perth W.A. All participants were tested under the same conditions, which included one trial at a self-paced tempo, without the music, and one trial at the fast music tempo fast tempo (144 bpm). The fast tempo conditions and the step-knee-up task were the same as described earlier for Study 1.

At the self-paced condition before and after the training, participants were instructed to perform the task at the most comfortable stepping speed or preferred tempo over the 30 seconds trial. Before training, at preferred tempo two participants completed 5.5 cycles while four participants managed to perform 6 cycles in 30 seconds. After training, five participants performed 6 cycles and one performed 5 cycles in the 30 seconds trial. Therefore the last five cycles were considered in the analysis for each of the six participants.

The adopted stepping frequency for the self paced condition before and after training, was calculated as a ratio of the number of cycles (n = 6) and the trial time (t = 30 sec.): f = 6 cycles / 30 seconds;

f = 1/5 s^{-1} (.2 Hz) and, consequently the period time T= 5 seconds ($T = f^{-1}$).

Data were collected using four Samsung 8mm video cameras. Two video cameras recorded the performance from the frontal view, one from the left and one from the right side (see Figure 6).

Before pre-test trials, the task was demonstrated to the participants by the researcher under the self paced tempo condition only. Throwing up the fluorescent ball marker in front of the participant indicated the start signal and enabled camera synchronisation. Data were collected for the six novice participants ten stepping cycles.

After the pre-test data collection, each participant was supplied with a step aerobic platform and an audio tape with only the fast tempo recorded. The duration of the music track was 5 minutes. Five consecutive sequences of 30 seconds of the fast music tempo (144 bpm) and 30 seconds of silence for the resting time were recorded. The training procedure, for which the program was provided, included one session daily for 12 consecutive days. A session consisted of five trials, with one trial involving 30 seconds of stepping. A resting time of 30 seconds was given between trials. The day after completion of the 12 training sessions, participants attended the post-test data collection. All participants were tested under the same conditions as for the pre-test.

The training sessions were conducted over the two weeks at the Fremantle Tennis Club hall, three times per week (Monday, Thursday and Friday afternoons) and on Tuesday, Wednesday and Saturday afternoons at participants' homes. All sessions were supervised by the examiner and practised only under the fast music tempo.

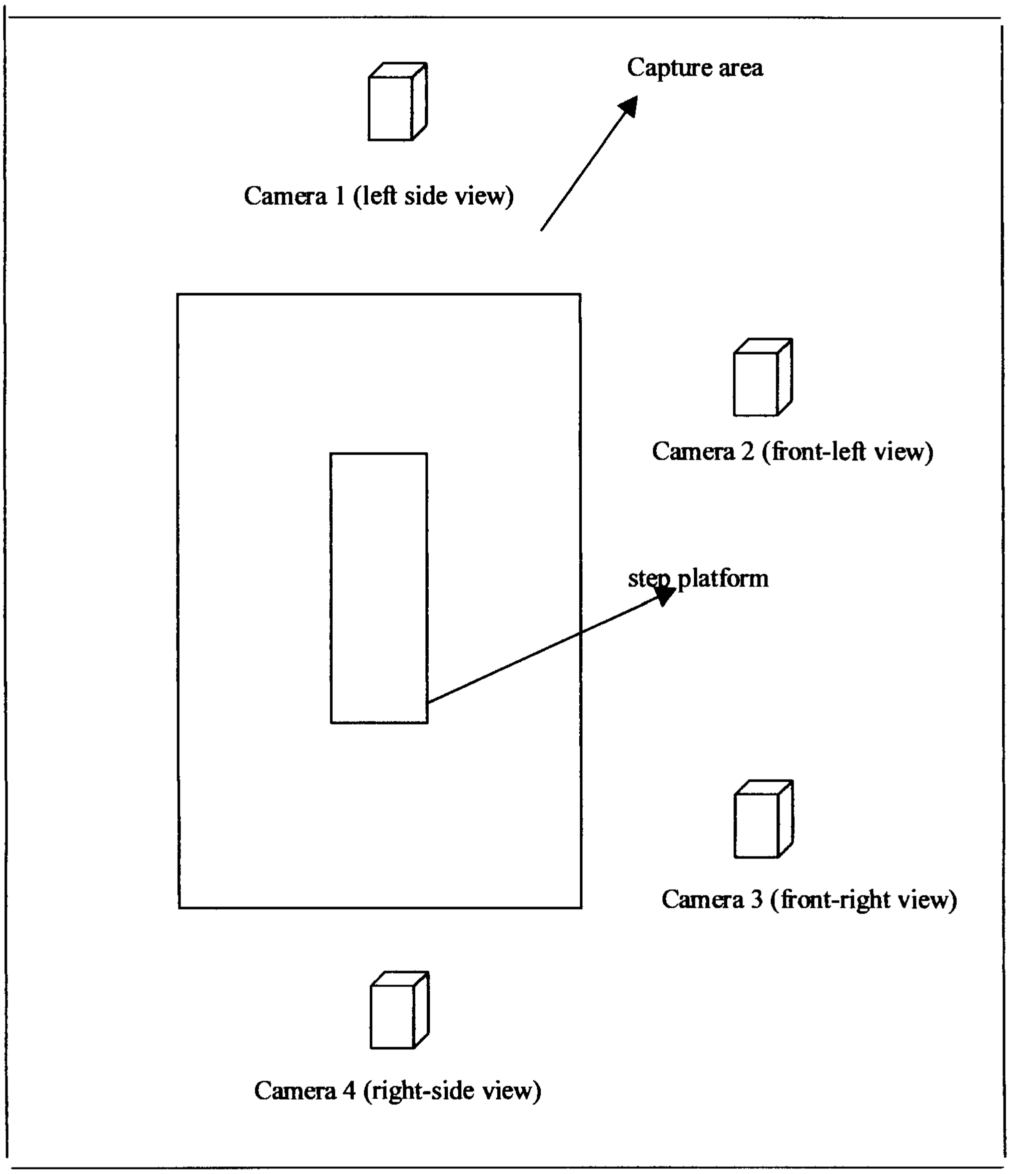


Figure 6. Camera set-up for Study 2

Statistical Design

The last five cycles in each condition were analysed with a cycle being defined as in Study 1 (see Procedure, and Statistical Design for Study 1).

In order to compare variability in kinematic parameters between the pre-test and post-test, conditions and limb sides quantitatively, repeated measures ANOVA for Test (2) x Tempo (2) x Limb side (2) were performed on the joint angular position of the variables hip (θH), knee (θK) and shoulder (θS), at the maximum hip flexion at 'knee-up' position.

Within a trial, variability was calculated as discrete relative phase variability (VDRP) considering average relative phase standard deviation (SD) at the relevant joint angle position ('knee-up'), as in Study 1. The variability of the pattern was analysed between tests (pre and post), between conditions (self-paced and fast) and body side (left and right) by applying repeated measures ANOVA on the relative phase SD data for Test (2) x Tempo (2) x Limb side (2) on the average standard deviation for the discrete relative phase. Follow up analysis of Paired sample t-Test comparison, with Bonfferoni adjustment, for 8 observed pairs, was further applied for the control of family wise type 1 error.

In both studies the conventional statistics design was preferred to directional statistics because the data were observed at the discrete points of time, at knee up position, not continuously during the trial and observed range of relative phase angles was less then 90° (for details see Burges-Limerick et. al 1993).

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results from Study 1 and Study 2 are presented and discussed.

Study 1

The first research question addressed the variability in interjoint co-ordination affected by different tempos in unskilled (novice) and skilled (expert) performance. The second question queried the extent to which unskilled and skilled participants adjust their movement co-ordination to cope with changes in performance conditions, while still achieving the criterion task. It was hypothesised that:

1. Discrete relative phase variability in inter-joint co-ordination patterns would be higher at a fast tempo than at a slow tempo in both novice and expert performances.

Relating to the second research question, it was further hypothesised that:

2. Novices would demonstrate higher variability than experts at both slow and fast tempos in attempting to achieve the performance task.

Kinematic Parameters

The kinematic parameter (θ) measures, observed at 'knee-up'position, are presented in Table 1 as a summary of descriptive statistical data for the left and right shoulder joint angle, and the left and right hip and knee joint angle.

GLM repeated measure ANOVA design with between subject factor: Group (2- expert, novice) and within subject factors: Tempo (2-slow, fast) x Side (2-left, right), was applied on shoulder, hip and knee joint angle variables (see Table 2). Repeated measure analysis was selected because it could provide the required control over fewer experimental units, such as human subjects. However, some difficulties also may be encountered with using repeated measurement procedures. These difficulties include the learning effect that may influence the interpretation of the results. Learning effect assumes that in relatively simple motor tasks such as stepping, the response may improve by repetition of the task independent of any treatment. To control for this effect, participants demonstrated only one trial of six cycles at each condition with five cycles being considered in the analysis.

Descriptive procedure results are presented in Table 1.

At the fast tempo, novices demonstrated higher variability (SD) in left hip angle θH (7.8°) and in the right knee angle θK (5.1°), when compared to θH (5.7°) and θK (2.4°) at slow tempo.

However, at the fast tempo, experts demonstrated higher variability (SD) in the right shoulder angle θS (5.7°) and in the right hip angle θH (8.0°), compared to θS (4.7°) and θH (5.5°) at the slow tempo.

Table 1.

Summary Results of Descriptive Statistics for Kinematic Parameters: Shoulder (θS), Hip (θH) and Knee (θK) Joint Angular Position (θ) at 'Knee-up' Position in Novice and Expert Performance.

Side:	LEFT		RIGHT	
Tempo:	Slow Mean (SD)	Fast Mean (SD)	Slow Mean (SD)	Fast Mean (SD)
Novice				
θS	13.0 (5.6)	7.3 (3.3)	12.6 (4.9)	9.1 (4.9)
θH	12.0 (5.7)	11.6 (7.8)	9.7 (3.9)	13.6 (4.0)
θK	11.1 (3.9)	9.1 (9.6)	7.3 (2.4)	9.6 (5.1)
Expert				
θS	16.1 (8.9)	12.8 (7.1)	12.5 (4.7)	12.5 (5.7)
θH	7.9 (2.8)	9.8 (2.8)	9.1 (5.5)	13.1 (8.0)
θK	16.5 (8.3)	17.7 (4.9)	15.0 (12.5)	16.3 (3.9)

Note: Mean data were calculated as the average of SD data. Mean and SD are presented in degrees.

In novices, higher variability (SD) was found in the right shoulder θS (4.9°) at slow tempo, in the left hip θH (7.8°; 5.7°) at fast tempo and at the slow tempo respectively, and in the left knee θK (9.6°) at the fast tempo. In experts, the variability in the right shoulder θS at slow tempo was 4.7°, in the left hip θH at fast and slow tempo variability was 2.8°, and in the left knee θK at fast tempo the variability was 3.9°.

Further analysis at the single joint level revealed no significant differences for tempo and side effect in both groups (see Table 2)

Table 2.

ANOVA Summary Table of Tempo, Side and Group Effects on Arm (θS), Hip (θH) and Knee (θK) Joints Angular Position (θ) at 'Knee-up' in Novice and Expert Performance

	Tempo x Side x Group Effects		Group Effects	
	F (1, 10)	p	F (1, 10)	p
SHOULDER (θS)	.034	.856	4.727	.023
HIP (θH)	.251	.627	5.550	.040
KNEE (θK)	.100	.759	.191	.672

* Significant at $p \leq .05$

At an alpha level ≤ .05 the group effect was statistically significant in shoulder joint angle (θS): F (1, 10) = 4.727, p = .023, and in the hip joint angle (θH): F (1, 10) = 5.550, p = .040. However, the conventional statistical analysis at single joint (segment) kinematic parameters may not be an adequate method for the interpretation of interjoint co-ordination. Therefore, it was necessary to apply another method, which could quantitatively describe multijoint co-ordination during complex actions more accurately (Burges-Limerik, Abernethy and Neal, 1993). This method involves the calculation of the phase angle and the relative phase angle.

Phase Plots

Quantification of the interjoint co-ordination was performed by using phase angle (φ), a phase plot analysis variable. In order to calculate phase angle and to minimise the influence of different movement amplitudes, phase plot variables (angular displacement and angular velocity) were normalised for each condition. These data were calculated to ascertain relative phase angles and therefore have not been analysed at the single joint level. Typical phase plots of shoulder, hip and knee joint movements in an exemplar novice participant, for one cycle at slow tempo are presented in Figure 7. Data points (i e, movement direction) and the time progress in these phase plots follow an anticlockwise direction.

The cycle starts at the point (-1; 0) or $\theta = \theta min$, for $\omega = 0$ and $\phi = 180^\circ$ (as for maximum hip flexion, the joint angle is minimum at 'knee-up' position). This is the first counted temporary stationary movement ($\omega = 0$) observed at the 'knee-up' position when the hip angle θH is at maximum flexion. The second stationary position ($\omega = 0$) and phase angle $\phi = 0^\circ$ is when the hip angle θH is at maximum extension ($\theta H = 178^\circ$; normalised corresponds to $\theta H = 0.8$). This is the case just before the start of the 'step-knee-up' action. The end of a cycle is at the second 'knee-up' position in the same limb.

As θH maximum flexion may differ from cycle to cycle in each condition for each participant, different joint angle positions would correspond to the normalised hip joint position $\theta H = -1$ and the phase angle $\phi = 180^\circ$. In the sample presented in Figure 7, the maximum hip flexion $\theta H = 96^\circ$ (- 0.95), which corresponds to $\phi = 180^\circ$ and angular velocity ($\omega = 0$) at that point. Shoulder and knee joint angle positions were observed in each cycle corresponding to this discrete phase angle measure. This discrete point in the movement was analysed in order to determine limb position in the space at that point, as the task itself may affect the whole body balance particularly at 'knee-up' position.

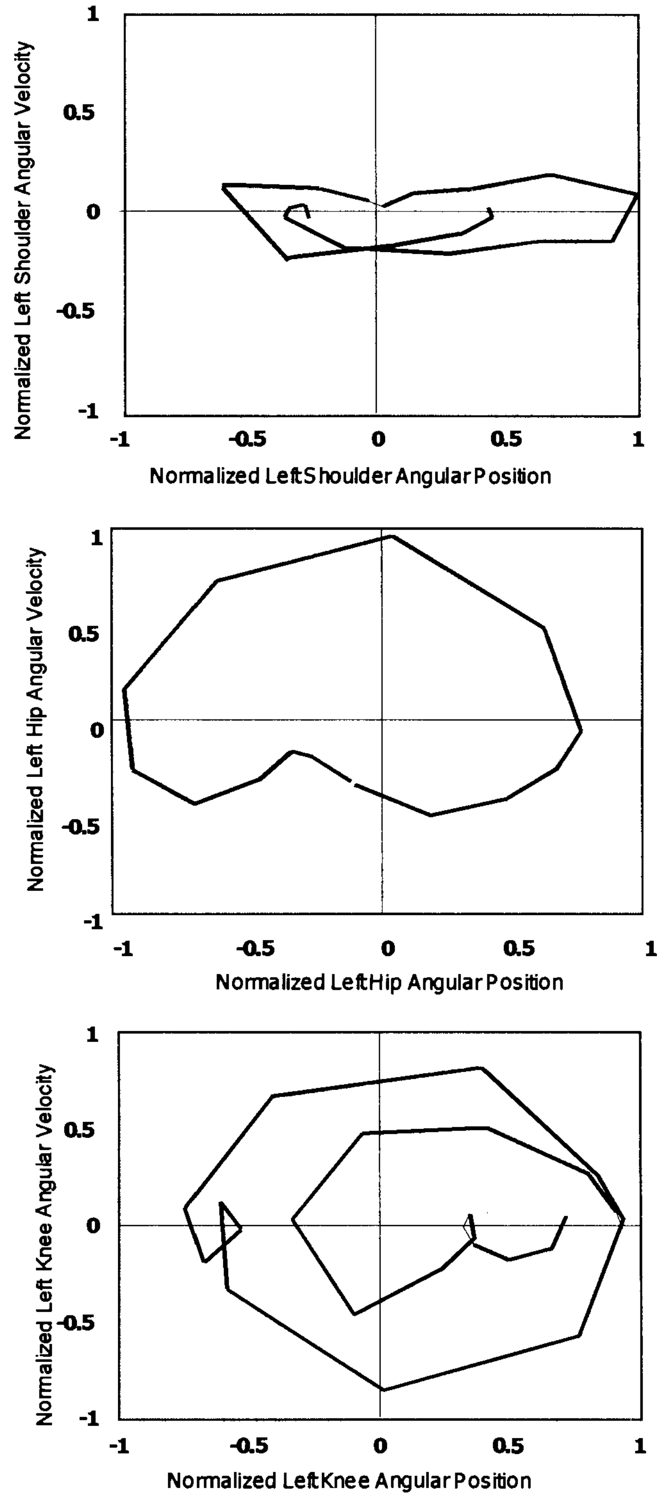


Figure 7. Left shoulder, hip and knee joint movements at slow tempo during a stepping cycle from a novice participant.

The relationship between left shoulder angular position and angular velocity was observed during one-stepping cycle at slow tempo in a novice participant. The range of normalised data (from -0.4 to 0.3) indicated that the movement velocity did not reach its maximum (+1) neither the minimum (-1) during this cycle. The left shoulder movement was slow in both directions reaching just about 30-40 % of the absolute value of normalised angular velocity (1.0) observed across the trial of six cycles.

Relative Phase Variability

Relative phase variability in selected joint pairs was calculated for five cycles in each trial as the standard deviation (SD) measure of the average relative phase observed at 'knee-up'position (see Table 3, and Figures 8 and 9). Repeated measures ANOVA summary results are provided in Tables 4 and 5. The first hypothesis stated that:

1. The temporal variability (variability in the discrete relative phase) in inter-joint co-ordination was higher at fast tempo than at slow tempo in both novices and experts.

The following results were revealed in relation to the above hypothesis:

At fast tempo, novices demonstrated higher relative phase variability (SD) in shoulder joint coupling (left side view) R Shoulder-L Shoulder (10.9°) and in the L Hip-L Knee coupling (6.4°), compared to the R Shoulder-L Shoulder (9.4°) and the L Hip-L Knee (4.3°) at slow tempo.

Similarly, at fast tempo, experts demonstrated higher variability (SD) in the R Shoulder-L Shoulder (6.7°), L Shoulder-R Shoulder (6.5°) and in the R Hip-R Knee (4.1°), when compared to the R Shoulder-L Shoulder (1.3°), the L Shoulder-R Shoulder (4.6°) and the R Hip-R Knee (1.8°) at slow tempo.

Further results are presented in relation to the second hypothesis which stated that:

2. Novices will demonstrate higher variability than experts at both slow and fast tempos in attempting to achieve the performance task.

Novices demonstrated higher variability (SD) than experts in the L Shoulder-R Shoulder coupling (9.4°; 10.9°) at slow and fast tempos respectively, in the L Shoulder-R Shoulder (5.3°) at slow tempo and in the R Hip-R Knee coupling (8.9°; 7.2°) at slow and fast tempos respectively. In experts, variability in shoulder joints observed from the left side view in the R Shoulder-L Shoulder coupling was 1.3° and 6.7° at slow and fast tempos respectively and, from the right side view in the L Shoulder-R Shoulder 4.6° at slow tempo. Variability in the R Hip-R Knee coupling was 1.8° and 4.1° at slow and fast tempos respectively (see Table 3, Figures 8 and 9).The relative phase angle in shoulders was observed separately for left and right sides. From the left side view, the relative phase in shoulder movements was calculated as a difference between the right and the left shoulder joint angle. In natural activities (i e, walking and stepping) the right shoulder follows the left knee-up movement by moving forward, while the left arm swings backwards. In other words, shoulders perform an anti-phase movement.

Similarly, from the right side view, the relative phase in the shoulder movements was calculated as the difference between the left shoulder and the right shoulder joint angle, assuming that the left arm naturally follows the right knee-up movement by moving forward. However, participants were instructed to move both arms forward and backward together (or in-phase) while stepping up and down on the platform.

The movement direction was indicated by the values of the mean relative phase data. The phase angle of the forward moving arm was considered positive ($+\phi$) and the phase angle of the movement in the opposite direction was calculated as a negative angle ($-\phi$). If both hands moved in a different direction, for example, the left shoulder phase angle $\phi ls = +39°$ and the right shoulder phase angle $\phi rs = -28°$ as in novices at fast tempo (see Table 3), then the relative phase ($RP_{LS\text{-}RS}$) in the L Shoulder–R Shoulder coupling was calculated:

$$RP_{LS\text{-}RS} = \phi ls - \phi rs = 33° - (-30°) = 63°$$

Similarly, for $\phi ls = +55.2°$, and $\phi rs = +51°$, ($RP_{LS\text{-}RS}$) in L Shoulder–R Shoulder coupling as in novices at slow tempo, the relative phase was calculated:

$$RP_{LS\text{-}RS} = \phi ls - \phi rs = +55.6° - 51°) = 4.6°$$

Consequently, when both phase angles were equal, relative phase would result in zero and the movement would be ideally in-phase. When the relative phase is positive, in the above calculation the left shoulder joint, leads the right shoulder joint. Accordingly, a negative relative phase would indicate that the proximal joint is behind the distal joint.

Similarly, the relative phase in the hip and knee joint angles may be an indication of the lower leg kick at the 'knee-up'position. This is the case when the distal joint or knee, leads the proximal joint or hip, thus, the relative phase is negative. Further comments are provided in the discussion section. Mean relative phase data are presented in Table 3, and Figures 10 and 11.

Table 3.

Mean Discrete Relative Phase Angle (DRP) and Average Standard Deviation (SD) at 'Knee-up' for Selective Interjoint Coupling in Novice and Expert Performance.

Side:	Left		Right	
	(observed at L Hip max. flexion)		(observed at R Hip max. flexion)	
Tempo:	SLOW	FAST	SLOW	FAST
	Mean SD	Mean SD	Mean SD	Mean SD
Interjoint Coupling: Shoulders				
	R Shoulder-L Shoulder		L Shoulder-R Shoulder	
Novice	4.9 (9.4)	57.3 (10.9)	4.6 (5.3)	63.2 (3.5)
Expert	5.2 (1.3)	4.2 (6.7)	4.9 (4.6)	3.7 (6.5)
Interjoint Coupling: Legs				
	L Hip- LKnee		R Hip-RKnee	
Novice	25.5 (4.3)	29.8 (6.4)	26.8 (8.9)	20.4 (7.2)
Expert	29.4 (9.5)	20.2 (8.8)	10.9 (1.8)	9.5 (4.1)

Note: Mean and SD are presented in degrees.

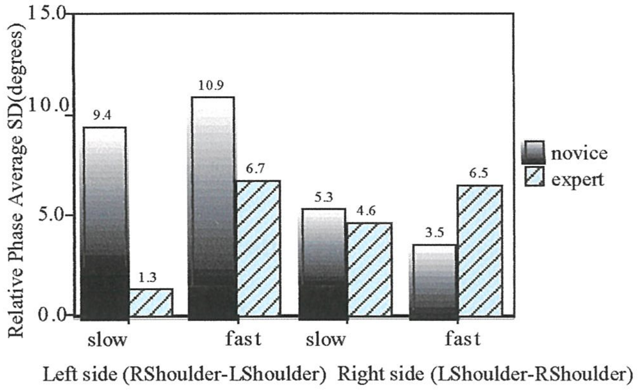


Figure 8. Average standard deviation (SD) in discrete relative phase (VDRP) at left 'knee-up' for the R Shoulder-L Shoulder and at right 'knee-up' (right side view) for the L Shoulder- R Shoulder interjoint coupling at slow and fast tempos in novices and experts.

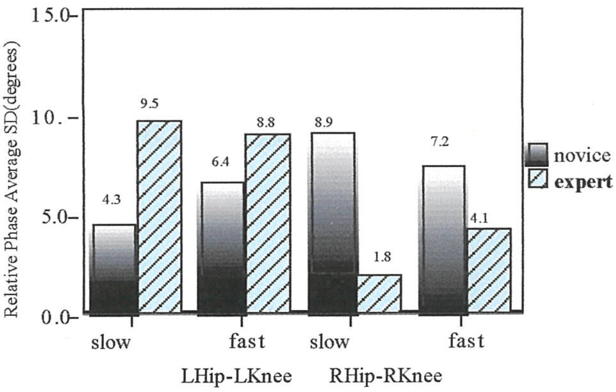


Figure 9. Average standard deviation (SD) in discrete relative phase (VDRP) at left 'knee-up' (left side view) for the L Hip – L Knee and at right 'knee-up' for the R Hip – R Knee interjoint coupling at slow and fast tempos in novices and experts.

At alpha level ≤ .05, the Group effect was statistically significant, in Hip-Knee interjoint coupling, F (1,10) = 12.788, p = .005, as well as the Tempo x Side interaction effect, F (1,10) = 8.908, p = .01. Significant Tempo x Side interaction was also revealed in Shoulder–Shoulder interjoint coupling, F (1,10) = 12.521, p = .005 (see Table 4).

Follow-up statistical tests results for Tempo and Side effect within each group at alpha level ≤ .025 are presented in Table 5.

Table 4.

ANOVA Summary Table of Tempo, Side and Group Effects on Discrete Relative Phase Angle Variability at 'Knee-up' for Selective Interjoint Coupling in Novice and Expert Performance.

	Tempo x Side x Group Interaction		Group Effects	
	F (1, 10)	p	F (1, 10)	p
Interjoint Coupling:				
Shoulder –Shoulder	12.521	(.005)	2.073	(.181)
Hip-Knee	9.908	(.01)	12.788	(.005)

* Significant at p ≤ .05

Table 5.

Results of the Follow-up Test for Simple Effect of Tempo and Side Within Novices and Experts

Group:		Novice		Expert	
		F (1, 5)	p	F (1, 5)	p
Interjoint Coupling:					
Shoulder-Shoulder					
	Tempo	.365	.572	.804	.411
	Side	6.570	.050	62.329	.001
Hip-Knee					
	Tempo	.101	.764	2.726	.160
	Side	2.117	.205	35.965	.002

* Significant at p ≤ .025

At the adjusted alpha level ≤ .025, the effect of side (left vs. right) was statistically significant in leg interjoint couplings, Hip-Knee, F (1,10) = 35.965, p = .002, and Shoulder-Shoulder couplings, F (1,10) = 8.908, p = .01, in experts.

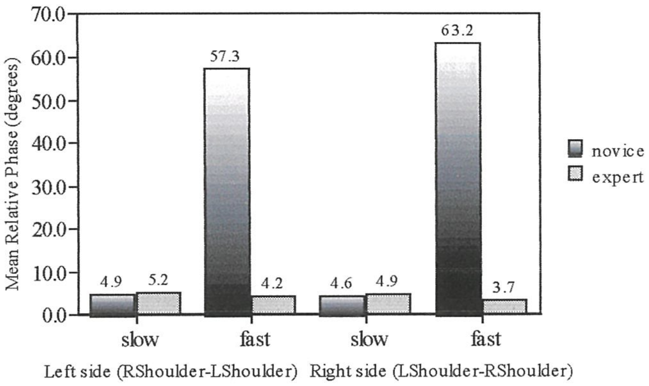


Figure 10. Average discrete relative phase (DRP) at left 'knee-up' (left side view) for the R Shoulder-L Shoulder and at right 'knee-up' (right side view) for the L Shoulder- R Shoulder interjoint coupling at slow and fast tempos in novices and experts.

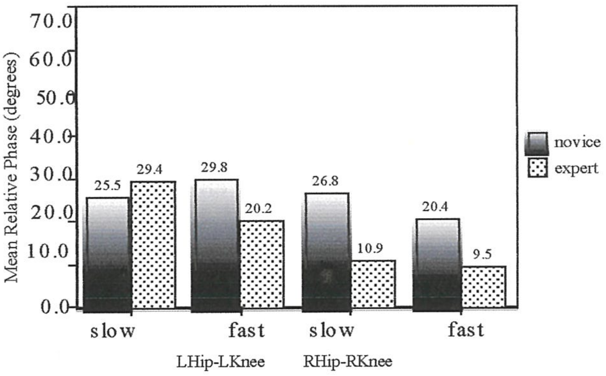


Figure 11. Average discrete relative phase (DRP) at left 'knee-up' in the L Hip-L Knee and at right 'knee-up' in the R Hip-R Knee interjoint coupling at slow and fast tempos in novices and experts.

Discussion

Results of the first study demonstrate that interjoint coupling in experts was more consistent (less variable) at both slow and fast tempos, in all limbs except in the left leg, when compared to novices. While Tempo and Side effects in novices were not significant, further statistical analysis (follow–up tests) in experts revealed a significant Side effect on both the shoulder joint couplings and hip-knee joint. Higher variability was found in the left leg interjoint coupling (LHip-LKnee) at both tempos, compared to the right leg. In arms, however, higher variability, was found only at the slow tempo for the right side observation of the L Shoulder-R Shoulder as compared to the left side.

These results show that in experts homolateral hip-knee interjoint coupling strength is a function of the body side, showing less resistance to both tempo perturbations in the left leg compared to the right leg. In contrast, heterolateral shoulder-shoulder interjoint coupling strength observed from the left side was more stable, but only at slow tempo, when compared to the right side.

In the current study, average discrete relative phase data were calculated as positive in all-interjoint couplings. These results therefore, indicate the lead of the proximal joint (or segment).

This was observed in particular, in novices' shoulder joint couplings at fast tempo (57.3°, 63.2°), left and right side view respectively, as compared to slow tempo (4.9°, 4.6°). These data reveal that in novices at fast tempo, at 'knee-up position', the proximal joint (or the upper arm segment) was in the lead.

In other words, arm movement direction initially specified by the task as the simultaneous swing forward (iso directional or in-phase movement) shifted to a movement of each arm in the opposite direction (anti-phase). In general these findings highlight the nature of difficulties that human performers experience when learning to produce incompatible spatiotemporal pattern simultaneously. Namely, in walking, running and stepping tasks, arms naturally swing in an anti-phase direction which is, therefore, a compatible spatiotemporal pattern.

These changes are evidence of spontaneous self-organisation in movement co-ordination as has been described for a number of other, open, complex systems (Haken, 1977, 1983). However, in terms of HKB model predictions, in-phase co-ordination was found to be a less stable mode at higher frequencies resulting in phase transitions to the anti phase-mode. This was particularly the case in the experiments where initial movements were performed in anti-phase direction.

In the current study, arm movements started in the in-phase direction, but at the fast tempo when the oscillating frequency increased, novices shifted their arm movements to the anti-phase direction. Therefore, it was revealed that in-phase stability is also sensitive to rising frequency. In addition, the L Shoulder-R Shoulder interjoint co-ordination (right side view) at the anti-phase mode (at fast tempo in novices SD = 3.5) is the most stable compared to other conditions. However, these findings may not be generalised, as they refer only to novices and one interjoint coupling. The significant side effect which was revealed in experts' arm movements, was the result of higher variability in the right side view of Shoulder-Shoulder coupling at slow tempo compared to left side.

Whitall, Forester and Song (1999) have observed similar unexpected findings. Their study revealed that preferred frequency finger tapping tended to have higher frequencies and to be less stable for in-phase than for anti-phase tasks. In terms of HKB model predictions, however, the in-phase co-ordination mode is more stable.

In addition, these observations support Smethurst and Carson's (2001) findings that the anti-phase pattern remained more stable than the practised in-phase pattern throughout the trial. The results also support the finding by Lee et al. (1995) who advocates that during learning the natural co-ordination tendencies of the system are, contrary to the theoretical predictions, suppressed, but not completely destabilised.

The stability differences observed in different joint–couplings and at different tempos in the stepping task may be the result of the stepping task itself. Experts, for example, may demonstrate a more flexible movement pattern, while novices in attempting to cope with the tempo spontaneously performed more compatible in-phase arm movement.

Observations of interjoint co-ordination in hip-knee couplings revealed that the thigh segment (the proximal joint) was in the lead with reference to the shank (the distal joint) according to the positive values of average relative phase data in novices and experts in both tempos. Thus, neither experts nor novices demonstrated a kicking action at the 'knee-up position'. The significant side effect which was revealed in the experts' leg movements performance was the result of a higher variability in left leg interjoint coupling compared to the right leg.

Furthermore, as frequency related measures refer to an event occurring in an individual component, not between components, it is expected that one segment (the shank or the thigh) would move faster than the other would. Frequency competition or detuning term should be considered in the analysis of such interjoint couplings. This effect can be classified by HKB equation:

$$d\phi/dt = \Delta\omega - a \sin(\phi) - 2b \sin(2\phi) - c \cos(\phi) - 2d \cos(2\phi),$$

where ϕ represents the relative phase, $\Delta\omega$ is the detuning frequency, 'b/c' is the frequency threshold parameter, 'c' is the coefficient relevant to the extent of the fixed point shift and 'd' is the asymmetric coupling term. A stable frequency difference between oscillating components (segments in limb movements) would be obtained for $d\phi/dt = 0$.

A general detuning term '$\Delta\omega$' may represent an asymmetry existing at neurophysiological, but not mechanical, level within the system. Therefore, '$\Delta\omega$' can be ascribed to neurophysiological limits at near maximal cyclical frequency rates.

Muscle relaxation time relating to agonist-antagonist activation, in repetitive actions imposes a limited constraint. These constraints may also be different for dominant and non-dominant limbs. This was revealed as a 'side' effect in the stepping task performance.

Differences in co-ordination dynamics may result in certain co-ordination tasks from a particular class of constraints termed 'anchoring'. Anchor points are defined as instances within the cycle, which usually determine the time and/or the position of joint or segment reversal, such as observed at the 'knee-up position'. The information that enhances segment reversals is considered to be intrinsic. This information includes morphological constraints, such as the limits of range of motion of a joint with respect to task constraints, proprioceptive feedback (via muscle spindles or joint mechanoreceptors) and the extent of cortical connections serving the agonist muscles (Carson, 1995; Byblow, Choa & Goodman, 1995). Differences in either any or all of these factors affect the co-ordination at the anchoring point. This was particularly relevant to the observed differences in co-ordination dynamics at the discrete point such as the 'knee-up' position in the stepping task.

Listening to music while performing the task may shift attention away from intrinsic anchoring information and towards auditory cues. As a result, an auditory cue may increase the focus on the timing, producing more stable coupling. In fact it may be easier to perform the task when enhanced by music. This may be the reason why the variability in certain interjoint couplings, either in experts or in novices, decreased at fast tempo when compared to slow tempo (see Table 3).

It appears that the processes underlying interjoint coupling stability are informational in nature. Accordingly, a complete theory of informational interactions is a challenge to the dynamically based accounts of behaviour, as reported earlier by Schmidt, Carello and Turvey (1990).

Study 2

This section includes the results and discussion from Study 2 in which the effect of 12 training sessions at the fast tempo was observed in interjoint co-ordination variability.

The research question addressed in Study 2 considered the effect of practice under the fast tempo on interjoint co-ordination stability in the former intrinsic dynamics (self-paced tempo performance).

It was hypothesised that the variability in interjoint co-ordination at self-paced performance after training would decrease when compared to the self-paced condition before training.

The effect of practice on the coupling strength between selected joints was investigated by comparing discrete relative phase variability measure standard deviation (VDRP) in self-paced and fast tempos before and after the training.

The transfer effect from the practised pattern to the pattern performed at the preferred (self-paced) tempo was also observed. The transfer effect was measured by comparing the self-paced to fast tempo performance after training at fast tempo.

Kinematic Parameters

Descriptive statistical results of the joint angle position (θ), measured at 'knee-up'position in the left and right shoulder joint angle and in the left and right hip and knee joint angle, are presented in Tables 6.

The descriptive procedure results reveal the following differences between kinematic parameters:

After training, a decrease in variability (SD) at self-paced tempo was found only in left knee angle θK (6.0°) when compared to fast tempo θK (9.6°).

Also, after training, the self-paced tempo variability (SD) increased in the left and right shoulder angle θS (5.3°; 6.9°) respectively, when compared to θS (4.7°; 4.1°) before training.

GLM repeated measures design with factors: Test (2 levels: pre-test and post-test), Tempo (2 levels: slow and fast) and Side (2 levels: left and right), was applied on shoulder, hip and knee joint angle variables. At alpha level $p \leq .05$, summary results revealed significant Tempo x Side x Test interaction effect, $F(1, 5) = 11.676$, $p = .007$, (see Table 7). Although these results appear significant, they are not discussed further because the observation of kinematic parameters at a single joint may not be relevant in analysing variability of interjoint co-ordination.

Table 6.

Mean and Standard Deviation calculated for Kinematic Parameters: Shoulder (θS), Hip (θH) and Knee (θK) Joints Angular Position (θ) at 'Knee-up' in Pre-test and Post-test.

Side:	LEFT		RIGHT	
Tempo:	Self-paced Mean (SD)	Fast Mean (SD)	Self-paced Mean (SD)	Fast Mean (SD)
Pre-test				
θS	11.3 (4.7)	10.0 (5.5)	8.8 (4.1)	8.1 (3.5)
θH	13.5 (8.6)	16.1 (8.2)	10.3 (8.1)	8.2 (8.4)
θK	27.5 (12.5)	15.6 (9.2)	19.8 (8.2)	13.5 (3.9)
Post-test				
θS	11.3 (5.3)	8.5 (4.2)	11.3 (6.9)	13.6 (5.4)
θH	10.7 (5.4)	10.5 (5.2)	11.2 (7.8)	16.0 (4.2)
θK	14.3 (6.0)	10.1 (9.6)	18.0 (7.5)	14.1 (5.9)

Note: Mean and SD data are presented in degrees.

Table 7.

ANOVA Summary Table of Tempo, Side and Test (pre-post) Effects on Shoulder (θS), Hip (θH) and Knee (θK) Joints Angular Position (θ) at 'Knee-up'.

	Tempo x Side x Test Effects	
	F (1, 5)	p
ARM (θS)	.344	.571
HIP (θH)	11.676	.007
LEG (θK)	.656	.437

* Significant at p ≤ .05

Relative Phase Variability

Results are presented in relation to the proposed hypothesis, which stated that, "the variability in interjoint co-ordination at self-paced performance after training would decrease when compared to the self-paced condition before training".

At self-paced tempo after training relative phase variability (SD) increased in the R Shoulder-L Shoulder, left side view, (9.6°), and in the right leg interjoint coupling defined by R Hip-R Knee (16.3°) when compared to self-paced tempo before training: R Shoulder-L Shoulder (2.7°) and R Hip-R Knee (6.7°). Variability at self-paced tempo in other interjoint couplings decreased in the post-test.

Table 8.

Mean Discrete Relative Phase Angle (DRP) and Average Standard Deviation (SD) at 'Knee-up' for Selective Interjoint Coupling in Pre-test and Post-test Performance.

Side:	LEFT (observed at L Hip max. flexion)		RIGHT (observed at R Hip max. flexion)	
Tempo:	Self-paced Mean (SD)	Fast Mean (SD)	Self-paced Mean (SD)	Fast Mean (SD)
Interjoint Coupling: Shoulders				
	R Shoulder- L Shoulder		L Shoulder- R Shoulder	
Pre-test	7.7 (2.7)	52.7 (12.7)	9.9 (11.3)	57.3 (11.0)
Post-test	46.8 (9.6)	48.2 (11.1)	38.7 (6.0)	50.9 (10.4)
Interjoint Coupling: Legs				
	L Hip- LKnee		R Hip-RKnee	
Pre-test	41.4 (25.8)	19.0 (20.8)	29.5 (6.7)	28.3 (16.6)
Post-test	38.1 (24.4)	37.0 (12.2)	32.7 (16.3)	32.2 (12.0)

Note: Mean and SD are presented in degrees

After training, the variability at self-paced tempo in the left and right leg interjoint coupling (24.4°; 16.3°) respectively, was higher, compared to fast tempo (16.3°; 12.0°) respectively. However after training, the variability in the shoulder joint couplings was higher at fast tempo: R Shoulder-L Shoulder (11.1°), L Shoulder-R Shoulder (10.4°) when compared to self-paced tempo R Shoulder-L Shoulder (9.6°), L Shoulder-R Shoulder (6.0°). Results are presented in Table 8, and Figures 12 and 13.

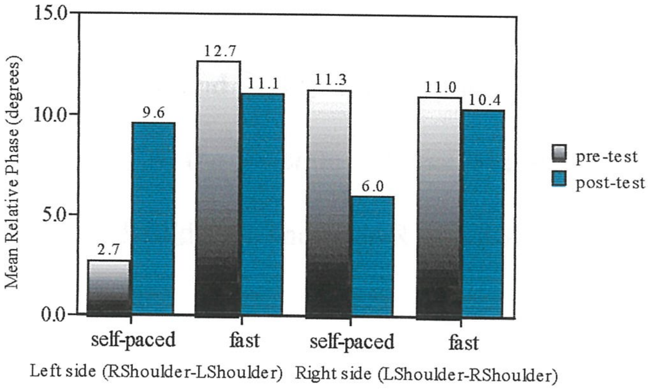


Figure 12. Average discrete relative phase (DRP) at left 'knee-up' (left side view) for the R Shoulder-L Shoulder and at right 'knee-up' (right side view) for the L Shoulder- R Shoulder interjoint coupling at pre-test and post-test.

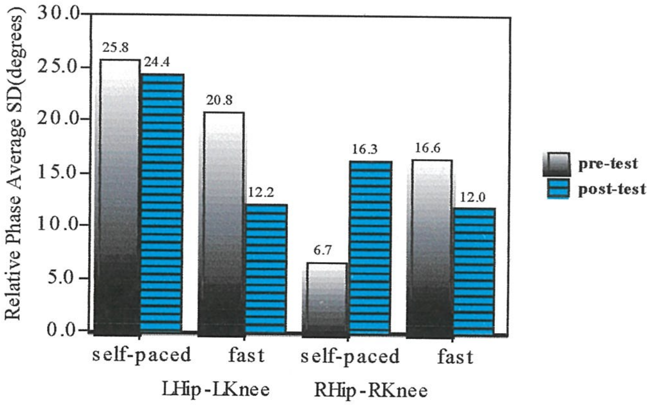


Figure 13. Average discrete relative phase (DRP) at left 'knee-up' in the L Hip-L Knee and at right 'knee-up' in the R Hip-R Knee interjoint coupling at pre-test and post-test.

GLM repeated measure design with between subject factor: Test (2 levels: pre – test and post-test) and within subject factors: Tempo (2 levels: slow and fast) x Side (2 levels: left and right) was applied on average standard deviation (SD) measures of the discrete relative phase in joint coupling variables: R Shoulder-L Shoulder, L Shoulder-R Shoulder, R Hip-R Knee and L Hip-L Knee (see Table 9).

Table 9.

ANOVA Summary Table of Tempo, Side and Test (pre-post) Effects on Relative Phase Angle Variability (SD) at 'Knee-up' for Selective Interjoint Coupling.

	Tempo x Side x Test Interaction	
	F (1, 5)	p
Interjoint Coupling:		
Shoulder –Shoulder	9.798	(.026)
Hip-Knee	1.066	(.349)

* Significant at $p \leq .05$

At alpha level ≤ .05, significant Tempo x Side x Test interaction was found in Shoulder–Shoulder interjoint coupling, F (1, 5) = 9.798, $p = .026$ (see Table 9). Plots of estimated marginal means are presented in Appendices.

Follow up analysis of paired sample t-Test comparison, at adjusted alpha level ($p = .05 \div 8$), $p \leq .0062$, showed no significant changes after training in all of 8 observed paired variables (see Table 10).

Table 10.

Results of the Follow-up Paired samples t-Test in selected Interjoint Couplings at Pre-Post Test.

Side: left (L) Tempo: self - paced (sp) Test: pre-1
right (R) fast(f) post-2

Interjoint Coupling	t	df(5)	Sig.(2-tailed)
Hip/Knee/L/ sp 1- Hip/Knee/ L / sp 2	-1.282		.256
Hip/Knee/L /f 1 - Hip/Knee/L/f 2	.324		.759
Hip/Knee/R/sp 1 - Hip/Knee/R/sp 2	- .960		.381
Hip/Knee/R /f 1 - Hip/Knee/R/f 2	- .300		.977
Shld/Shld/L/sp 1- Shld/Shld/L/sp 2	-2.145		.001
Shld/Shld/L/f 1- Shld/Shld/L/f 2	.891		.414
Shld/Shld/R/sp 1- Shld/Shld/R/sp 2	1.904		.115
Shld/Shld/R/f 1- Shld/Shld/R/f 2	.272		.796

* Significance calculated at $p \leq .05$, ** Adjusted Sign. $p \leq .0062$,

Results show that training under the fast tempo did not significantly affect overall performance at the self-paced or the fast tempo. However, it was noted that before training, at the self-paced condition, the right side view, Shoulder-Shoulder interjoint coupling was less stable and indicated higher variability (11.3°) when compared to left side (2.7°), (see Figure 12).

A decrease in SD at self-paced tempo after training (16.3°) indicated that the right Hip-Knee interjoint coupling was more stable than the left Hip-Knee interjoint coupling at self-paced tempo (24.4°). By comparison, at fast tempo there was a little difference between the right (12.2°) and the left (12.0°) Hip-Knee interjoint couplings (see Figure 13).

Discussion

Results of the second study showed that training at fast tempo did not significantly affect the overall performance at self-paced tempo after training. However, changes in interjoint coupling stability were observed with the self-paced condition after training with reference to the body side when compared to the same condition before training. It was hypothesised that at self-paced condition after training a decrease in interjoint co-ordination variability would be demonstrated when compared to the self-paced condition before training. As a decrease in variability at self-paced condition after training was noted only in the arm movements (right side) the hypothesis can be only partly accepted (see Figure 12).

As noted in the methods chapter, the preferred stepping cycle frequency after training, was relatively similar to before training (.02 Hz). This means that the stepping speed at preferred tempo after training was not affected by training under the fast tempo.

In their research, Kugler and Turvey (1987) found that the most stable co-ordination was demonstrated in the rhythmic pattern produced at the preferred frequency. The above findings, however, do not support Kugler and Turvey's observations in interjoint co-ordination stability in the stepping task. As the HKB model does not address preferred frequencies, it may not be suitable for analysing co-ordination responses at the preferred condition in this study.

Nevertheless, what causes variability in intrinsic dynamics could be considered by various intrinsic sources of timing information such as cortical drive. In addition, variability also could originate from external constraints such as the metronome, the music tempo and other environmental information (Newell, 1986).

According to Schoner, Haken and Kelso (1986), co-ordination of movement is governed by a dynamic control structure. Its evolution can be described by the following function: $F\ (x_i,\ t,\ c_i,\ \S) = 0$, where '$x_i$' represents state space properties, 't' is time, 'c_i' is the control parameter that is manipulated to change the topology and, hence, the stability of the system dynamics. The stochastic noise process is represented by §. The optimal organisation of these variables is a function of the individuals' skill and ability to reduce instability to a minimum. From the Dynamic Systems Theory perspective, co-ordination can be defined as the setting up of the above function. Values assigned to variables would provide optimisation of variables that would reduce instability to a minimum (Newell, 1985). The optimisation criteria are derived from a thorough understanding of the interaction of constraints from the system, environment and task. These constraints determine the optimal co-ordination and control, which is specific for each individual in a given activity.

The functioning of a dynamic control structure and its optimisation over repeated actions are two separate processes. From a behavioural perspective, the relative motion and scaling characteristics of body and limb kinematics may operationally define the distinction between the co-ordination and control. This distinction is particularly important in the acquisition of complex motor tasks.

The optimal parameterisation of the co-ordination function, which refers to the skill, may be difficult to perform due to limited understanding of optimisation criteria in physical activities and the need to involve of measures other than kinematic. Indeed, the optimal parameterisation of the co-ordination function would require a certain set of phase relationships between the cyclical characteristics of different systems. Therefore, the examination of the manner in which the phase relationships in human locomotor activities, such as a stepping task, change with practice may require more specific limitations to the task description. These limitations should include the concept of efficiency, which is central to the optimal parameterisation of the co-ordination function. Efficiency is normally defined as the ratio of work done to energy expended and is reflected in work and energy related variables. In the current study, such variables were not proposed, therefore detailed discussion is not possible. However, in the observation of training effect on changes in interjoint coupling strength, the individual differences in efficiency might be considered as contributing to the performance variability or stability. The learning effect should be addressed, therefore, with respect to external and internal factors as well as the amount of practice.

Schöner and Kelso (1988) point out that learning and adaptation processes occur in a time period that is larger than the time required for adjusting to environmental conditions. Changes, however, may be revealed slowly, as the process to adapt is longer. Furthermore, the ability of a biological system to adjust its motor behaviour to environmental conditions is one form of flexibility and it is defined by individuals' openness to information. This means that individuals may have different abilities in perceiving the same information and this would result in different outcomes and thus different coupling strengths.

From the Dynamic Systems Theory, learning is not only an improvement in accuracy and consistency, but also involves a perturbation to stable behaviour (Lee et al. 1995). The destabilisation of the existing behaviour results in a temporary change in co-ordination stability. Thus, even if the participants in the current study had been capable of adapting to fast tempo stepping cycle frequency (.033 Hz) over the relatively short training period (12 sessions training), their performance at self-paced condition might yet strongly resist changes, at least in some interjoint couplings. These changes are considered in Dynamic Systems Theory as the effect of learning on intrinsic dynamics.

Observations of training effects on intrinsic dynamics from the current study support Zanone and Kelso's (1992) statement that learning involves changes of co-ordination dynamics which may result in a decrease or an increase in co-ordination coupling strength.

Learning effects can also be interpreted with motor learning transfer principles. Motor learning transfer considers the application of learning achieved in one task to the performance of either some other task or the same task performed in another settings (Schmidt, 1982). Schmidt and Young (1987) argue that intrinsic pattern behaviour might remain unchanged when a new task is learned. In motor learning, the above phenomena is attributed to the positive transfer of learning, which occurs when fundamental parts of the task are not changed if the task is performed under different conditions, or if the new task is learned. Then invariant characteristics of the task are common to the pattern behaviour in all conditions. However, if the intrinsic dynamics are changed because of practise or experience in another skill or condition, this is attributed to the negative transfer of learning. In the current study, the intrinsic dynamics in interjoint co-ordination remained relatively unchanged after the task was practised under different conditions, so the positive transfer of learning was supported.

The discussion of the findings from both studies with respect to the proposed hypotheses is considered in the next chapter.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

Summary

`The theoretical framework used in this study was the Dynamic Systems Theory. Two key issues were tested: a) changes in interjoint co-ordination stability in novices and experts, when the performance was affected by changes in the control parameter, ie, the music tempo, and b) the effects of training on the intrinsic pattern of interlimb co-ordination. The task was a step aerobic task, which involved the whole body in rhythmical movements under different tempo conditions. In the first study the effects of slow and fast tempos on novice and expert performances were investigated. Effects of fast tempo training on intrinsic dynamics were observed in the second study. The following research questions were proposed in the first study:

1. How is the interjoint co-ordination pattern stability affected by different performance tempos in novices and in experts?
2. To what extent do unskilled and skilled participants adjust their movement co-ordination to cope with changes in performance conditions but yet still achieve the criterion task?

Accordingly, it was hypothesised firstly that the temporal variability (ie, variability in discrete relative phase) in inter-joint co-ordination would be higher at fast tempo than at slow tempo in both, novices and experts. Secondly, it was stated that novices would demonstrate a higher variability than experts at both slow and fast tempos in attempting to achieve the performance task.

In the first study tempo effects on interjoint co-ordination coupling strength was observed in whole body rhythmical task for experts and novices. The results indicated that:

a) Interjoint coupling for experts was more consistent (less variable) at both slow and fast tempos, in all limbs except in the left leg, when compared to novices.
b) The Tempo and Side effects in novices were not significant.
c) In the experts a significant Side effect was found in the shoulder joint coupling and hip-knee joint coupling. Higher variability was found in the left leg interjoint coupling (L Hip-L Knee) at both tempos, when compared to the right leg. In arms, higher variability was found only at the slow tempo for the right side observation in the L Shoulder-R Shoulder coupling as compared to left side.
d) The arm movement direction initially specified as in-phase movement, shifted to anti-phase at fast tempo (higher frequency) thus, being in contrast to HKB predictions.

The second study investigated how practicing the same task under the fast tempo would affect the interjoint co-ordination stability at the preferred tempo after the training.

It was hypothesized that the variability in interjoint co-ordination at self-paced performance after training will decrease when compared to the self-paced condition before training.

Training effects were observed as either decreases or increases in different interjoint couplings when compared to the same condition before training. The results demonstrated that:

a) Training under the fast tempo did not significantly affect the overall performance at self-paced or fast tempo.
b) Different changes in interjoint couplings strengths observed before and after training were a function of the body side.

On the basis of these results it can be concluded that the flexibility of movement co-ordination is highly specific to interaction between the task, the performance condition at the skill level. However it cannot be simply assumed that variability is a measure of the skill level until the analysis of the movement behaviour and pattern dynamics is based on an individual approach.

Finally, it must be stated that results from the present study can also be addressed from any other relevant perspectives on skilled and unskilled performance and learning. However, the advantage of the Dynamic Systems Theory is that it is an integrated approach based on physical science principles that guide the evolution of system behaviour and system self-organisation. Therefore the Dynamic Systems Theory has been strongly supported in studying changes in different complex systems.

Recommendations for Further Study

On the basis the findings in this research, the following recommendations for future research are suggested.

1. A larger sample of women and men in the younger age groups of 16–21, middle age group 40-59 and in older age groups such as 60-65 should be observed to verify tempo and training effects in different age groups and, within and between different genders.
2. It is recommended that changes in control parameters be considered, such as scaling tempo with respect to self-paced tempo and scaling the height of the step platform with respect to participants' height.
3. In addition, the same design could be considered in further research, but with the criterion task being changed from stepping task to other real life (ie, ecologically valid) gross motor cyclical tasks.
4. It is recommended further, that the training period to be extended to investigate how different amounts of practice would affect learning and variability in performance.
5. Finally, a dynamic analysis is recommended including variables such as body weight, timing and force direction, which may better clarify the issue of variability within Dynamic System Theory.

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APENDICES

1.Consent and recruitment letter-Study 1

2. Consent and recruitment letter-Study 2

3. Step test recruitment questionnaire

4. Variable calculation graph

5. Plots of the Estimated marginal means of relative phase measures in Study 2

APPENDIX 1

April 1998
School of Biomedical and Sport Science
ECU, Joondalup WA 6027

RECRUITMENT AND CONSENT LETTER

Dear Madam,

I am a PhD student at ECU and for my current research I need to recruit participants selected from 17 to 45 years old, healthy females, with the experience in step aerobic exercise. The purpose of the research is to investigate the effect of self-paced, slow and fast music tempos on interlimb co-ordination in expert and novice step-knee-up task performance.

If you are interested to participate in the experiment please complete the recruitment questionnaire, attached. Information provided will be kept confidential.
Your involvement in this research considers:

- Performing step-knee-up exercise on cca. 20 cm high step platform (minimum 10 steps with each foot at each of 4 tempos including self - paced tempo). The examiner will demonstrate the task. You will need to attend the testing procedure only once, during weekends or at the time negotiated. The test will take about 20 minutes including the preparation time for marking your limb joints with 16 florescent small ball markers. You may withdraw from the testing procedure at any time if you feel uncomfortable.
- Testing procedure will take place at the motion analysis studio, Sport Science School, ECU, Joondalup. Travelling expenses will be compensated.

- If you decide to participate, please sign the consent form below return to the researcher in person or by mail in the envelope provided. For further enquires please call Gordana on 9400 5156 (ECU).

……………………………………………………………………………………

CONSENT FORM

I ________________ HAVE BEEN INFORMED ABOUT ALL ASPECTS OF THE RESEARCH PROJECT AND I AGREE TO PARTICIPATE IN THE PROJECT, REALISING THAT I MAY WITHDRAW AT ANY TIME.
I AGREE THAT THE RESEARCH DATA GATHERED FOR THIS PROJECT MAY BE PUBLISHED PROVIDED THAT I AM NOT IDENTIFIABLE.

________________________ Participant

________________________ Date

________________________ Researcher

________________________ Date

APPENDIX 2

November 1999
School of Biomedical and Sport Science
ECU, Joondalup WA 6027

RECRUITMENT AND CONSENT LETTER

Dear Madam,

I am a PhD student at ECU and for my current research I need to recruit minimum 6 participants selected from 17 to 45 years old, healthy females, without the experience in step aerobic exercise. The purpose of the research is to investigate the effect of practising a step aerobic task at the fast tempo (130-140 b/min)) on interlimb co-ordination and performance variability. If you are interested to participate in the experiment please complete the recruitment questionnaire, attached. Your involvement in this research considers:

- Attending pre-testing procedure, which would require you to perform a step-knee-up task on cca. 20 cm high step platform, a trial at fast tempo and a trial at self-paced tempo. The examiner will demonstrate the task. The test will take about 20 minutes including the preparation time for marking your limb joints with 13 florescent small ball markers. You may withdraw from the testing procedure at any time if you feel uncomfortable.
- Participate in training program over 12 sessions. A session consists of practising the step-knee-up task for 5 minutes under fast tempo, including resting time. The training will take place at Fremantle tennis club hall or at your place, at the time convenient to you. The researcher will supervise all training sessions.
- Attending post-testing procedure within couple of days after completing the training. All testing procedures will take place at the motion analysis studio, Sport Science, ECU, Joondalup. Testing procedures will be conducted during weekends or at the time negotiated. Travelling expenses will be compensated plus $10 for participating in the training.

All recorded information will be kept confidential. If you decide to participate, please sign the consent form below, and return it to the researcher in person or by mail in the envelope provided. For further enquires please call Gordana on 9400 5156 (ECU).

CONSENT FORM

I ______________HAVE BEEN INFORMED ABOUT ALL ASPECTS OF THE RESEARCH PROJECT AND I AGREE TO PARTICIPATE IN THE PROJECT, REALISING THAT I MAY WITHDRAW AT ANY TIME.
I AGREE THAT THE RESEARCH DATA GATHERED FOR THIS PROJECT MAY BE PUBLISHED PROVIDED THAT I AM NOT IDENTIFIABLE.

______________________	__________________
Participant	Date
______________________	__________________
Researcher	Date

APPENDIX 3

STEP TEST – Recruitment Questionnaire

Name: ______________________________

Contact phone number: ________________

Please circle YES *or* NO:

Do you currently participate in any sport or fitness exercises? YES NO

If YES, please indicate in what activity you have been involved, for how many, years, months so far, and how often you attended the training sessions (how many hours p/w):____

____

____

What is your experience in practising the step-aerobic task?
Please circle the number next to your answer below:

1. I have no experience in the step-aerobic task.
2. I have practised the step aerobic task over the last 2 years at least for an hour p/w.
3. I am a qualified fitness instructor with more then 3 years experience practising and teaching the step aerobic task

How would you define your current Health and Fitness condition?
Please circle the number next to your answer below:

1. I am mentally and physically fit and healthy.
2. I suffer from arthritis pain.
3. I suffer from muscular soreness.
4. Other (indicate any recent health problems):________________________

____

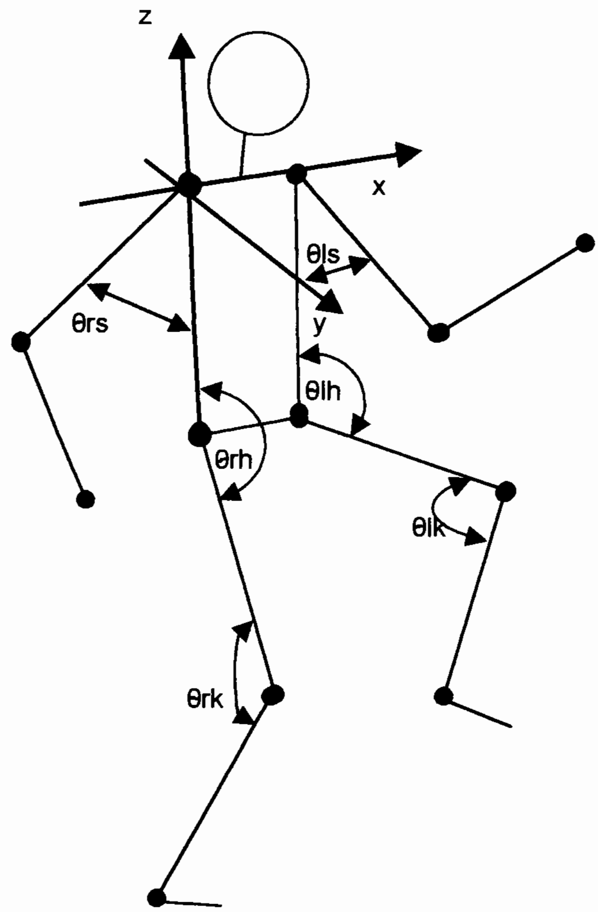
____

Thank you for participating!

____

Researcher

APENDIX 4



Variable definition

θls- left shoulder angle
θrs- right shoulder angle
θlh- left hip angle
θrh- right hip angle
θlk- left knee angle
θrk- right knee angle

APPENDIX 5

Plots of the Estimated marginal means of relative phase measures in Study 2

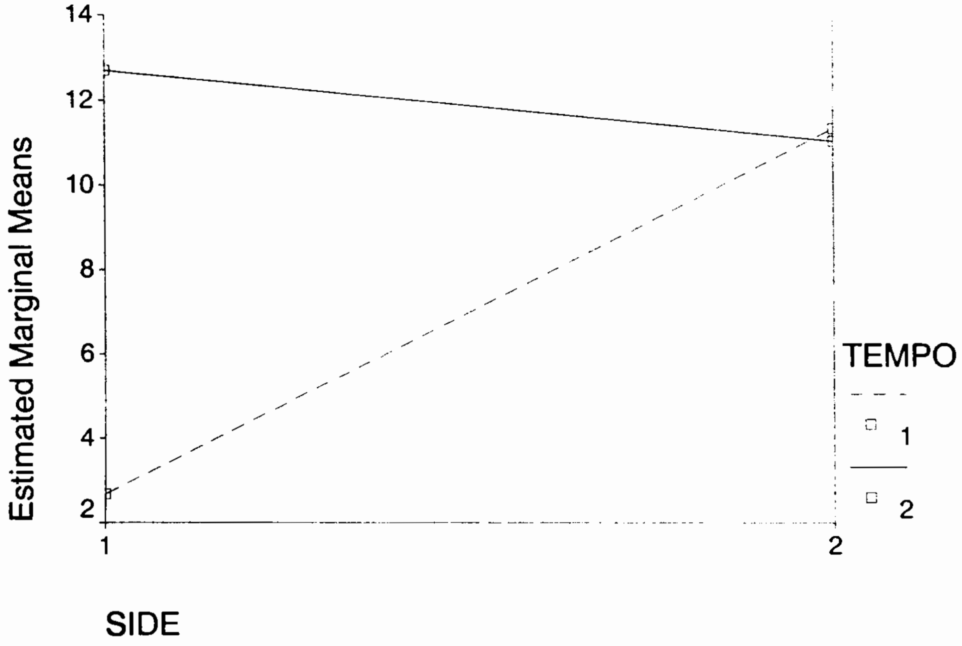
Estimated Marginal Means

TEST * TEMPO * SIDE

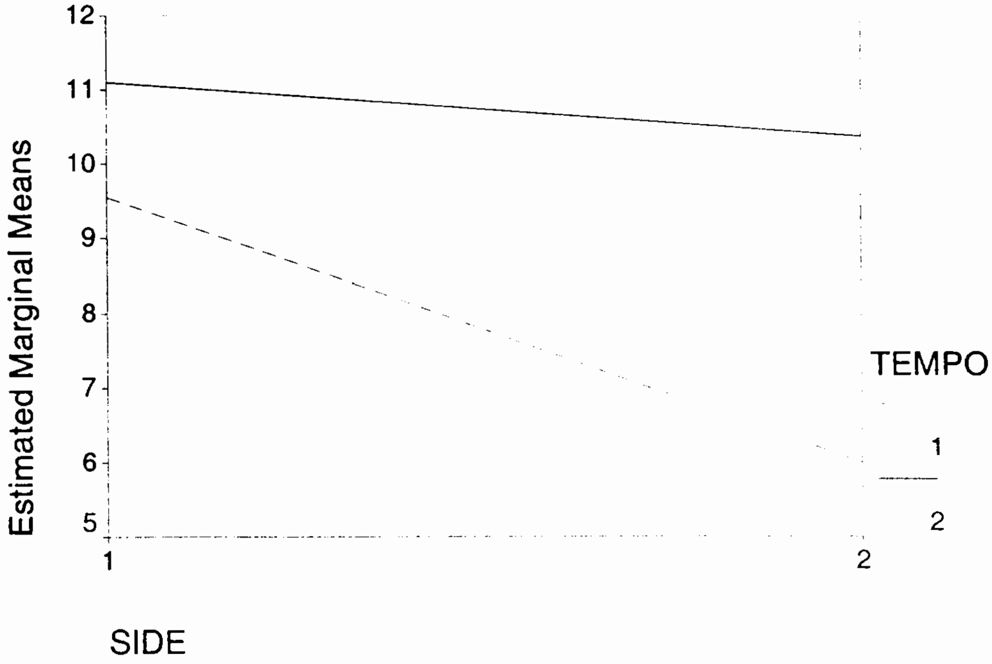
						95% Confidence Interval	
Measure	TEST	TEMPO	SIDE	Mean	Std. Error	Lower Bound	Upper Bound
ARM	1	1	1	2.683	.290	1.937	3.430
			2	11.333	3.007	3.603	19.064
		2	1	12.700	1.817	8.028	17.372
			2	11.033	1.716	6.622	15.444
	2	1	1	9.550	1.023	6.921	12.179
			2	6.000	1.483	2.187	9.813
		2	1	11.100	1.816	6.431	15.769
			2	10.367	2.334	4.366	16.368
LEG	1	1	1	11.000	2.745	3.945	18.055
			2	16.667	2.525	10.175	23.158
		2	1	25.767	2.634	18.997	32.537
			2	20.783	4.313	9.697	31.870
	2	1	1	16.333	1.856	11.563	21.104
			2	12.333	2.963	4.717	19.949
		2	1	24.433	3.158	16.315	32.552
			2	20.833	3.736	11.228	30.438

Estimated Marginal Means of ARM

At TEST = 1

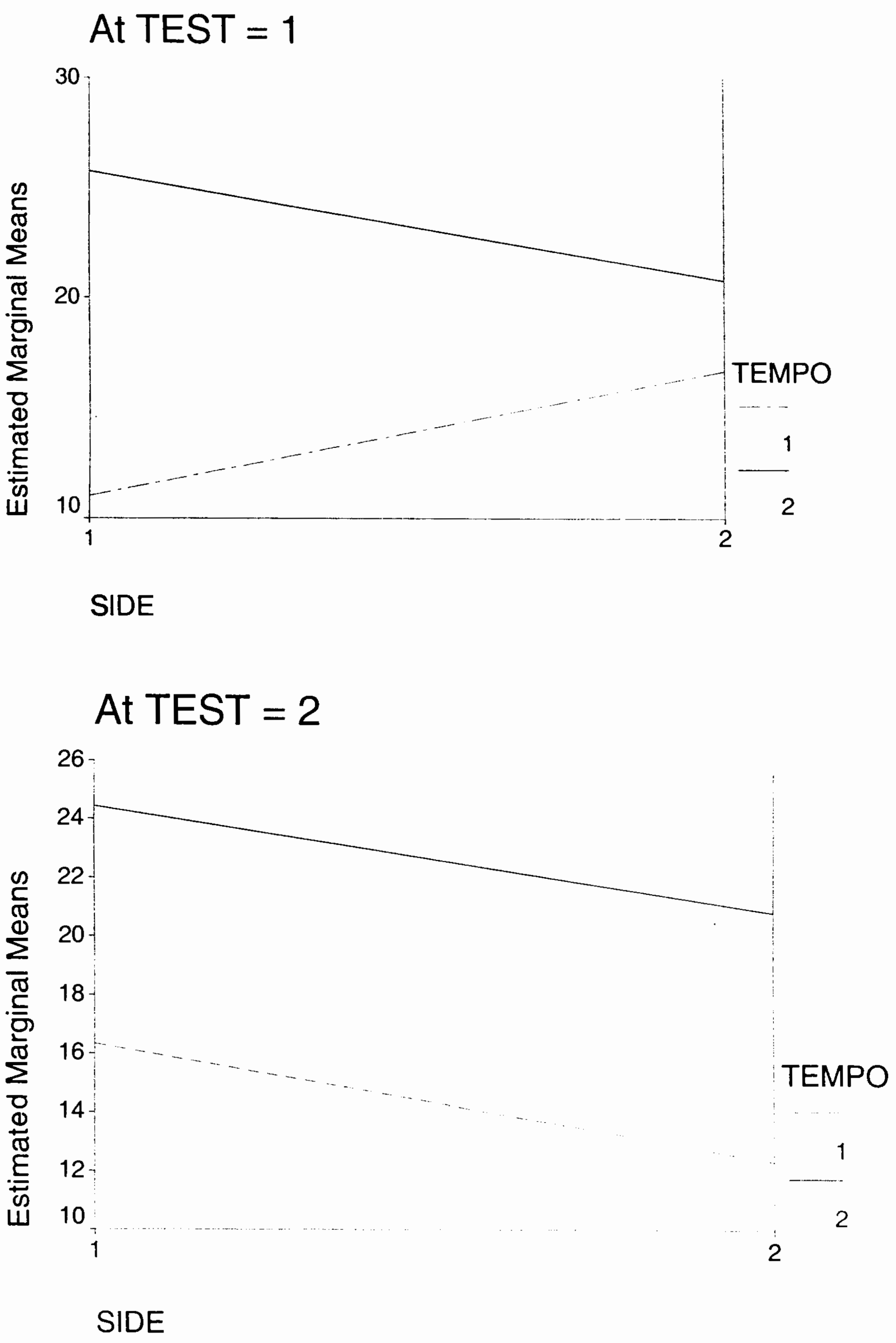


At TEST = 2



* For details see Figure 12 and corresponding text

Estimated Marginal Means of LEG



* For details see Figure 13 and corresponding text