An Examination of Learning Design in Elite Springboard Diving

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Keywords

Adaptability; adaptive movement variability; baulking; complex systems; ecological dynamics; functional variability; learning environment; movement patterns; neurobiological degeneracy; practice task constraints; representative design; springboard diving; variability.

Abstract

The overarching aim of this programme of work was to evaluate the effectiveness of the existing learning environment within the Australian Institute of Sport (AIS) elite springboard diving programme. Unique to the current research programme, is the application of ideas from an established theory of motor learning, specifically ecological dynamics, to an applied high performance training environment. In this research programme springboard diving is examined as a complex system, where individual, task, and environmental constraints are continually interacting to shape performance. As a consequence, this thesis presents some necessary and unique insights into representative learning design and movement adaptations in a sample of elite athletes. The questions examined in this programme of work relate to how best to structure practice, which is central to developing an effective learning environment in a high performance setting. Specifically, the series of studies reported in the chapters of this doctoral thesis: (i) provide evidence for the importance of designing representative practice tasks in training; (ii) establish that completed and baulked (prematurely terminated) take-offs are not different enough to justify the abortion of a planned dive; and (iii), confirm that elite athletes performing complex skills are able to adapt their movement patterns to achieve consistent performance outcomes from variable dive take-off conditions.

Chapters One and Two of the thesis provide an overview of the theoretical ideas framing the programme of work, and include a review of literature pertinent to the research aims and subsequent empirical chapters.

Chapter Three examined the representativeness of take-off tasks completed in the two AIS diving training facilities routinely used in springboard diving. Results highlighted differences in the preparatory phase of reverse dive take-offs completed by elite divers during normal training tasks in the dry-land and aquatic training environments. The most noticeable differences in dive take-off between environments began during the hurdle (step, jump, height and flight) where the diver generates the necessary momentum to complete the dive. Consequently, greater step lengths, jump heights and flight times, resulted in greater board depression prior to

take-off in the aquatic environment where the dives required greater amounts of rotation. The differences observed between the preparatory phases of reverse dive take-offs completed in the dry-land and aquatic training environments are arguably a consequence of the constraints of the training environment. Specifically, differences in the environmental information available to the athletes, and the need to alter the landing (feet first vs. wrist first landing) from the take-off, resulted in a decoupling of important perception and action information and a decomposition of the dive take-off task.

In attempting to only practise high quality dives, many athletes have followed a traditional motor learning approach (Schmidt, 1975) and tried to eliminate take-off variations during training. Chapter Four examined whether observable differences existed between the movement kinematics of elite divers in the preparation phases of baulked (prematurely terminated) and completed take-offs that might justify this approach to training. Qualitative and quantitative analyses of variability within conditions revealed greater consistency and less variability when dives were completed, and greater variability amongst baulked take-offs for all participants. Based on these findings, it is probable that athletes choose to abort a planned take-off when they detect small variations from the movement patterns (e.g., step lengths, jump height, springboard depression) of highly practiced comfortable dives. However, with no major differences in coordination patterns (topology of the angle-angle plots), and the potential for negative performance outcomes in competition, there appears to be no training advantage in baulking on unsatisfactory take-offs during training, except when a threat of injury is perceived by the athlete. Instead, it was considered that enhancing the athletes’ movement adaptability would be a more functional motor learning strategy.

In Chapter Five, a twelve-week training programme was conducted to determine whether a sample of elite divers were able to adapt their movement patterns and complete dives successfully, regardless of the perceived quality of their preparatory movements on the springboard. The data indeed suggested that elite divers were able to adapt their movements during the preparatory phase of the take-off and complete good quality dives under more varied take-off conditions; displaying greater consistency and stability in the key performance outcome (dive entry). These findings are in line with previous research findings from other sports (e.g., shooting, triple jump and basketball) and demonstrate how functional or compensatory movement variability can afford greater flexibility in task execution. By previously only practising dives with good quality take-offs, it can be argued that divers only developed strong couplings between information and movement under very specific performance circumstances. As a result, this sample was sometimes characterised by poor performance in competition when the athletes experienced a suboptimal take-off. Throughout this training programme, where divers were encouraged to minimise baulking and attempt to complete every dive, they demonstrated that it was possible to strengthen the information and movement coupling in a variety of performance circumstances, widening of the basin of performance solutions and providing alternative couplings to solve a performance problem even when the take-off was not ideal.

The results of this programme of research provide theoretical and experimental implications for understanding representative learning design and movement pattern variability in applied sports science research. Theoretically, this PhD programme contributes empirical evidence to demonstrate the importance of representative design in the training environments of high performance sports programmes. Specifically, this thesis advocates for the design of learning environments that effectively capture and enhance functional and flexible movement responses representative of performance contexts. Further, data from this thesis showed that elite athletes performing complex tasks were able to adapt their movements in the preparatory phase and complete good quality dives under more varied take-off conditions. This finding signals some significant practical implications for athletes, coaches and sports scientists. As such, it is recommended that care should be taken by coaches when designing practice tasks since the clear implication is that athletes need to practice adapting movement patterns during ongoing regulation of multi-articular coordination tasks. For example, volleyball servers can adapt to small variations in the ball toss phase, long jumpers can visually regulate gait as they prepare for the take-off, and springboard divers need to continue to practice adapting their take-off from the hurdle step.

In summary, the studies of this programme of work have confirmed that the task constraints of training environments in elite sport performance programmes need to provide a faithful simulation of a competitive performance environment in

order that performance outcomes may be stabilised with practice. Further, it is apparent that training environments can be enhanced by ensuring the representative design of task constraints, which have high action fidelity with the performance context. Ultimately, this study recommends that the traditional coaching adage ‘perfect practice makes perfect”, be reconsidered; instead advocating that practice should be, as Bernstein (1967) suggested, “repetition without repetition”.

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Glossary

Davids, Button and Bennett (2008)

Action fidelity: The degree of association between behaviour in an experimental task with that of the performance setting to which it is intended to be generalised

Baulk: In a diving context, a dive take-off where the diver completes the approach and hurdle steps, but does not complete the take-off and somersaulting phases of the dive

Complex systems: Highly integrated systems that are made up of many interacting parts or subsystems

Decomposition: Practising a subset of task components as a precursor to practice or performance of the whole task

Degeneracy: Refers to the theory that different parts of the neurobiological systems, can achieve the same movement outcomes

Degrees of freedom: The independent components of a system that can fit together in many different ways

Dry-land: A training environment designed for land-based diving practice

Dynamical systems theory: A theoretical approach that views the learner as a complex neurobiological system composed of independent but interacting degrees of freedom or subsystems

Ecological dynamics: Refers to an integrated approach using concepts and tools of ecological psychology and dynamical systems to understand phenomena that emerge in the transactions between individuals and their environments

Ecological validity: In Ecological Psychology, Brunswik's ecological validity referred to the correlation between the perception of a proximal cue and the distal property of the world i.e., the informativeness of the cue. More recently, ecological validity has been used to surmise the external validity of research designs and evaluate the transfer of findings from laboratory settings to performance environments

Functional variability: Variability that supports performance flexibility and an ability to adapt to changing environmental constraints

Invariant: When an underlying essential structure remains constant despite changes in the superficial structure

Learning: Defined as the set of underlying processes associated with practice leading to relatively permanent behavioural changes

Motor learning: Behavioural changes that are typically attributed to practice or experience

Movement variability: Encompasses the normal variations that occur in motor performance across multiple repetitions of a task over time

Performance: Refers to an observable execution of a motor skill, quantifiable both in terms of its outcome and form

Redundancy: An engineering term; redundancy is built into control systems to allow system components to take over processes when a specific component fails

Representative learning design: Refers to the composition of experimental task constraints so that they represent the behavioural setting to which the results are intended to be generalised

Task simplification: Task simplification reduces the complexity of the task while maintaining the coherence of the task and the perception-action cycles during practice

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AIS	Australian Institute of Sport
COG	Centre of gravity
DOF	Degrees of freedom
DST	Dynamical systems theory
FINA	Fédération Internationale de Natation

Statement of Original Authorship

The work and publications contained in this thesis have not been previously submitted to meet the requirements for an award at this or any other higher education institute. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is given. In cases where chapters are based on published outputs, reference has been made to those outputs.

Signed: QUT Verified Signature Date: 21/01/2013

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Bug. Thank you for consistently surprising (shocking) me by saying something inappropriate when I least expect it. Those proper belly laughs make my life better

Ralph. Thank you for putting up with me. I'm not really a sarcastic and cynical person who believes children on aeroplanes belong in the overhead lockers; that's just a by-product of the sleep deprivation associated with this thesis. I'm sure to be a much nicer person in 2013

Mum and Dad. This is it. I promise. However, while this may be my last thesis, and as such, my last acknowledgements page, it is unlikely to be the last time I acknowledge your unwavering support throughout what can only be described as a '*very lengthy'* education period. Thank you for always being there to chat (except during Master Chef), offer advice (roast chicken = 20-25mins per 500g), contribute to my education (the differences between meths and turps are now clear) and for humouring me when my OCD takes over and I have to rearrange (tidy) your linen cupboard. Most importantly thank you for ensuring that I never ran out of good quality single malt whisky. We all know I could not have done this without you. I love you 81

Finally, to my 7th form dean Debbie Clarke. You were right. Three degrees later and it looks like I am, in fact, destined for a supermarket checkout

Research Outputs

Peer-reviewed journal articles

Barris, S., Farrow, D., & Davids, K., (2012). Principles of ecological dynamics and elite sports performance- Application in springboard diving. *Journal of sport and exercise psychology*, *34*, Supplement, June 2012

Harrison, S., Cohen, R., Cleary, P., Barris, S., & Rose, G., (2012). *Forces on the body during elite competitive platform diving.* Ninth International Conference on CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, December 2012

Barris, S., Farrow, D., & Davids, K., (2012). Do the kinematics of a baulked take-off in springboard diving differ from a completed dive? *Journal of Sport Science* doi:10.1080/02640414.2012.733018

Barris, S., Davids, K., & Farrow, D., (2013). Representative learning design in springboard diving: Is dry-land training representative of a pool dive? *European Journal of Sports Science* doi:10.1080/17461391.2013.770923

Barris, S., Farrow, D., & Davids, K., (2013). Increasing functional variability in the preparatory phase of the take-off improves elite springboard diving performance. *Research Quarterly for Exercise and Sport*

Technical reports

Barris, S., (2011). National protocol for introducing variability into practice. Australian Institute of Sport diving programme. Brisbane, Australia

Barris, S., (2012). Not making a splash- The anatomy of a perfect Olympic dive. Article for theconversation, https://theconversation.edu.au/not-making-a-splash-the-anatomy-of-a-perfect-olympic-dive-8082

Academic conference presentations (oral)

Improving performance outcomes in Australian diving (2010). National Talent Identification (NTID) Conference, Australian Institute of Sport, Canberra, June

Movement pattern variability and learning design in elite springboard diving (2010). Australasian Skill Acquisition Research Group (ASARG) Conference, Canberra, July

Movement pattern variability and learning design in elite springboard diving programmes (2010)**.** PhD Confirmation Seminar, Queensland University of Technology, Brisbane, Australia, August

Principles of ecological dynamics and elite sport performance: Application to springboard diving (2012). North American Society for the psychology of sport and physical activity (NASPSPA), Honolulu, Hawaii, USA, June

Invited applied presentations (oral)

Skill acquisition and diving (2010). Diving Australia Board and Judges, Brisbane, Queensland, January

Performance outcomes in Australian diving (2010). High Performance Research Workshop, Australian Institute of Sport, Canberra, May

Practising perfect (2011). Technology in Sport Symposium, University of Otago, Dunedin, New Zealand, September

Using skill acquisition to enhance performance (2012). National Talent Identification (NTID) Coaching Workshop, Brisbane, August

Using movement variability to enhance performance (2012). Western Australian Institute of Sport (WAIS), Perth, August

Other

Implementation of a baulking training programme with the Western Australian Institute of Sport (WAIS) programme. August 2012

Practice: “repetition without repetition”

-Bernstein 1967

CHAPTER ONE – Introduction and thesis outline

Introduction and thesis outline

This thesis reports a series of studies investigating representative learning design and movement adaptability, specifically as applied to performance behaviours in an elite sport context. The purpose of practising skills in sport is to increase performance capability in competitive environments. Complex movement skills such as a tennis serve, a rugby penalty kick or a multi-rotational somersault during springboard diving, require a great deal of practice to allow athletes to perform them effectively under competitive constraints. It is, therefore, important to facilitate the chance of future success of these skills by *designing suitable practice environments, which simulate competitive performance environments*. In this regard, an overarching purpose of this programme of work was to evaluate the effectiveness of the existing learning environment within the Australian Institute of Sport (AIS) elite springboard diving programme.

Statement of the problem

Since the 1980s few scientific investigations have addressed biomechanical or motor learning issues in the sport of springboard diving. Of the few biomechanical papers that have been published in the past three decades, the analysed performances are rarely of nationally or internationally ranked divers (Miller, 1984; Miller & Munro, 1985a, 1985b) and, to date, there have been no attempts to investigate athlete behaviours in a high performance training environment. In the existing body of literature on motor learning and representative learning design, there has been little applied research using elite populations and no previous work in the sport of diving. Although empirical evidence exists to support current motor learning and control theories relating to practice structure and design, these studies have largely been conducted under laboratory conditions with novel tasks, novice participants and short term learning intervention designs with long periods of detraining before retention tests (Araújo, Davids, & Hristovski, 2006; Goode & Magill, 1986; Hodges, Hayes, Horn, & Williams, 2005; Shea & Morgan, 1979; Wulf & Shea, 2002). These are not realistic conditions for studying behaviours in a high performance sport setting where the athletes are highly skilled, the task is well practised and a period of non-practice to measure skill retention is not feasible. Due to associated disruptions to their normal training routine, elite athletes rarely consent to participation in experimental trials (Barnett, Cerin, Reaburn, & Hooper, 2010). For this reason, participants in experimental trials are typically novice university students or well-trained lower level athletes (Barnett, et al., 2010; Coutts, Wallace, & Slattery, 2007). Unfortunately, the use of novice or lower level athletes limits the extent to which current literature can be interpreted and applied to understanding performance and advanced learning in elite sporting populations.

Elite springboard divers, currently train between 28-30 hours per week and use both aquatic and dry-land training environments. In the pool, they complete traditional wrist first entries into water. In contrast, the dry-land training environment is in a purpose-built gymnasium designed for land-based diving practice (see Chapter 3, Figure 3-1 for examples of equipment and activities). The dry-land facility allows divers to practice the early preparatory phase (approach and hurdle) of the dive take-off with a feet first landing. Anecdotally, this training facility allows divers to experience a higher volume of dives during practice than they can achieve in the pool environment where time is lost exiting the water and climbing towers to the springboard (personal communication with the National Head Coach, Aug 2009). The motor learning strategy behind the use of a dry-land training environment is based on the assumed value of allowing athletes (directed by their coaches) to isolate small components of a dive coordination pattern and practise them independently. However, the constraints of the practice environment prevent the same number of somersaults being performed in the dry-land area as in aquatic practice or elite competition; the reduction in the task difficulty in such instances may therefore significantly affect a diver’s movement characteristics, including step and hurdle lengths, and forces required to be imparted on the springboard. The use of these two distinctly separate training facilities poses an interesting problem for motor learning, given the inherent differences in landing (head first vs. feet first) and the information sources imposed by the different practice task constraints. Although divers may practice the *same* preparation phase, take-off and initial aerial rotation in both environments, to date, there is no evidence to suggest that the task components completed in the dry-land training environment are representative of those performed in the competition environment. Although the rationale for dry-land training is to allow the athlete to isolate small manageable parts of the task, the constraints placed on the training tasks in the dry-land facility (fewer somersaults and a feet-first landing), may compel athletes to create new movement patterns that are neither functional for, nor representative of, the actual performance task.

Further, observations of the training behaviours of high performance divers have revealed that, in attempts to practice only high quality dives and achieve invariant movement patterns, squad members ‘baulk’ frequently (personal observation of daily training sessions). A baulked dive is defined as a take-off where the diver completes the approach and hurdle steps, but aborts the intended movement before the take-off phase if he/she considers the preparation to be imperfect. Examples of this phenomenon can be seen in other sports (particularly those with a locomotive component) where athletes begin the initial preparatory phase of the action but do not complete the full skill e.g. long jump, high jump, pole vault, volleyball spike. Over a week of training in diving, this approach can result in upwards of 100 baulks (approximately 20% of all dives attempted) (personal observation of daily training sessions). The implication of this approach is that athletes only practice the execution of dives off what they perceive to be a ‘good’ approach and hurdle phase. This type of approach reduces the volume of practice achieved by an individual and can have detrimental effects in competition with a two-point baulking penalty or ‘no-dive’ result awarded by the judges. Consequently, divers often attempt to complete dives in a competitive environment that they would not complete in training. Despite this common practice, currently, there is no empirical evidence to suggest the existence of significant movement pattern differences (temporal, kinematic or kinetic) in the preparation phase of baulked and completed dives in high performance athletes. It is possible; therefore, that this training habit is predicated on the misconception that only the best dives must be practiced at all times in order to enhance skill in a sport like diving.

A recent article in USA Diving magazine suggested that existing experiential knowledge of elite diving performers tends to support the idea that baulking should be avoided (Lowery, 2010).

> “The athletes took notice when Louganis mentioned he rarely baulked in training, instead seeing a poor take-off as an opportunity to challenge himself. Stanley said he’s found himself making adjustments in his workouts after listening to Louganis.”“His comment about baulking, to go no matter what, really stood out to me. I think I’ve baulked maybe once since then,” Stanley said. “Before, I would baulk over and over again until I got a good take-off.” (2010, p.9)

This statement suggests that in practice, Louganis would continue with a poor take-off, exploring the functional variability of an imperfect preparatory phase, and that he saw the ability to ‘rescue’ the dive entry as a challenge. Put simply, current divers may be baulking in response to slight inevitable variations in their approach phase, essentially, stopping and restarting instead of trying to adapt and use a different strategy for solving the movement problem, as required under competitive task constraints. Since the athletes attempt to eliminate take-off variations during training, skilled divers may not be affording themselves the opportunity to develop compensatory movement strategies to achieve the required performance outcome goal (rip entry into the water with minimal splash), from a varied take-off movement pattern.

Theoretical framework

Contemporary accounts of motor control and motor learning typically offer two theoretical perspectives of motor learning which have emerged from the domains of experimental/ cognitive psychology and ecological psychology/ dynamical systems theory (DST) (Coutts, et al., 2007). The work presented in this thesis is interpreted using an ecological framework.

By definition, ‘ecological’ refers to ‘the branch of biology that deals with relations of organisms to one another and to their physical surroundings’ Pearsall, 1998, P.586 cited in Coutts et al., (2007). Within an ecological approach, the nature of relationships between organisms and their environment are described as dynamical systems, characterised by constant change, activity or progress (Anson, Elliott, & Davids, 2005; Coutts, et al., 2007). The juxtaposition of theoretical ideas from DST and coordination dynamics with those of ecological psychology inform the understanding of how movement coordination functions are controlled with respect to dynamic environments. An ecological dynamics approach provides a powerful theoretical framework for interpreting recent advances in the psychological, social and neuro-sciences, and has clear implications for understanding behaviour in sport (Barnett, et al., 2010; Warren, 2006). The term 'ecological dynamics' refers to an approach using concepts and tools of dynamical systems to understand phenomena that emerge in the transactions between individuals and their environments. Specifically, ecological dynamics suggests that the structure and physics of the environment, the biomechanics of each individual's body, perceptual variables, and specific task demands all serve to constrain behaviour as it is expressed during goal-directed activity (Araújo, Davids, Bennett, Button, & Chapman, 2004; Warren, 2006). Adaptive behaviour, therefore, emerges from the interactions of this range of personal and environmental constraints under the conditions of a particular task goal or intention, rather than being imposed by a pre-existing internal structure (Araújo, et al., 2004; Davids, Araújo, Button, & Renshaw, 2007).

The theoretical insights of Egon Brunswik (1956) in ecological psychology also provide a powerful theoretical rationale for considering the role of the environment in studying learning behaviour. Brunswikian notions of *representative task design* have questioned traditional empirical research where the organisation of many experimental tasks has been an abstraction from the daily environmental experiences of the individual (Pinder, Davids, Renshaw, & Araújo, 2011b). Instead representative design refers to the degree to which environmental conditions adopted in a research study reflect those present in the situations where the task is implemented (Brunswik, 1956; Davids, et al., 2007). For example, do practice task conditions in a dry-land diving training environment represent those of the competition or performance environment (e.g., diving pool)? Further, questions have been raised regarding the athletes behaviour during lab-based experiments. For example, if an individual is provided with specific instructions and asked to provide informed consent in agreement that they are participating in an experiment, then there is the potential for their resultant behaviours to be influenced by this prior knowledge and the associated expectations (Araújo, Davids, & Passos, 2007). In this instance, the experimental environment may become a stand-alone environment and no longer be representative of the performance environment. Consequently, in order to study behaviour where the findings are truly representative of the task, it may be more beneficial for athletes to be observed and measured in their actual training and performance environments.

To this end, using an ecological dynamics framework and studying performance in a representative task design, the current programme of research will address current gaps in the motor learning literature, examining movement adaption and learning design in a complex task with highly trained elite performers, and determine how changes to the current learning design might affect athlete performance. In this research programme, an applied high performance springboard diving environment is used as a vehicle to represent sports in general.

Significance of the current studies

Unique to the current research programme, is the application of established theories of motor learning to an applied high performance training environment. In this programme of work springboard diving is examined as a complex system, where individual, task, and environmental constraints are continually interacting to shape performance. Elite, internationally successful athletes (Australian national representatives) participated in these studies and were analysed in their normal training environments (dry-land and aquatic), without large sample sizes, control groups or lengthy periods of detraining. As a consequence, this research programme presents some necessary unique insights into movement adaptations, representative of elite populations, in what has traditionally been considered a ‘closed’ skill (Gentile, 1972). Specifically, movement adaptations are examined as a function of changes in learning design and practice in elite sport training environments. The questions examined in this programme of work relate to how best to structure practice, which is central to developing an effective learning environment in a high performance setting. Specifically, the current programme of work addresses the following questions:

i. Are the preparatory phases of practice tasks performed in the dry-land training environment, representative of those performed in the aquatic training environment? (Chapter Three)
ii. Do differences in movement kinematics exist between completed and baulked (prematurely terminated) take-offs in diving practice? (Chapter Four)
iii. Does exploiting functional variability of the take-off, improve performance outcomes stability in elite springboard diving? (Chapter Five)

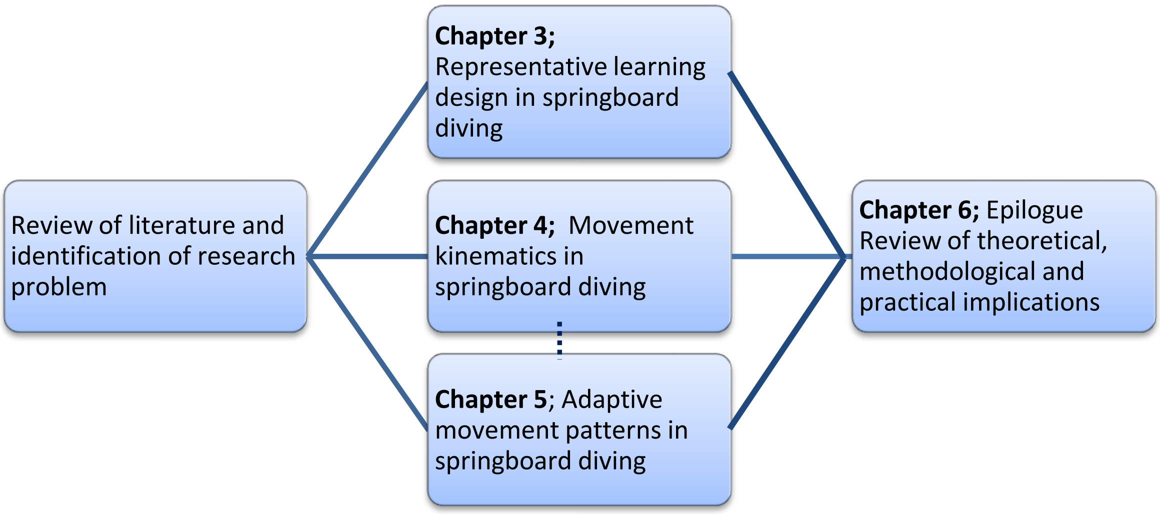


Figure 1-1 Structure and overview of the current programme of research

Study One (Chapter Three) provides some important insights for considering the representative design of training environments in elite programmes. The use of two separate training facilities poses an interesting problem for practice in diving, given the inherent differences in landing (head first vs. feet first). Although divers practice the same preparation phase, take-off and initial aerial rotation in both environments, there is no evidence to suggest that the two tasks require or follow the same movement pattern. Therefore, it is currently unclear whether training tasks in the dry-land facility are representative of the actual performance task completed in the aquatic environment. Consequently, Study One examines the influence of environmental constraints on the athlete’s approach to practice by assessing elite divers’ movement kinematics in both the aquatic and dry-land training environments.

Study Two (Chapter Four) examines current athlete training behaviours in normal diving practice environments (dry-land and aquatic). Observations of athlete training behaviour revealed that in attempt to practice only high quality dives and achieve invariant movement patterns, elite divers baulked frequently- aborting planned take-offs. This traditional approach to training exemplifies the athletes and coaches belief that only the best dives must be practiced at all times in order to enhance skilled performance in diving. This conception of practice fits, intentionally or not, with the notion of the existence of a common optimal movement pattern, towards which it is believed that all athletes should aspire (Brisson & Alain, 1996; Davids, Button, Araújo, Renshaw, & Hristovski, 2006). Study Two, therefore, aimed to determine whether kinematic differences existed between baulked and completed take-offs that might justify the abortion of a planned dive.

A training programme was used in Study Three (Chapter Five) to determine whether elite athletes were able to adapt their movement patterns during a complex task (the approach and hurdle phases of a multi-somersault springboard dive take-off) and stabilise the performance outcome (entry into the water) rather than removing variability in the performance by baulking. Recent investigations in motor learning have described the ability of elements that are structurally different to perform the same function or achieve the same output in simple movement tasks. The possibility that many different routes can achieve the same performance outcome goals is functionally significant for springboard divers where the performance environment is highly variable (e.g., an oscillating springboard). This empirical evidence has suggested that variability in performance may not be noise (measurement error) as previously thought, but may instead be functional, allowing performers to adapt to perturbations in the performance or the environment and achieve stable outcomes. How this may relate to performance in multi-articular tasks with highly trained participants, is yet unknown. Study Three provides a powerful rationale for coaches to consider functional variability or adaptability of motor behaviour as a key criterion of successful performance in sports like diving.

In summary, this research programme provides theoretical and experimental implications for representative learning design and movement pattern variability in applied sports science research. In particular, the research provides a principled framework for researchers, coaches and sport scientists working in a high performance diving environment. Theoretically, the PhD programme contributes empirical evidence to demonstrate the importance of representative design in the training environments of high performance sports (see Chapter Three). Further it provides justification for, and execution of, integrating movement pattern variability into complex skill performance (Chapters Four and Five respectively).

Collectively, this programme presents a broad critique of previous experimental designs, and provides empirical evidence to demonstrate the importance of high action fidelity between practice and performance contexts in a representative learning environment. Practically, the examination of training behaviours and environments provides significant implications for elite sport programmes, such as diving, and advocates changes to the existing practice and learning designs. For example, the use of a training programme to reduce baulking in practice or scaling the amount of time spent in the dry-land environment to minimise the negative effects of task decomposition on performance. Such information may be invaluable for future development and coaching in Diving Australia's national and state talent development programmes.

Structure of the thesis

The current programme of work is submitted as a traditional thesis, and includes a combination of initial background literature, chapters based on published journal articles or work under peer-review. Consequently, there is some repetition of content throughout the thesis to allow the chapters to be read as standalone articles, and demonstrate the contribution to the literature at each stage of the PhD programme. In such instances, edits have been made to ensure language and formatting consistency throughout the thesis, and additional information has been included where necessary. The theoretical theme throughout this thesis is developed throughout each chapter and promotes a representative learning design, and adaptive movement variability, rather than supporting the acquisition of a common optimal movement pattern, as a template towards which all performers should aspire. The progression of this programme of work is presented in three independent chapters

(Studies One, Two and Three) that link to previous sections (introduction and literature review) as displayed in Figure 1-1.

At the time of lodgement, this thesis has yielded three peer-review journal articles, and several conference and applied presentations (e.g., coaching). See page xviii for a list of publications and presentations.

CHAPTER TWO – Review of literature

Review of literature

This review of literature is divided into four main sections and considers the learning environment in springboard diving from an ecological perspective. The first section introduces theoretical ideas from ecological psychology and dynamical systems theory, which have been integrated to form an ecological dynamics approach. The second section evaluates learning, Brunswik's (1956) concept of representative task design and its implications for practice in sport. The third section reviews existing research on the biomechanics of springboard diving. Finally, the fourth section addresses movement pattern variability, specifically the role of functional variability in complex systems.

An ecological approach for understanding human movement

Ecological Psychology and Dynamical Systems Theory

By definition, '*ecological*' refers to 'the branch of biology that deals with relations of organisms to one another and to their physical surroundings' (Pearsall, 1998, p.586 cited in (2005). An *ecological approach*, therefore, considers the nature of relationships between organisms and their environment, viewing them as dynamical systems that are characterised by constant change, activity or progress (Anson, et al., 2005; Turvey, Shaw, Reed, & Mace, 1981). The integration of theoretical ideas from ecological psychology with those of DST and coordination dynamics inform the understanding of how movement coordination functions are controlled with respect to dynamic environments.

The ecological approach to learning originated with a rejection of enrichment theories of learning (Gibson & Gibson, 1955). In enrichment theories, stimulus variables are ambiguous with respect to the environment; and this ambiguity is resolved by enriching information-poor stimuli through processes such as inference or with memories (Anson, et al., 2005). Enrichment theories explain the emergence of expertise as an increase in the sophistication of the enrichment processes (Jacobs & Michaels, 2007). In contrast, ecological theories, propose that learning results from changes in the environmental properties to which perceptual systems are sensitive (Jacobs & Michaels, 2007). As such expert performance results from the improved fit of experts to their environments, rather than from an increased complexity of computational and memorial processes (Shaw, 2003).

Ecological psychology characterises the role of information in behaviour, specifically, the coupling of information and movement. This approach emphasises the importance of environmental information where, an animal's movement generates perceptual information that, in turn, constrains further movements. This notion is fundamental to the ecological approach and emphasises the circular relations that exist between the perceptual systems and the movement systems of humans. This position was summarised by James Gibson in his statement that; 'We must move in order to perceive, but we must perceive in order to move' (Gibson, 1979). For example, light reaches the eyes of a diver after being reflected off the surrounding surfaces, – the pool-deck, the walls ahead of the platform- and moving objects- other divers, the springboard, and the water in the pool environment and provides the performer with information specific to that context. Gibson's insights (1979) provide a sound theoretical rationale for carefully structuring practice tasks in sport to maintain relationships between key sources of information and action for learners. Different sources of perceptual information present different opportunities for performers to execute specific actions in sport. For this reason, care should be taken in designing learning environments (Pinder, Davids, Renshaw, & Araújo, 2011a).

In complex neurological systems, states of order and rich patterns of behaviour and coordination emerge under specific constraints, varying between performance contexts. A 'constraints-based' framework emphasises the study of movement behaviour emerging under the continuous and cyclical interactions between the neurobiological movement systems and the environment in which it is based (Davids, et al., 2008; Newell, 1986). In human movement, the constraints on the individual are numerous, and limit the number of movement and outcome possibilities available to the system (Davids, et al., 2008). Constraints are defined as boundaries that constrain the interactions of system components, and are classified as organismic (individual), task and environmental (Newell, 1986). Organismic constraints refer to the individual's specific characteristics, such as physical or mental aspects (e.g., anthropometry). Task constraints are typically more specific to performance contexts, such as task goals, specific rules, performance boundaries, size of equipment and use of implements or tools (Davids, et al., 2008). Environmental constraints are global physical features of nature, such as ambient light, gravity of temperature (Newell, 1986). Consequently, the ability to vary motor performance under different performance contexts is considered a critical feature of skill acquisition and expertise. Further, these theoretical implications describe movement systems as dynamical systems due to the numerous degrees of freedom to be coordinated and controlled during environmental interactions.

Dynamical systems theory is a multidisciplinary, systems-led approach encompassing mathematics, physics, biology, psychology and chemistry, and provides a framework for understanding neurobiological movement coordination and control (Davids, et al., 2008; Davids, Glazier, Araújo, & Bartlett, 2003; Handford, Davids, Bennett, & Button, 1997). Central to this theory, is the idea that natural phenomena can be explained, at multiple scales of analysis, with the same underlying abstract principles regardless of the systems structure and composition. The theoretical basis of this approach is in understanding how humans, with many redundant degrees of freedom (DOF), develop control and coordination to perform goal-directed movements (Bernstein, 1967).

These key ideas from dynamical systems theory have been associated with the theoretical insights of the Russian physiologist and biomechanist, Nikolai Bernstein. Bernstein (1967) demonstrated, that the achieved accuracy in the result of an anvil hammering task, contrasted with the observation of the trajectories of the multi-joint arm, which are virtually always different (Müller & Sternad, 2004). In the same way that throwing a dart to the same target position can be achieved with many different release positions and release angles (Müller & Sternad, 2004). Consequently, Bernstein formulated the fundamental problem for movement systems as the ‘process of mastering the redundant degrees of freedom’ or more succinctly, ‘the organisation of the control of the motor apparatus’ (Bernstein, 1967, p. 127). Bernstein used the term *redundant* degrees of freedom to refer to the biomechanical DOF that exceed the minimum number required to successfully accomplish any given motor task (Bernstein, 1967).

The many degrees of freedom available for the regulation of movements, demonstrates the wealth of options from which the central nervous system can select for motor task performance (Davids, Bennett, & Newell, 2006; Davids & Glazier, 2010). This abundance of motor system degrees of freedom can be both a resource and a problem for the human central nervous system during the process of learning a movement (Davids & Glazier, 2010). For example, even a simple movement like reaching and grasping an object (such as a pen or a cup) with the hand and arm could require the individual to regulate seven degrees of freedom. This involves the flexion-extension, abduction-adduction, and axial rotation of the joints. Three of these degrees of freedom are at the shoulder, one at the elbow, one in the radio-ulnar joints, and two at the wrist. Further, the hand may also acts as many degrees of freedom, where, the fingers and thumb can be configured together in many different ways depending on task requirements. Consequently, the number of degrees of freedom to be regulated significantly increases with the increased complexity of the movement; for example, a backward three and a half somersault off a 3m springboard in diving.

Self-organisation processes are an inherent property of many animate and inanimate complex systems in which rich patterns of behaviour can emerge at a global level from localised interactions of some system components (Kelso, 1995). The process of self-organisation in neurobiology provides a movement system with theability to adapt to the changing constraints of the environment (Davids, et al., 2008). Notably, functional patterns of behaviour of complex systems are context specific and dependent on the interacting constraints exploited by the system. As such, behaviour emerges as a variable and adaptive process dependent on the constraints of the action. Although strategies adopted by early learners may meet the initial goals of a beginner, the assembly of an immediately functional and skilled coordination solution is beyond the capacity of many learners. To cope, learners control the movement system by overly constraining the available motor system degrees of freedom, producing rigidly fixed movements. Progressively, with learning and experience, the fixed characteristic of coordination is altered as movement system degrees of freedom are released and allowed to reform into coordinative structures, that is different configurations or synergies for specific purposes (Turvey, 1990; Zong-Ming, 2006). Typically, as a result of extended practice, the initial strong couplings between system degrees of freedom are gradually unfixed and formed into task-specific coordinative structures, so that internal and external forces can be exploited to increase movement economy and efficiency (Zong-Ming, 2006).

The term 'coordinative structure' captures how coordination emerges between motor system components during goal-directed behaviour. These structures are functional relationships formed between important anatomical components of a performer's body design for a specific purpose or activity (Hamill, Haddad, & van Emmerick, 2005). For example; groups of muscles or joints temporarily assemble into coherent units to achieve specific task goals, such as hitting a ball or performing a dive (Hamill, et al., 2005; Kugler, Kelso, & Turvey, 1980). The formation of specific functional muscle-joint linkages or structures is essential to manage the many degrees of freedom in the human movement system (Davids & Glazier, 2010; Davids, et al., 2003). Such functional groupings compress the physical components of the movement system and specify how the relevant degrees of freedom for an action become mutually dependent (Davids, et al., 2003). The development of synergies between motor system components helps to make the discovery and assembly of joint couplings more manageable for learners as they attempt to cope with the many degrees of freedom in the movement system (Newell, 1985; Newell, 1986; Zong-Ming, 2006).

Ecological dynamics

The term 'ecological dynamics' refers to an integrated approach using concepts and tools of ecological psychology and dynamical systems to understand phenomena that emerge in the transactions between individuals and their environments (Araújo, et al., 2006; Scholz & Schöner, 1999). Specifically, ecological dynamics suggests that the structure and physics of the environment, the biomechanics of each individual's body, perceptual variables, and specific task demands all serve to constrain behaviour as it is expressed during goal-directed activity (Araújo, et al., 2006; Scholz & Schöner, 1999). Critically, ecological approaches recognise the close and reciprocal link between a living system and its environment, where; living systems possess their own sources of energy and are 'open' to energy exchanges with the environment (Davids, et al., 2008). In essence, these sources of energy act as perceptual information for supporting, guiding, and regulating movement. Adaptive behaviour, therefore, emerges from the interactions of this range of personal and environmental constraints under the conditions of a particular task goal or intention, rather than being imposed by a pre-existing internal structure (Araújo, et al., 2004; Davids, et al., 2007). A major challenge for the ecological dynamics approach is to understand how each individual learns to perceive the surrounding layout of the performance environment in the scale of his/her body and action capabilities (Warren, 2006). As such, the aim of ecological learning theories is to explain how perceivers take advantage of the informational richness of environmental properties (Jacobs & Michaels, 2007). Learning in sport, therefore, requires the attunement to and construction of successful functional relations between movement and information in specific contexts. Consequently, an ecological dynamics approach provides a powerful theoretical framework for interpreting recent advances in the psychological, social and neuro-sciences, and has clear implications for understanding behaviour in sport (Araújo & Davids, 2011).

There are two complementary attributes of accurate and functional performance in dynamic environments (Scholz & Schöner, 1999): stability and flexibility. Although successful performance can be characterised by stable and reproducible low-dimensional patterns, which are functional actions consistently reproducible over time and resistant to perturbation; at the same time “behaviour is not stereotyped and rigid but flexible and adaptive” (Warren, 2006 P. 359)**.** While action patterns exhibit regular morphologies, skilled performers are not locked into rigidly stable solutions (e.g. technical, tactical) but can instead modulate their behaviours (Scholz & Schöner, 1999). Therefore, to be successful, performers need to adapt their actions to the dynamically shifting environment that characterise competitive sport (for example variability detected during the preparatory phase of a springboard dive take-off). This flexibility is tailored to the current environmental conditions and/or task demands, and implicates perceptual control of action (Araújo, et al., 2006). For example, failing to generate enough downward force on the springboard, changes the information received from the performance environment, ultimately changing the task constraints and requiring online skill adaptability by the performer. Consequently, as environmental circumstances change, skilled athletes are able to vary the nature of their coordination to achieve the same task goal in slightly different, yet functional ways.

These variations in coordination behaviour in response to changes in task or environmental constraints can be measured using an intra-individual research design. Intra-individual or single-subject research design is a methodology used extensively in the experimental analysis of behaviour and applied behavioural analysis (Bartlett, 2007; Mullineaux, Bartlett, & Bennett, 2001). This research design has two main components: (1) a focus on the individual and (2) a design where each individual acts as their own control. Rather than comparing large groups of participants, an intra-individual design relies on the comparison of treatment or behaviour effects on a single subject or group of single subjects. In this way, the behaviour of one individual is compared to a second behaviour (by the same individual) at a different point in time (e.g. pre- and post-training programme). Focusing on the performance or responses of an individual (or group of individuals) differs from other research designs, such as experimental and quasi-experimental designs, which look at the average effect of an intervention within or between large groups of people. Recent arguments in behavioural sciences have demonstrated how functional variability observed in individual participants can be masked by averaging performance data for statistical analysis (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). For this reason, a single subject research design is often considered the best for measuring changes in behaviour.

This approach is particularly pertinent to studies in ecological dynamics, where emergent behaviour is considered the result of interactions between the *individual* and their environment. How *each individual's* behaviour adapts in response to personal and environmental constraints cannot be examined using group measures, owing to each individual's anthropometry and available degrees of freedom, and therefore must be examined on an individual basis (Schöllhorn, et al., 2009). However due to the individual nature of the analysis, any findings from a single-study design are limited in their application to a wider audience (Mullineaux, et al., 2001).

Acquisition of skill

The acquisition of motor skills have traditionally been described as the internal processes that bring about relatively permanent changes in the learners movement capabilities (Schmidt & Lee, 2011). These changes are usually achieved through practice, which, in sport is designed to improve an athlete's capability to perform skills in competitive performance enviornments. From a constraint-led perspective, the acquisition of skill is characterised by the learner’s search for stable and functional states of coordination during goal-directed activity (Davids, et al., 2008). Temporary states of coordination are assembled during different phases of learning to resist perturbations that may upset the stability of the system. In many complex performance environments (such as a dynamic springboard diving environment), learners need to develop a repertoire of movement attractors (stable states of coordination) to satisfy the constraints of unpredictable contexts (Davids, et al., 2008). For example, movement skills routinely seen in springboard diving, such as a front 3 ½ somersault in a pike position (107B) require a great deal of practice over long periods to allow the diver to achieve a stable performance outcome.

Skilled performance, like that of the elite participants in this study, emerges from the dynamic relationship between the organism, its environment and the task. Highly skilled actions have a number of important properties, and are considered ‘skilled’ according to a number of features including the performer’s accuracy, aesthetic quality and efficiency. Additionally, these skilled actions are purposeful and reliable and are directed at attaining a particular outcome goal consistently (Manoel & Connolly, 1995). In this way, the development of goal directed behaviour has been seen as a transition from variable and inconsistent dysfunctional actions to patterned, consistent functional ones. Newell (1985) formulated a model for learning based on Bernstein’s (1967) insights on the mechanical DOF of the neurobiological system (Newell, 1985). Newell’s model consists of three stages of learning: coordination, control and skill. The first of these stages (coordination) is concerned with the assembly of a suitable coordination pattern from the available DOF in the system. The second stage (control) focuses on the development of relationships between an assembled coordination pattern and the performance environment (Newell, 1985). Finally, the third stage of the model (skill), refers to the optimisation of a coordination pattern that has gradually become more flexible and open exploiting environmental sources, and consequently enhancing efficiency and control (Newell, 1985).

The processes associated with learning skills cannot be observed directly; therefore, the primary measure of learning has historically been based on the degree of systematic change in the movement outcome over time (usually measured by tests of movement performance) (Newell, 1986). Experimental studies involving highly skilled athletes (stage three of Newell's model) are rare, due to associated disruptions to their normal training routine (Barnett, et al., 2010). Consequently the participants in the experimental trials that have traditionally informed motor learning theories, have typically been novice university students or well trained lower level athletes (Barnett, et al., 2010; Coutts, et al., 2007). As such, the extent to which the current literature can be interpreted and applied to understanding the performance and advanced learning of truly elite sporting populations is limited.

Representative learning design

Trying to understand how movements are coordinated in relation to key features of the environment has long been an important question for ecological psychologists. To date, the emphasis of this research has largely been on developing an understanding of the relationship between perception and action in many jumping, catching, kicking and hitting activities (Bootsma, 1989; Michaels & Beek, 1995; Montagne, Cornus, Glize, Quaine, & Laurent, 2000). This research has typically focussed on the coupling between perceptual information from the environment and the participant's movements during interceptive actions (Davids, Kingsbury, Bennett, & Handford, 2001). Nonlinear pedagogy is predicated on the mutual interdependence between perception and action in neurobiology, and it has been suggested that these processes should not function separately in learning design (Araújo, et al., 2006; Pinder, et al., 2011b). Gibson's (1979) insights suggest that practice tasks in sport need to be carefully structured and managed to maintain relationships between key sources of information and action for learners and performers during practice. Importantly, physical adjustments can be made in response to the changing demands of a performance context in diving. Diving skills can be considered dynamic, since key visual information is required by the divers to know when to initiate and decelerate rotations and movements. It is, therefore, important to maintain the relationship between perception and action during practice tasks in all diving training environments (dry-land and aquatic). Consequently, practice should occur in dynamic circumstances where all key sources of information are present.

Historically, the use of *ecological validity* in the motor learning literature has been used to surmise the external validity of research designs and evaluate the transfer of findings from laboratory settings to performance environments (Dicks, Davids, & Araújo, 2008; Hagemann & Memmert, 2006; Jobson, Nevill, Palmer et al., 2007; Palmer, Dennis, Noakes, & Hawley, 1996; Rogers, Kadar, & Costall, 2005; Smith, Davison, Balmer, & Bird, 2001). Alternatively, *Representative design*, a concept introduced by Brunswik (1956), refers to the composition of experimental task constraints so that they *represent* the behavioural setting to which the results are intended to be generalised (for detailed discussion see Pinder et al. (2011b) and Araújo, Davids & Passos (2007)). Ecological psychologists have further adapted this concept to generalise task constraints in learning or practice environments to the constraints encountered in the performance or competition contexts (Araújo, et al., 2007; Davids, et al., 2007; Davids, et al., 2003; Dicks, et al., 2008). According to Brunswik, to perform successfully, individuals must adapt to multiple, noisy, messy situations, which occur in their environment. He argued that to hold all variables constant, except one, as in traditional empirical experiments, was to remove research from its relevant context, influencing the validity of empirical observations (Araújo & Davids, 2009). For example, if an individual has to perform a task in an artificial laboratory environment or provide informed consent that they are participating in an experiment, then there is the potential for their resultant behaviours to be influenced by this prior knowledge and the associated expectations (Araújo, et al., 2007). Araújo and colleagues suggest that without a representative design, the experimental environment becomes a stand-alone environment and therefore not representative of the environments to which the results are generalised. Instead, Brunswik contends that scientists should represent those messy, irregular conditions in experimental testing environments to truly discover how individuals overcome uncertainty in their natural performance environment (Araújo, et al., 2007). Consequently, important questions exist regarding the extent to which perceptions, actions and behaviours in one context, correspond to those in another context (Araújo, et al., 2007). These Brunswikian notions of representative task design have subsequently made redundant the traditional dichotomisation of empirical research as either ‘laboratory or field-based’. Instead, promoting an understanding of the interaction between key organismic, task and environmental constraints when designing natural, representative tasks, regardless of whether they are located in a laboratory or field-setting (Davids, et al., 2007).

Despite technological and methodological advances, Brunswikian concepts still have not been widely integrated into psychological and motor learning research. Consequently, questions still exist over the representativeness of many experimental designs in sport science research (Cotterill, Sanders, & Collins, 2010; James, 2010; Pinder, et al., 2011a); with many researchers traditionally opting for systematic designs for experimental control, jeopardising the generalisability of research findings (Araújo, et al., 2007; Pinder, et al., 2011b). Previous research on perceptual–motor skill in sport has been criticised for failing to maintain the functional coupling of perception and action processes in experimental designs (Dicks, et al., 2008). The implications of this are significant, since in sports science, small changes in task constraints can lead to substantial changes in performance outcomes and movement responses (Hristovski, Davids, Araújo, & Button, 2006; Jobson, et al., 2007; Wilson, Simpson, van Emmerick, & Hamill, 2008). For example, studies investigating 'ecological validity' in cycling, have shown that such extreme differences exist between the findings of research conducted in the laboratory and what occurs in an applied setting that guidelines established from laboratory testing cannot be extrapolated to exercise in the field (Jobson, et al., 2007). Further, some studies of perception and action have demonstrated significant differences in visuo-motor behaviours observed between laboratory conditions and task conditions representative of performance contexts (e.g., video simulation vs. in situ tasks). Specifically, the limitations of the occlusion and video simulation methodologies have been attributed to the removal of key sources of information in experimental design and a failure to ensure that neuro-scientific knowledge of visual system functioning underpins research designs (Davids, et al., 2008; Pinder, et al., 2011b; Van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008).

Traditionally, experimental designs have not ensured that selected task constraints support the use of functional information–movement couplings. That is, environmental information presented in experimental tasks and the action responses required (e.g., verbal, written, or simplified movements) do not allow performers to replicate the same perception and action processes as those displayed in representative performance environments (Féry & Crognier, 2001; Jackson, Warren, & Abernethy, 2006; Poulter, Jackson, Wann, & Berry, 2005; Rowe & McKenna, 2001; Savelsbergh, van der Kamp, Williams, & Ward, 2005; Weissensteiner, Abernethy, Farrow, & Müller, 2008; Williams & Burwitz, 1993). As such, research has typically been focused on substantiating expertise effects, rather than on comparing participant movement behaviours across varying task constraints (Pinder, et al., 2011b). Consequently, it has been argued that elite athlete populations may benefit most from training practices that accurately sample and simulate representative task conditions and maintain perception and action couplings (Dicks, et al., 2008). Important for the current investigation, is the notion that these practices can encourage athletes to utilise and develop functional and adaptive (degenerate) movement solutions through the manipulation of the practice task constraints, allowing the athletes to learn to attend to varying information sources (Dicks, et al., 2008).

The degree of association between behaviour in an experimental task with that of the performance setting to which it is intended to generalise, is known as action fidelity (Araújo, et al., 2007; Lintern, Sheppard, Parker, Yates, & Nolan, 1989). In the use of flight simulations, Stoffregen and colleagues (2003) described action fidelity as the 'fidelity of performance', and suggest that fidelity is present when there is a successful transfer of performance from the simulator to the simulated system (Araújo, et al., 2007; Pinder, et al., 2011a). The purpose of action fidelity is to examine whether a performer's responses (e.g. actions or decisions) remain the same in two or more contexts (e.g. a flight simulator compared to flying a plane). In this respect, practice, training and learning tasks in sport could also be viewed as simulations of the performance environment that need to be high in action fidelity (Pinder, et al., 2011a). In this instance, the degree of fidelity could be measured by analysing the task performance (e.g. time taken, joint kinematics) in both the simulated training environment and the competition or actual performance context (Araújo, et al., 2007). For example, Pinder and colleagues (2009) analysed the movement responses of cricket batters when responding in representative performance tasks of batting against a 'live' bowler and a ball projection machine. In this situation, the ball machine was used to simulate aspects of the performance environment. The authors argued that the significant differences observed in the spatiotemporal responses of the batting action in the ball machine condition, were in response to the removal of key perceptual information sources and a delay in movement initiation times. They concluded that the removal of perceptual information from the environment (specifically kinematic information from the bowler's actions prior to ball release) limited the athlete's ability to use environmental information to guide their movement response (Pinder, et al., 2009). These findings highlight the importance of adequately replicating the performance environment in practice tasks to allow learners to detect affordances for action, and coupling actions to key information sources within those specific contexts, settings and situations.

According to Gibson (1979) an event or object affords what it does because it has certain specific properties. However, these properties are not intrinsic to the object and realising these affordance properties requires the organism to regulate their activity according to information concerning both the object and the performer (Araújo, et al., 2007). Consequently, many of the affordances the organism uses in its environment requires extensive practice and learning to be perceived or to be used (Dicks, et al., 2008). More simply, the perception of environmental information is specific and constrained by each individual performance setting. Therefore, coaches need to be fully aware of the constraints of the sport, and consider how the design of the practice tasks and interventions allow the maintenance of coupled perception and action processes that reflect the functional behaviour of athletes in specific performance contexts (Dicks, et al., 2008; Pinder, et al., 2011a). The practical application of this is important for diving where athletes currently spend up to forty percent of their training time participating in land-based activities in a separate performance environment.

Current AIS diving training environments

Australian divers, currently train 28-30 hours per week and use both aquatic and dry-land training environments.

Pool

The aquatic training environment has one 5m deep pool with a diving tower above it (see Figure 2-1). The diving tower has both springboards (1m and 3m) and platforms at different heights (1m, 3m, 5m, 7.5m & 10m). In this environment, divers complete both feet first and traditional wrist first entries into the water. Individual training programmes are written for each diver for each training session and cover basic water entries (to correct technique), take-off skills, competition compulsory dives (lower degree of difficulty dives performed in the preliminary rounds at competitions) and optional dives (dives with a higher degree of difficulty performed in competition). Divers traditionally complete seven to ten repetitions of each type of dive in their programme before moving on to the next skill. Between repetitions, the athlete receives external feedback from the coach and from delayed video footage shown on pool deck. For safety reasons, the athletes never perform a dive without a coach first signalling that the water below them is clear of other divers. Coaches are also frequently needed to ‘call’ (yell out while the diver is rotating in the air, signalling the point where they should stop rotating to enter the water correctly). For these reasons, divers are unable to work on skills without a coach over seeing training. Additional precautions are taken by elite divers to ensure their safety during complex dives. Each athlete carries a ‘chamois’ (small towel) that they use to dry themselves between each dive. Removing the water from their bodies prevents their hands from slipping when they ‘grab’ their legs in a tucked or piked position, similar to gymnasts using chalk powder to grip apparatus.

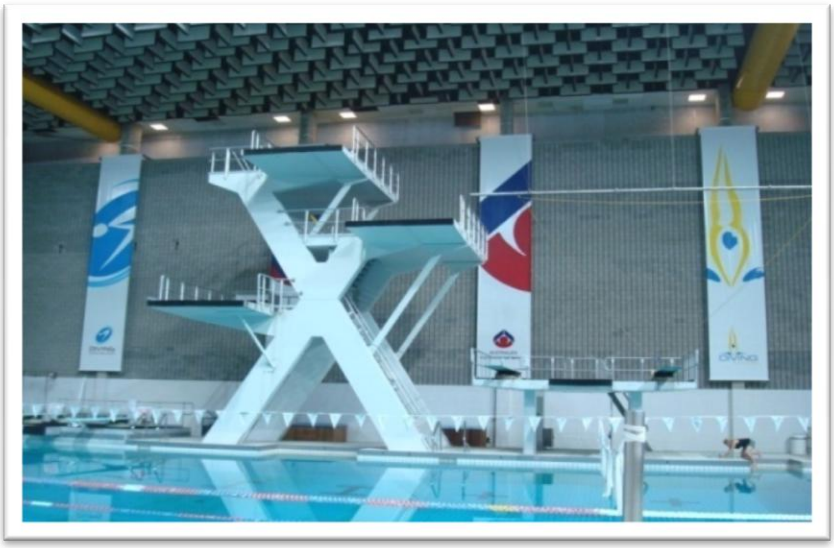
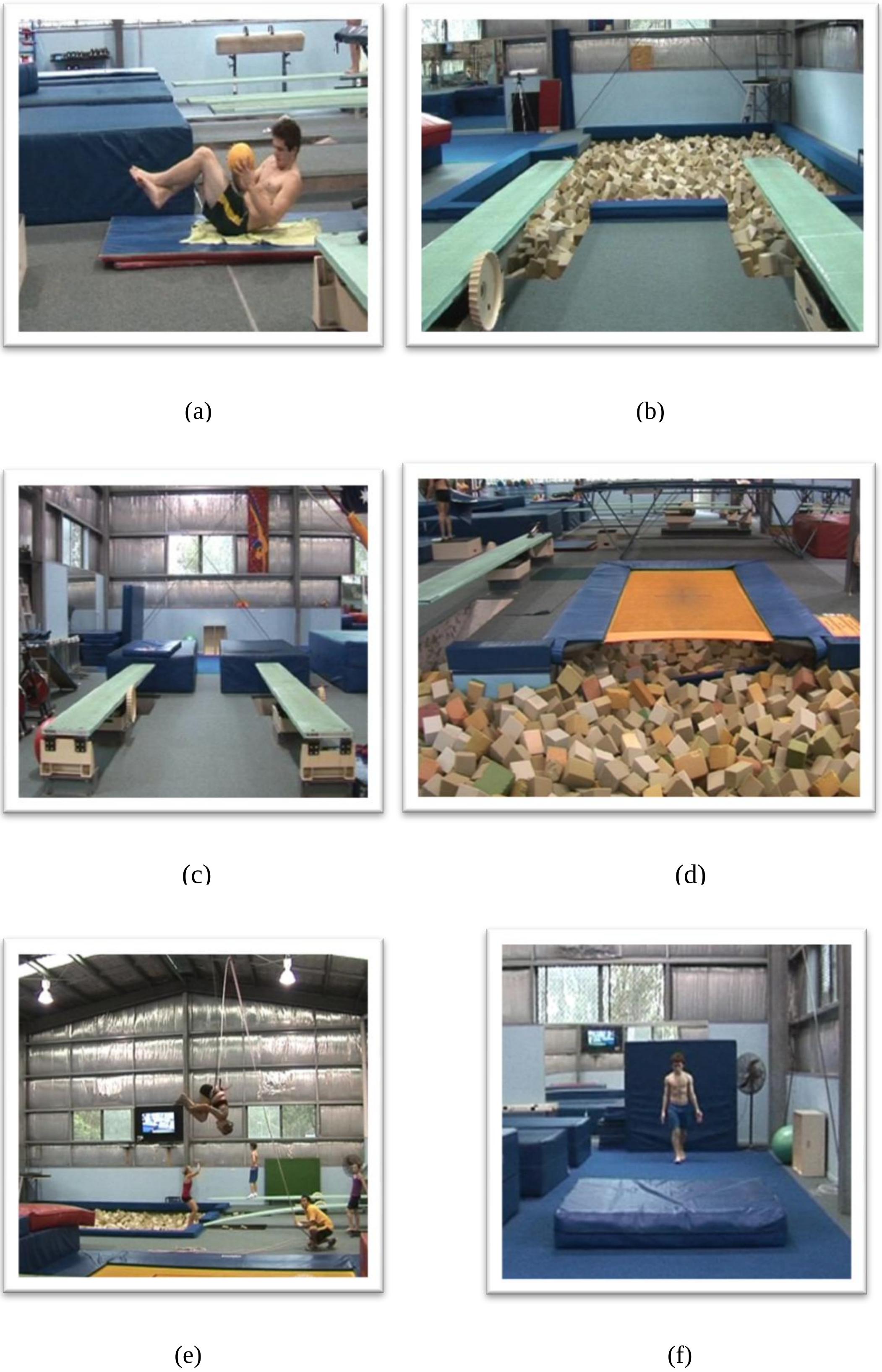


Figure 2-1 The diving tower in the aquatic centre

Dry-land

The dry-land training environment is a purpose built gymnasium designed for land-based diving practice (see Figure 2-2 (a-f)). The divers use this centre to warm up, for strength and conditioning skills (a) and to part-practice diving skills. Foam pits with springboards (pit boards) are set up for divers to practice the early phases of the dives with a feet first entry (b). Dry-boards with foam crash pads are also available for practising dive preparation and take-offs (c). Trampolines in the dry-land facility are used by the divers for practising the somersault and twist phases of the dives (d-e). Anecdotally, the dry-land facility allows divers to get through a higher volume of dives during practice than they can in the pool environment where time is lost exiting the water and climbing towers (personal communication, Hui Tong, Head Coach, August 2009). This type of environment also allows the coach to get closer to the athlete and provide haptic feedback, manually placing the athlete in key positions; ‘spot’ movements, standing next to the rotating athlete to help with rotation if needed; and to help the athlete get the ‘feel’ for new skills controlling their height with a harness (d). Further, the dry-land training environment allows the divers to decompose tasks, isolate phases of the skill, and practice them independently. For example, the approach step, hurdle step, hurdle jump and take-off can be practiced on the dry/ pit boards; and the somersaulting phase can be practiced on mats on the floor, on the trampoline, in a harness or into the foam pit. However, the constraints of the dry-land environment prevent the completion of the same number of somersaults that are possible in the aquatic environment. For example, in the dry-land the diver can only complete one or two somersaults before landing feet first on the mat or in the pit. Although it has traditionally been assumed that divers are able to practice the same preparation phase, take-off and initial aerial rotation in both environments, as yet, there is no evidence to suggest that skills practiced in the dry-land are positively transferred to the main aquatic performance environment.

In the extant literature on learning design, there has been little applied research using elite athletic populations’ and none specific to diving. In particular, the use of two separate training facilities (aquatic and dry-land) poses an interesting problem for learning in diving, given the inherent differences in the training environment, notably the key perceptual information and the movement task itself (head first vs. feet first). This current investigation will examine the influence of task representativeness and action fidelity across aquatic and dry environments in a high performance diving programme (Study One, Chapter Three). Measurements of task performance like (e.g. flight time, board depression, joint kinematics) will be used to establish the fidelity between the two environments and assist in determining the representative nature of the two training environments.



(a) (b) (c) (d) (e) (f)

Figure 2-2 The dry-land training environment

Biomechanical analysis of diving technique

Springboard characteristics

Many significant changes have occurred in competitive springboard diving since its introduction to the modern Olympics. Springboards, which were once rigid wooden planks sloping upward, have undergone a radical transformation into tapered and perforated aluminium alloy boards mounted level and fitted with moveable fulcrums (Miller, Pizzimenti, & Jones, 1989). The difficulty of dives performed in springboard competitions have steadily increased during the past 30 years (Miller, 2008; Sprigings, 1990). Where once only few elite competitors were capable of performing front 1½ somersaults from a 3m springboard, dives like a front 4½ somersaults are now being performed routinely. Although much of this improvement in performance can be attributed to the development of better coaching methods, advances in springboard technology have undoubtedly played a significant role (Sprigings, 1990).

As an engineering system, the modern springboard is extremely complex (Miller, Osborne, & Jones, 1998). The board is 4.8 m long and 0.5 m wide and constructed of a basic ribbed one-piece extrusion of aluminium alloy. A moveable fulcrum is located at the thickest region of the springboard (0.051 m) and from this point the board is machine tapered back to the hinged anchor (0.032 m) and forward to the tip (0.022 m) (Jones & Miller, 1996; Miller, et al., 1998). The area at the tip of the board (labelled C in Figure 2-3) includes perforations making this region more compliant than the rest of the board.

In order to execute a successful springboard dive, the athlete must interact effectively with this complex mechanical system during the approach and take-off phases (Kooi & Kuipers, 1994; Miller, 1998). During these phases, the springboard acts like a linear spring, where, applying a load to the springboard causes the tip of the board to move down in proportion to the load (Miller, 2008; Sprigings, 1990). A greater load causes a greater deflection, therefore obeying Hooke’s law; that elastic material strain is directly proportional to stress (Miller, 2008).

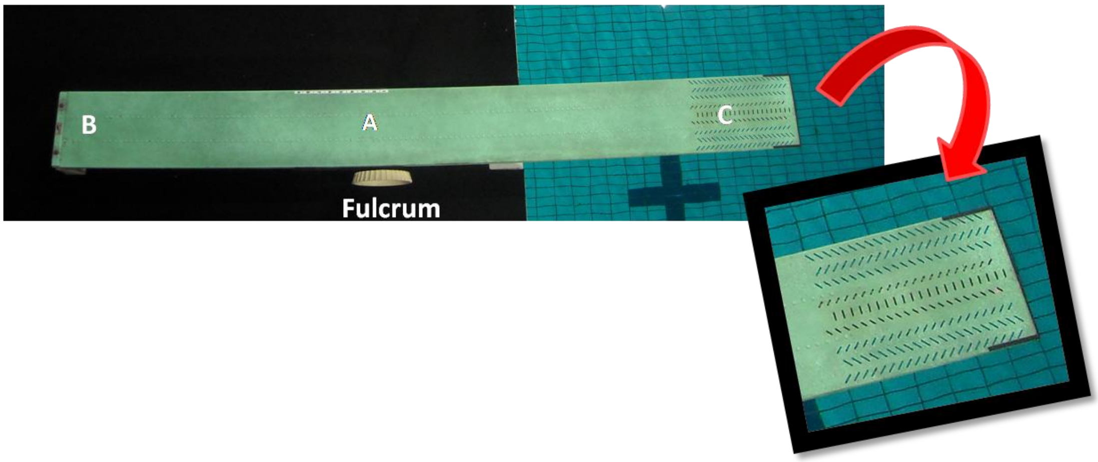


Figure 2-3 (A) Region of greatest thickness (B) Hinged anchor (C) Perforated board tip

The relationship between load and deflection is given by the spring constant (*k*), which has units of N.m^{-1}. A board with a spring constant of 5000 N.m^{-1} requires a force of 5000 N to deflect 1 m (Miller, 2008). A load (like a diver) that is applied to the board between the fulcrum and the tip, and then removed quickly will cause the board tip to oscillate up and down. A small deflection will cause the board to remain in contact with the fulcrum and oscillate in a regular fashion with the oscillations becoming progressively smaller (Miller, 2008). A large deflection, similar to the support phases of the hurdle and take-off, will cause the board to lose contact with the fulcrum as it rides up. During the subsequent downward motion, it will collide with and bounce off the fulcrum. These deflection and oscillation characteristics are influenced by the position of the fulcrum of the springboard (Miller, 2008).

The position of the fulcrum can be manipulated forward or back and is identified by a number, 1-9, that can be read from a tape fixed to the board surface. Years of training and experience allow highly skilled divers to select optimal fulcrum settings for performance (Miller, 2008). When the fulcrum is closest to the free end (lower fulcrum numbers), the board is said to be stiff or hard. When the fulcrum is closer to the hinged anchor end (higher fulcrum numbers), the board is described as being loose, soft or compliant (Miller, 2008). The difference in stiffness between the tightest and loosest fulcrum settings is approximately 1500 N.m^{-1}. If the fulcrum is moved towards the board tip, making it stiffer, the board oscillates more quickly. Conversely, moving the fulcrum back towards the anchor causes the board to become more compliant. When it is loaded and released the result is a more slowly oscillating board (Miller, 2008). Divers tend to select different positions for running (forward and reverse) and standing (backward and inward) approaches, with most divers having the fulcrum back further from the tip for running approaches, which provides a softer, looser board (Jones & Miller, 1996).

For a given fulcrum setting and all else being equal, the board deflection and oscillation characteristics are also affected by the location and magnitude of any load applied to the board (Miller, 2008). A board that is loaded, as with a diver, will deflect the board more if the force is applied closer to the end of the board tip than if it is applied nearer the fulcrum (Miller, 2008). Therefore a diver who lands back from the end of the board in a take-off will not be able to depress the board as far as a diver who lands on the end (Miller, 2008).

Appreciating the characteristics of the springboard are particularly important for understanding the variable environment within which the divers train and compete. For example, increases in the oscillation of the board (resulting from changes in location and magnitude of force application) result in increases in the variability of the environment (the board oscillates faster or slower). This may have practical implications for understanding divers' training behaviour. For example, if a diver lands back from the end of the board (as mentioned above), this may cause divers to baulk (not complete the take-off phase of the dive) as they believe they are unable to generate enough height to complete the required rotations to complete the dive successfully. However, it may be advantageous for elite athletes to gain valuable experience in adapting to variability in their movement patterns or environmental changes (e.g. an oscillating board) and attempt to complete a quality dive under varying take-off conditions. While previous research has theoretically and empirically supported the notion of functional variability in performance (Davids, Bennett, & Newell, 2004; Davids, Bennett, et al., 2006; Davids, et al., 2003), there have previously been no attempts to introduce this important idea into an elite sport performance training programme (see Chapter Two, Movement pattern variability).

Springboard diving mechanics of the front and reverse dives

Springboard dives from the forward and reverse groups include the approach steps, hurdle step, take-off, flight and entry into the water. Because the initial conditions of the flight, specifically, the angle of projection at take-off, velocity of the centre of mass, and angular momentum, are established during the take-off, this phase plays a major role in determining the success of the dive (Bergmaier, Wettstein, & Wartenweiler, 1971; Miller, 1974). During the take-off, divers' must produce sufficient vertical momentum for the flight of the dive, adequate horizontal momentum to clear the take-off surface and enough angular momentum to execute the required number of twists and /or somersaults (Miller, 1974). The success of the dive is determined by a combination of the divers' position at last contact with the take-off surface and the magnitude and direction of the forces and that have been applied during the take-off phase. Consequently, the actions of the diver in the air are largely dependent on their actions before they leave the board. This is an important point to consider in the design of training programmes for elite and developing springboard divers, as outlined later in this document.

Approach, hurdle and take-off

In the performance of springboard dives from either the forward or the reverse group, the diver begins with an approach consisting of a minimum of 2 steps followed by a hurdle and take-off (see Figure 2-4). The major function of the approach and hurdle in running springboard dives is to establish optimal conditions for an effective take-off. While there are several reports on the biomechanical aspects of the take-off (Batterman, 1968; Golden, 1981; Miller, 1981; Miller & Munro, 1984), only Miller and Munro (1984) have focussed upon the performances of nationally ranked divers and these were in a competitive environment.

Final approach step

The final approach step is defined as the period between toe-off of one foot and toe-off of the opposite foot immediately preceding hurdle flight. During the support phase following the final step the diver builds up horizontal and vertical velocity needed for the hurdle flight (see Figure 2-4) (Miller, 1984). A good diver is lifted into the hurdle by the action of the board, not by jumping up himself or herself.

Consequently, the foot placement of the third step is critical and serves to help push the board down. As the knee flexes, mass of the body moves down and the momentum starts depressing the board. At the same time the lifting of the arms and the other knee increase the downward force because, according to Newton's third law, the reaction to these lifting movements is a downward press of the body against the board (Batterman, 1968).

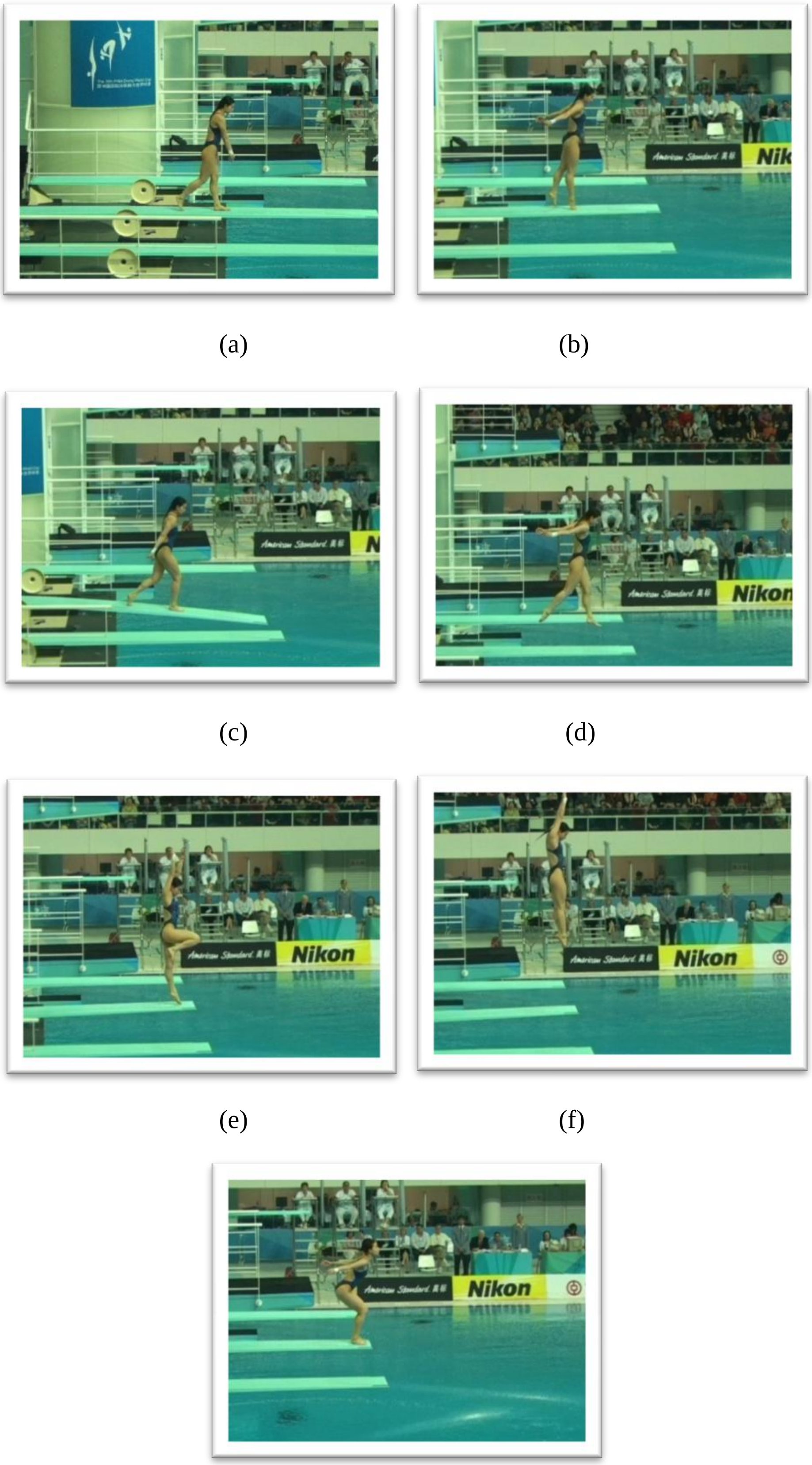
Hurdle

Traditionally, the hurdle step is the length of a normal step and moves in a forward direction with the same momentum as the preceding two steps (Batterman, 1968). In executing the hurdle, the diver steps off one foot and travels forward to the end of the board (see Figure 2-4). The application of force by the diver to depress the board during hurdle support, and its subsequent release during hurdle flight, causes the board-tip to oscillate. Hurdle flight encompasses the airborne phase of the movement and occurs between last contact with the hurdle support foot and initial contact with both feet near the end of the board to begin the take-off (Miller, 1984). The process of generating the necessary vertical velocity for the flight phase of the dive begins during the support phase preceding the hurdle. While free in the air during the hurdle, the diver is influenced only by gravitational force. Consequently, vertical velocity decreases to a value of zero at the peak and then becomes progressively more negative during descent back to the board (Miller, 1983). The magnitude of the diver's downward velocity at the end of the hurdle jump is determined by the peak height of the jump. The diver's centre of gravity is shown to be considerably lower at touch-down than at the beginning of the hurdle, averaging 31 cm and 26 cm lower for men and women respectively (Miller, 1983).

With a long hurdle step, the diver has considerable forward momentum so that after the feet land and are stopped by friction, the body continues to move forward. Due to inertia, the momentum remains constant and the diver lands at the end of the board with no lean. The lean develops after the feet land, during the time the board moves up and down (Batterman, 1968). During the drop back to the board, the head is rotated down, eyes looking at the end of the board. The body is straight, and the diver falls back to the board, landing on the balls of their feet. As the diver falls, their arms circle back, down and around. This causes a downward force that is transmitted to the board with both feet to begin the take-off (Batterman, 1968).

Take-off: Depression

The take-off phase of the dive is divided into two parts: the depression and recoil. Depression of the board in the forward approach occurs during the hurdle and take-off. At the end of the last step of the three-step approach, the board is depressed by the diver's body weight. When the board is depressed during the support phase of the take-off, elastic strain energy is stored in the board (Miller, 1983; Sanders & Wilson, 1988). The extent of the depression of the board is further increased through flexion of the knee of the supporting leg, which lowers the body weight, and by simultaneous forward and upward lifting of the arms and the knee of the non-supporting leg (Michaels & Kerr, 1980; Miller, 1998). The amount of energy stored depends upon the stiffness of the spring and how much it is depressed. Much of the energy stored in the springboard at maximum depression is available to help project the diver into the flight of the dive. Assuming the diver can catch the board (time the landing of their jump with the oscillation of the springboard) effectively, the higher the hurdle, the greater the diver's downward velocity on contact with the board and the more kinetic energy that can be transferred to the board to aid in its depression.



(a) (b)

(c) (d)

(e) (f)

(g)

Figure 2-4 Key events of a forward and reverse take-off (a) the final approach step, (b-c) the hurdle step, (d-e) the right leg driving the diver into the air, (f) peak height of the hurdle jump, (g) landing from hurdle jump just prior to take-off

The contact force (reaction) exerted by the board on the diver is equal in magnitude and opposite in direction to that exerted by the diver on the board (action) in accordance with Newton’s Third Law of Motion (Batterman, 1968; Michaels & Kerr, 1980; Miller, 1981; Panayi & Hosford, 1993). Specifically, if the diver pushes down and back toward the fulcrum, the board reacts with an upward and forward force of an equal size. The magnitude of the reaction force can be determined from Newton’s Second Law where, the Sum of the force (F) = mass of the diver (m) x acceleration (a). Since only two external forces act on the diver, weight (W) and reaction force (R), this relationship can be stated as R-W=ma. Therefore, a direct relationship exists between the springboard reaction and the product of the diver’s mass (m) and the acceleration (a) of the centre of gravity (COG) (Miller, 1981).

To supplement board depression resulting from the diver’s kinetic energy at the beginning of the take-off, divers use knee extension, trunk rotation and arm-swing to accelerate upwards with respect to the board. Because the board is compliant, this relative acceleration assists in pushing the board down. Divers have a definitive period of upward acceleration with respect to the board during the initial half of springboard depression (Miller & Munro, 1984; Sanders & Wilson, 1988). This relative upward acceleration occurs as a result of the arms slowing their downward velocity at the end of the downswing and then increasing their upward velocity at the beginning of the upswing. The lower arm segments therefore push down against the shoulders during this period. If the diver is in contact with the board and the segment link system of the diver’s body is sufficiently rigid, this relative arm force will be transmitted down through the body to help depress the springboard.

Take-off: Recoil

During the take-off, the board is depressed and then recoils, projecting the diver up and slightly forward into the flight of the dive (Miller, et al., 1998). As the board begins to rise, the arms continue to reach, and the diver rides the lifting board, extending the legs and pointing the toes. With the final lift of the board, the arms continue to reach up in reverse dives or begin to move down in forward spinning dives, before the feet leave the board. During the recoil, plantar-flexion occurs at the ankle and most of the angular momentum needed for flight is generated. During dive preparation there is little, if any, total body angular momentum with respect to the COG. As the take-off proceeds, for the reverse group, the total body angular momentum is in the intended direction of rotation since the rotational direction of the trunk and arms does not change (Miller, 2008). Once the diver leaves the board the body is projected upward at an angle and the body's centre of gravity moves in a parabolic path with the horizontal velocity remaining constant (Batterman, 1968). The path of the centre of gravity from take-off becomes unalterable regardless of changes to the shape of the body itself, without the introduction of an outside force. For example, when a diver leaves the board for any dive, whether he spins into a two-and-a-half somersaults, twists, goes forwards or reverse, the path of the centre of gravity remains parabolic (Batterman, 1968; Golden, 1995). However, the body position and the distribution of its mass around the COG may change.

When body rotations are required, the horizontal force component should be increased as the number of rotations required increases. Once the body is in free space the diver has the same angular momentum from take-off until they enter the water (Michaels & Kerr, 1980). Since angular momentum is the product of the body's inertia and angular velocity, the diver can manipulate either component, which induces a change in the other. For example, the speed of rotation is a direct result of the distance of the body segmental masses from the axis of ration, COG. When the diver is in a layout position, all body parts are a maximal distance from the spinning axis. Here, the moment of inertia is at its greatest and the velocity of rotation at its least. In a tight tuck position however, all the body parts are as close to the axis of rotation as possible and consequently the moment of inertia is at its least and the velocity of rotation at its greatest (Michaels & Kerr, 1980; Panayi & Hosford, 1993).

The amount of time in the air is of fundamental importance to the success or failure of any diver's performance. The complex aerial manoeuvres being completed have become so demanding that fractions of a second often determine whether a dive can be completed as planned. Whether adequate time in the air is achieved for any dive depends on the diver's vertical velocity at the time of take-off.

Scientific investigation of springboard biomechanics during the past 30 years has provided a comprehensive overview of the key factors critical for success in springboard diving and showed that small changes in body position or the application of force in slightly varying board locations can lead to significant variations in springboard oscillation, creating a highly changeable and dynamic performance environment (Brown & Abraham, 1981; Golden, 1981, 1995; Kooi & Kuipers, 1994; Miller, 1983; Miller, et al., 1998; O'Brien, 1992). These insights are important since biomechanical analyses of preparatory movements in diving have highlighted the significance of the approach and hurdle steps for the successful execution of the complete dive. However, although detailed analysis has been provided with reference to technique (Miller, 1974, 1983, 1985; Miller & Munro, 1984, 1985a, 1985b; Miller, et al., 1989; Miller & Sprigings, 2001; Murtaugh & Miller, 2001; Sanders & Wilson, 1988), the initiation of height and rotation (Golden, 1981, 1995), momentum (Miller, 1981), and the characteristics of successful entries (Brown, 1982; Brown & Abraham, 1981; Brown, Abraham, & Bertin, 1984), the data collected is limited by the use of traditional experimental designs, which determined the average response within a group of divers. This is important as recent arguments in behavioural sciences have demonstrated how individual participants behaviour can be masked by averaging performance data for statistical analysis (Schöllhorn, et al., 2009). Further, in the existing literature, the analysed performances are rarely of nationally or internationally ranked divers and, as such, the extent to which the results can be interpreted and applied to an elite population is limited. Finally, to date, all analyses have been conducted retrospectively from competition or television footage (Miller, 1983; Miller & Munro, 1985a, 1985b; Miller, et al., 1989) and there have been no attempts to investigate athlete behaviours or the adequacy of learning design and environment in elite springboard diving.

Movement pattern variability

Variability in human movement patterns

Variability in human movement encompasses the normal variations that occur in motor performance across multiple repetitions of a task over time (Harbourne & Stergiou, 2009; Stergiou, Harbourne, & Cavanagh, 2006). Variability in movement is inherent within all biological systems and reflects variation in both space and time (Stergiou, et al., 2006). For example, as a person walks through sand or snow his or her footprints never repeat exactly, reflecting variability from step to step in a continuous cycle of movement (Harbourne & Stergiou, 2009). Subsequently, motor variability is inherently present throughout the multiple levels of movement organisation and occurs not only between, but also within individuals (Bartlett, Wheat, & Robins, 2007; Preatoni, Ferrario, Dona, Hamill, & Rodano, 2010).

Traditionally, the development of consistent performance outcomes by experts through hours of practice have been interpreted as evidence for a motor programme theory of control (Schmidt, 1975). This information processing approach, assumes that information has to be symbolically represented and processed in order to be meaningful to the performer. Further, that a set of instructions for movement, is organised prior to their execution (Schmidt, 1975). This set of instructions or information is then accumulated in various ‘storage systems’ called memory, from where the information can be recalled and ‘processed’. The term ‘processed’ suggests that the information is coded, that its code may be changed from one form to another, and that the information may be combined with other information. Finally, the stored information can be processed in various ways until eventually it is output as observable motor behaviour.

In this basic chronometric approach, the main measure of a participant’s behaviour is the interval between the presentation of a stimulus and the beginning of the response, inferring what happened in the stages in between (Anson, et al., 2005). Commonly, these stages are identified as stimulus identification, response selection, and response programming. The ability of the human brain to discriminate between the identified stimuli, allows all the selection processes to be identified and the best option chosen from among a specific set of alternatives. However, if the selections are to convey information to the performer, then the set of choices must be known in advance. By viewing the human performer as a linear, deterministic, control system, the problem of noise, or variability in motor output, can be eliminated or minimised through practice and task experience (Anson, et al., 2005). The consistency of movement is then argued to be the result of consistent motor programming (Bootsma & van Wieringen, 1990; Miller, 2000; Schmidt, 1975). Consequently, decreased variability is associated with increased competence, skill and health (van Emmerik & van Wegen, 2002).

If this were true, it seems reasonable to expect that consistent movement patterns would produce consistent movement outcomes in a static environment (Kudo, Ito, Tsutsui, Yamamoto, & Ishikura, 2000). For example, if a throwing action aimed at a stationary target becomes consistent, it could be assumed that the release parameters, which determine the trajectory of the projectile, would also become consistent, resulting in consistency of the overall performance. Vorro (1973) observed that with 20 days of practice, limb velocity as well as performance outcome in a novel underarm ball-throwing task became more consistent. Similarly, Higgins and Spaeth (1972) found that the variability of the limb trajectory and the release point was decreased with practice in a dart throwing task (Higgins & Spaeth, 1972).

However, if measured precisely, results showed that neither the trajectories of the projectile nor the throwing movements were exactly the same from trial to trial (Kudo, et al., 2000). Instead, research by Bernstein (1967), Arutyunyan, Gurfinkel and Mirskii (1968), Bootsma and van Wieringen (1990) and Vereijken, Whiting, Newell and van Emmerik (1992) suggested that consistent performance outcomes are accomplished by variable and complementary combined execution parameters rather than by fixed parameters with redundant DOF. More succinctly, outcome consistency does not require movement consistency (Bartlett, et al., 2007). Dynamical systems theory has provided an opportunity to theoretically re-evaluate the role of variability in movement behaviour. This re-evaluation is necessary, as traditional perspectives do not sufficiently account for the observation that some behaviour, which appears stable, paradoxically are performed in variable ways. This is especially evident when we observe elite sports players or musicians performing complex activities (i.e. Michael Jordon taking a jump shot or Roger Federer playing a cross court forehand). Not only is their performance more consistent than that of less capable individuals, but they also seem to have developed an infinite number of ways of performing. These individuals display a very stable behavioural state underlined by a ‘rich’ behavioural repertoire (Stergiou, et al., 2006).

Functional variability

The term stability implies something that is reproducible, enduring and resistant to change, while adaptability is suggestive of a more dynamic, temporary, and flexible behaviour. Paradoxically, everyday patterns of coordinated movement like standing or walking have been shown to be simultaneously stable and variable (Edwards, 1942; Riley & Turvey, 2002). They remain persistent in the face of perturbations, sustainable for relatively long periods and reproducible with a high degree of accuracy. At the same time, they are variable, from moment to moment and instance to instance. Historically, motor control theorists have struggled to explain such dexterity in human movement behaviour. Although movement pattern variability has traditionally been viewed by biomechanists as noise or error that must be eliminated, dynamical systems theory proposes an alternative approach to understanding variability in performance (Bartlett, et al., 2007). The introduction of the concepts and tools of non-linear dynamics and chaos theory to motor control has led to the possibility of interpreting movement variability as more than mere random variation. Random processes defy predictions of future states from earlier states, since randomness refers to the equi-probability of events occurring; which differs from variability, since a behaviour can be variable and yet deterministic (in that future events can be predicted from previous events) (Davids, Bennett, et al., 2004). Alternatively, the motor system's inherent noisiness results in variability being omnipresent, unavoidable in all high-dimensional complex systems. Nevertheless, this variability is functionally useful in allowing movement outcomes to be achieved in many different ways by dynamical movement systems.

Movement variability within expert individuals can be considered functional when it supports the performance flexibility needed to adapt to changing environmental constraints, where consistent performance outcomes can be achieved by different patterns of joint coordination available through the joint's biomechanical degrees of freedom (DOF) (Bernstein, 1967; Davids & Glazier, 2010). Klingsporn (1973) argued that variability is functional, and a necessary prerequisite to adaptation, whether genetic or behavioural, and that the sources of variability are intrinsic to the organism. Functional or compensatory variability therefore, refers to variability over which the individual has or can acquire control and which is essential for normal development (Bootsma & van Wieringen, 1990; Manoel & Connolly, 1995). Consequently, variability may be interpreted as the flexibility of the system to explore different strategies to find the most proficient one among the many available. This flexibility allows for learning a new movement or adjusting the already known one by gradually selecting the most appropriate pattern for the actual task (Preatoni, et al., 2010). For example, the performances of an apparently stable movement pattern, such as a penalty kick, under different weather conditions and on different terrains.

In the engineering of control systems, *redundancy* is built in to allow system components to take over processes when a specific component fails (Mason, 2010). In neurobiological systems, *degeneracy*, the ability of elements that are structurally different to perform the same function or yield the same output, (Edelman & Gally, 2001) provides the conceptual basis to explain movement pattern variability in performance. Essentially, it suggests that outcome consistency does not require movement pattern consistency (Bartlett, et al., 2007). Instead, a diversity of movement patterns may be functional in negotiating dynamic environments and may have specific importance in unpredictable environmental situations, e.g. bouncing on an oscillating springboard (Araújo & Davids, 2011; Davids, et al., 2007).

Inherent variability within human motor behaviour (facilitated by multiple system degrees of freedom) creates instability during the organisation of action and can be exploited to promote motor learning and performance (Newell & Corcos, 1991). Evidence of both inherent and functional coordination variability in sports performance has emerged from numerous studies of performance in a wide range of dynamic tasks including triple jumping (Wilson, et al., 2008), basketball shooting (Button, MacLeod, Sanders, & Coleman, 2003), table tennis (Bootsma & van Wieringen, 1990), locomotion (Hamill, van Emmerick, & Heiderscheit, 1999) and throwing (Bartlett, Muller, Lindinger, Brunner, & Morris, 1996; Bauer & Schöllhorn, 1997), as well as static tasks such as pistol shooting (Arutyunyan, et al., 1968; Scholz, Schöner, & Latash, 2000). The findings of these investigations have provided clear evidence that individual performers are capable of discovering different ways to achieve the goals of the task, even under similar performance constraints, through the coordination and control of a variety of functional movement patterns (Chow, Davids, Button, & Koh, 2008; Edelman & Gally, 2001).

An ability to solve the same motor problem by different or variable execution parameters becomes especially important when the external environment is dynamic, as skilled performance emerges from the dynamic relationship between the organism, its environment and the task. Skilled actions are considered to be those that are purposeful and reliable and are directed at attaining a particular goal consistently (Manoel & Connolly, 1995). Subsequently, the development of goal directed behaviour has been seen as a transition from variable and inconsistent actions to patterned, consistent ones.

Research has shown that skilled athletes are able to: produce functional, efficient and effective movement patterns that appear smooth and effortless; coordinate their actions successfully, with respect to important environmental surfaces, objects, and other individuals, demonstrating precise timing between movements; consistently reproduce stable and functional patterns of coordinated movements under competitive pressures; perform movements that are not automated in the sense of being identical from one performance to the next, but are subtly varied and precisely adapted to immediate changes in the environment; integrate different limb movements into an aesthetically pleasing pattern when necessary (Araújo, et al., 2004; Davids, Bennett, et al., 2004, 2006; Davids, Button, & Bennett, 2004; Davids, et al., 2003).

The development of skilled actions implies that a growing consistency and invariance is necessary to achieve system stability. Paradoxically, this comes about as a result of the individual's greater use of functional variability (Manoel & Connolly, 1995). For example Arutyunyan, Gurfinkel and Mirskii (1968) examined the shooting performance of skilled and unskilled marksmen, and identified different levels of variability at each joint of the upper arm in skilled performers. Greater variability was observed in the shoulder and elbow joints, allowing the wrist to maintain a stable position. The same patterns of functional variability were not observed in the unskilled shooters. The results of research conducted by Bauer and Schöllhorn (1997) also challenged the traditional view, that expert performance is characterised by invariant features, with higher levels of inter-individual variation observed within clusters of international discus throwers, when compared with the national athletes. Further, an analyses of javelin throwing release speed by Morris, Bartlett and Fowler (1997), reported significant differences between throwing styles and acceleration techniques of the silver and gold medallists and still further differences amongst the remaining competitors who displayed variations of the two distinct throwing styles. The authors argued that such differences, refute the existence of an optimal movement pattern or technique, and highlight the problems associated with learners trying to copy the most successful performers, rather than assemble their own movement solution (Bartlett, et al., 2007).

Although studies investigating motor programme control have reported very high levels of intra-individual consistency in skilled performers (Schmidt, 1985), research has shown that the distribution of variability *within* each trial can vary. For example, Bootsma and van Wieringen (1990), showed greater variation existed in the trajectory of a skilled player's paddle at the beginning of the forehand drive in table tennis. Further analysis showed that this level of variability was reduced to a minimal amount at the movement endpoint, or at the point of contact with the ball. Bootsma and van Wieringen viewed this reduction as a functional response by the skilled players and suggested that too much variability in spatial displacement of the paddle at the point of contact, would make the ball extremely difficult to control and would be a characteristic of novice and intermediate players (Bootsma & van Wieringen, 1990).

Similarly, empirical evidence in long-jump suggests that performers exhibit a two-phase approach strategy that includes: 1) an initial acceleration phase during which athletes attempt to maintain a stable stride pattern while progressively increasing their stride length as they accelerate down the track; followed by 2) a zeroing-in phase during which athletes attempt to modify stride length parameters over the final strides (Scott, Li, & Davids, 1997). Analyses of inter-trial footfall variability, in relation to the take–off board, demonstrated an ascending-descending trend that corresponded with the two distinct run-up phases (Scott, et al., 1997). During the acceleration phase, small inconsistencies in stride length, representative of inherent variability effects in motor systems, are accumulated until approximately four strides prior to the take-off board. The authors contend that after optimal horizontal velocity has been reached, visual control takes over during the zeroing in phase and stride length is regulated to remove the initial variability created during the acceleration phase, indicating that the variability observed in the last four strides is functional (Scott, et al., 1997).

Consistency and invariance in movements have traditionally been seen as the essential features of motor skill acquisition and development (Manoel & Connolly, 1995). This emphasis on the stabilisation of action has led to researchers traditionally overlooking the important process of movement adaptations in novel and more complex tasks with many sub-phases. Recent research has argued that this variability of motor behaviour has a major role in the adaptive process and consequently in the development of skilled actions (Bartlett, et al., 2007; Davids, et al., 2003; Manoel & Connolly, 1995). Although variability has often been viewed as noise or measurement error that needs to be eliminated, dynamical systems theory offers an alternative approach to understanding variability in performance (Davids, et al., 2008). Individual differences, and performance circumstances are constantly changing, consequently, variability of motor performance plays a functional role in helping people to adapt to constraints.

Variability in springboard diving: Baulking

Traditionally, it has been argued that a reduction in movement pattern variability is a characteristic of expert performance (Bartlett, et al., 2007), resulting in a decrease in performance variability as a learner becomes more skilful (Bootsma & van Wieringen, 1990; Higgins & Spaeth, 1972; O'Brien, 1992; Slobounov, Yukelson, & O'Brien, 1997). Based on these theoretical insights, some coaches, athletes and sport scientists believe that skilled performance in sport is characterised by a reduction of variability in movement patterns achieved through extensive training and practice over thousands of hours (O'Brien, 1992; Todorov & Jordan, 2002). Consequently, coaching practice has been dominated by highly repetitive training sessions which emphasise invariant repetition of a perceived optimal movement pattern (Brisson & Alain, 1996; O'Brien, 1992). This is particularly true of aesthetic sports, like gymnastics or diving, where movement form is a major task constraint. In these tasks, external environments can vary, yet great importance is placed on production of stable repeatable performance outcomes, which are judged subjectively using strict criteria-based guidelines for how actions should look (see the FINA handbook for detailed dive descriptions (2009-2013). The existence of these performance criteria may further contribute to the athlete’s desire to assemble a reproducible, invariant movement pattern, rather than allowing and encouraging functional variability in the performance of a dive or gymnastic skill[1].

However, motor learning research has demonstrated how adaptability and stability both form central parts of the learning process (Handford, 2006). For

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[1] It is important to note, that although divers in particular may find changes to movement patterns alter the execution of the task, ultimately influencing the performance outcome (e.g. changes to foot placement on the spring board may influence final dive entry into the water), these variations are not directly assessed by the judges. Instead, judging focuses on the overall aesthetics of the movement and the resulting performance outcome.

example, learners gain confidence from being able to perform a movement consistently. By recognising how behavioural demands can be mapped onto existing movement tendencies, the learner is able to establish strong information-movement couplings that encourage such stability (Davids, Bennett, et al., 2004; Davids, et al., 2003; Handford, 2006). Alternatively, unpredictable practice environments may facilitate adaptability in learners allowing them to cope with novel task constraints as performance conditions change.

Observations of high performance divers (Australian and International) training behaviour have revealed that squad members ‘baulk’ frequently if they consider the preparation phase of the dive to be imperfect (personal observation of daily training sessions). A baulked dive is defined as a take-off where the diver completes the approach and hurdle steps, but aborts the intended movement before the take-off phase (FINA, 2009-2013). Examples of this phenomenon can be seen in other sports (particularly those with a locomotive component) where athletes begin the initial preparatory phase of the action but do not complete the full skill e.g. long jump, high jump, pole vault, volleyball spike. The implication of this approach is that athletes only practice the execution of dives off what they perceive to be a ‘good’ approach and hurdle phase. Despite this common practice, currently, there is no empirical evidence to suggest the existence of significant movement pattern differences (temporal, kinematic or kinetic) in the preparation phase of baulked and completed dives in high performance athletes. It is possible; therefore, that this training habit is predicated on the misconception that only the best dives must be practiced at all times in order to enhance skill in a sport like diving. Put simply, divers may be baulking in response to slight inevitable variations in their approach phase, essentially, stopping and restarting instead of trying to adapt and use a different strategy for solving the movement problem, as required under competitive task constraints. Since the athletes attempt to eliminate take-off variations during training, skilled divers may not be affording themselves the opportunity to develop compensatory movement strategies to achieve a required performance outcome goal (rip entry into the water with minimal splash), from a varied take-off movement pattern.

The findings of previous research provide a powerful rationale for clinicians and coaches to reconsider functional variability or adaptability of motor behaviour as a key criterion of successful performance, rather than the ability of all performers to replicate an ideal movement template or optimal motor pattern (Davids, Bennett, et al., 2004, 2006). This view of variability suggests that the motor system's inherent noisiness results in variability being ubiquitous, unavoidable and yet functional in helping to produce stable movement outcomes (Davids, Bennett, et al., 2004). Despite the search for invariance in sports performance over the past decades, previous research in the sport domain from alternative theoretical perspectives have revealed that even elite athletes are unable to reproduce invariant movement patterns, despite years of practice (Arutyunyan, et al., 1968; Bartlett, et al., 1996). Instead, empirical evidence suggests that increasing expertise does not lead to movement invariance and the construction of a single, pre-determined motor pattern, as argued in cognitive theories of motor control.

Unlike other athletic movements such as cycling, running or jumping, diving somersaulting skills require athletes to adhere to imposed movement criterion and strict aesthetic judging guidelines (Gittoes, Irwin, Mullineaux, & Kerwin, 2011). These guidelines dictating how the skill *should* look may have detrimental effects on diving practice, forcing athletes to believe that they need to follow one optimal movement pattern to satisfy the judging criteria. The role of functional variability poses interesting questions for the sport of diving, where athletes traditionally train to minimise movement pattern variability and aim for replication of a perceived optimal motor pattern. While previous research has theoretically and empirically supported the notion of functional variability in performance, there have been no attempts to introduce this important idea into an elite sport performance training programme. Chapters Four and Five examine functional variability in an elite high performance training programme that has traditionally aimed to remove variability from performance. Specifically, Chapter Four examines whether kinematic differences exist between baulked and completed take-offs, and Chapter Five determines whether a sample of elite divers are able to adapt their movement patterns and complete dive take-offs regardless of the perceived quality of their preparatory movements on the springboard.

Quantifying movement patterns

Previous motor learning research has shown that changes in joint ranges of motion and joint couplings occur with practice, and can be used to identify when learning has occurred (Anderson & Sidaway, 1994). Examples of these changes have been observed in handwriting (Newell & van Emmerick, 1989), dart throwing (McDonald, van Emmerick, & Newell, 1989), and in a ski simulator task (Vereijken, et al., 1992). Additionally, research by Sparrow and Irizarry-Lopez (1987) identified changes in the topological characteristics of movement patterns as a result of practice. These studies have typically employed one or more homogenous subject groups and presented data describing the average performance of groups in various experimental conditions (Devita & Skelly, 1990). The results of several of these studies however, suggest that the group performance may not accurately represent the individual participant's performances and therefore provides incorrect information about each performer's response to the experimental conditions (Devita & Skelly, 1990).

Alternatively, individualised, in-depth analyses, or coordination profiling, can be used to examine how each *individual performer* uniquely satisfies specific task constraints during goal-directed behaviour. This approach recognises that individuals approach performance, training, practice, and rehabilitation with distinct intrinsic movement system dynamics shaped by many important and interacting constraints.

One frequently reported type of kinematic analysis is the angle-angle diagram or coordination plot (Sidaway, Heise, & Schoenfelder-Zohdi, 1995). This type of analysis was originally used by Grieve (1968) to analyse movement patterns of the lower limbs during gait cycles, but these plots are now frequently used to demonstrate the motion of one joint relative to another (Sidaway, et al., 1995). Angle-angle diagrams plot joint angles against each other to display joint coordination and show whether the angles are in-phase (e.g. when both joints are extending), anti-phase (e.g. when one joint is extending and the other is flexing) or displaying decoupled coordination (e.g. both joints flex, then one continues to flex whilst the other extends) (Bartlett, 2007). This technique allows easy qualitative comparisons of joint angles and distinguishing differences in patterns can be achieved by examining the 'topological equivalence' of the diagrams. Shapes are considered to be topologically equivalent if one can just be ‘stretched’ to form the other (e.g., the shapes are the same, but one is slightly smaller than the other). The shapes are not considered topologically equivalent if one has to be ‘folded’ rather than just stretched to form the other (e.g., the fundamental shape of the diagrams are different) (Bartlett, 2007). The topological characteristics of a movement describe the motions of the body segments relative to each other and changes in these patterns can provide evidence specific aspects of coordination change (Anderson & Sidaway, 1994; Chow, et al., 2008). For example, Southard and Higgins (1987) used a qualitative analysis of upper body movement patterns in a forehand racquetball shot, to show that increases in forearm and racquet velocities associated with practice were due to changes in the relative motion of the forearm and wrist.

A number of existing techniques have been used to quantify the coordination patterns represented by angle-angle plots including: chain-encoding (Whiting & Zernicke, 1982), cross correlation (Chow, et al., 2008; Sparrow & Irizarry-Lopez, 1987) and most commonly the correlation coefficient (Hodges, et al., 2005; McDonald, et al., 1989; Newell & van Emmerick, 1989; Vereijken, et al., 1992). This final approach correlates the changes in the angle of one joint with those of another joint. The results are expressed as a ratio demonstrating the extent to which changes in one variable are accompanied by changes in the other. However, this methodology is only appropriate when the relationship between the two sets of measures is linear (Sidaway, et al., 1995).

The variability of one dependent variable over time has traditionally be quantified by the coefficient of variation (Mullineaux, et al., 2001; Sidaway, et al., 1995), and can been used to assess the total variability across time. However, there are problems associated with using this method in quantifying variability in angle-angle plots where time is not represented on either axis (Sidaway, et al., 1995). According to Sidaway and colleagues (1995), dividing the variability of any cyclical pattern of coordination by a mean of each individual’s data, causes significant problems, creating a mean that is not representative of the non-linear pattern of coordination. Further problems could also be created by a few unrepresentative outliers who may skew the data.

Alternatively movement pattern data can be quantified by analysing changes in angle-angle plot stability. The root mean squared error is totaled for the number of trials collected and normalised with respect to the number of trials. This is called the normalised root mean squared technique (NoRMS). This method has been recommended for small trial sizes and normalised techniques (Mullineaux, 2000), and has successfully detected changes in stability of coordination in both linear and non-linear data, because unlike the correlation coefficient it is not influenced by the pattern of the coordination (Chow, Davids, & Button, 2007; Chow, et al., 2008; Sidaway, et al., 1995). Previous investigations have used angle-angle plots to depict qualitative changes in intra-limb coordination as a function of practice, and NoRMS to assess variability in the relationship between joint angles in: gait cycles of below-knee amputees (Button, Moyle, & Davids, 2010), kicking actions of skilled, intermediate and novice participants (Chow, et al., 2007), soccer chipping to different target positions (Chow, et al., 2008) and changes in coordination, control and outcome as a result of extended practice on a novel motor skill (Hodges, et al., 2005). Additionally, these investigations have used NoRMS to provide an index of consistency in intra-limb coordination, where higher NoRMS values equate to a higher level of variability in joint coordination.

Similarly, this programme of work uses angle-angle plots to *qualitatively* identify topological differences in lower limb movement coordination patterns of elite springboard divers performing complex diving tasks. Further, the amount of variability between each individual’s movement patterns is *quantified* using the NoRMS procedure established by Sidaway and colleagues (Chow, et al., 2007; Chow, et al., 2008; Sidaway, et al., 1995).

Summary

It is widely recognised that the primary purpose of practice in sport is to improve an athlete's capability to perform skills in future competitions. As such, coaches tend to primarily be interested in establishing those practice conditions that maximise the development of relatively permanent improvements in skill, that is, those that generate positive learning effects. However, training skills and environments do not always consider the importance of action fidelity, the association between behaviour in an experimental task with that of the performance setting to which it is intended to generalise. Consequently, coaching drills or tasks that facilitate optimal performance during practice sometimes result in less than optimal learning (for example, allowing athletes to remove variability from their performance by baulking or training in an environment that is different to the competition setting). Therefore, it is important that training environments are representative of performance environments to ensure that athletes are participating in effective learning and practice. The practical application of this may be important for diving where athletes currently spend up to forty percent of their training time participating in land-based activities. Consequently, important questions exist regarding the extent to which perceptions, actions and behaviours in one context, correspond to those in another context (Araújo, et al., 2007).

In traditional studies of movement pattern variability in motor learning, it has been argued that a reduction in variability is a characteristic of expert performance (Bartlett, et al., 2007). However, more recently, theoretical insights have emerged from a number of empirical studies showing the potential of movement pattern variability to be functional (Arutyunyan, et al., 1968; Bootsma & van Wieringen, 1990). These studies of motor learning have demonstrated that highly skilled athletes are not capable of invariant movement patterns, and instead are typically able to exhibit a close fit between their actions and immediate environmental demands. Further, they seem able to consistently reproduce stable patterns of coordinated activity under severe competitive pressure and can exploit passive, inertial and mechanical forces available free in the environment. For example, elite tennis players are able to improvise and produce appropriate versions of the forehand drive to suit the exact circumstances of the performance.

Although the development of skilled actions implies growing consistency and invariance necessary for the stability of the system, paradoxically, this seems to come about as a result of the individual’s greater use of functional variability. Consequently, variability in movement patterns may be interpreted as the flexibility of the system to explore different strategies to find the most proficient one among many available (Preatoni, et al., 2010). Instead of being movement ‘noise’ that must be eliminated, this flexibility allows for learning a new movement or adjusting the already known one by gradually selecting the most appropriate pattern for the actual task.

The theoretical possibility that specific performance goals can be achieved by organising different or variable execution parameters is clearly of significance to performance in sports such as springboard diving where the external environment can be highly variable (Kudo, et al., 2000). Scientific investigation of springboard biomechanics during the past 30 years has provided a comprehensive overview of the key factors critical for success in springboard diving and showed that small changes in body position or the application of force in slightly varying board locations can lead to significant variations in springboard oscillation, creating a highly changeable and dynamic performance environment (Brown & Abraham, 1981; Golden, 1981, 1995; Kooi & Kuipers, 1994; Miller, 1983; Miller, et al., 1998; O'Brien, 1992). These insights are important since biomechanical analyses of preparatory movements in diving have highlighted the significance of the approach and hurdle steps for the successful execution of the complete dive. That is, the actions of divers *after* take-off are largely dependent on their *preparatory* actions on the board (Jones & Miller, 1996; Miller, 1984; Slobounov, et al., 1997). Despite potential variations in the performance environment, elite divers and their coaches typically strive during practice to achieve a stable, highly reproducible and invariant movement pattern (Barris, Farrow, & Davids, 2012). The implication of this strategy is that divers only practice the execution of dives off what they perceive to be an ‘ideal’ approach and hurdle phase.

While previous research has theoretically and empirically supported the notion of functional variability in performance, to date, there have been no attempts to introduce this important idea into an elite sport performance training programme. Further, although, detailed analysis has been provided with reference to technique (Miller, 1974, 1983, 1985; Miller & Munro, 1984, 1985a, 1985b; Miller, et al., 1989; Miller & Sprigings, 2001; Murtaugh & Miller, 2001; Sanders & Wilson, 1988), the initiation of height and rotation (Golden, 1981, 1995), momentum (Miller, 1981), and the characteristics of successful entries (Brown, 1982; Brown & Abraham, 1981; Brown, et al., 1984), as yet, no investigation has examined movement pattern variability or the adequacy of learning design in elite springboard diving. Consequently, the questions examined in this programme of work relate to developing an effective learning environment in a high performance setting. Specifically: are the preparatory phases of practice tasks performed in the dry-land training environment, representative of those performed in the aquatic training environment? (Chapter Three); Do differences in movement kinematics exist between completed and baulked (prematurely terminated) take-offs in diving practice? (Chapter Four); and Does exploiting functional variability of the take-off, improve performance outcomes in elite springboard diving? (Chapter Five).

CHAPTER THREE – Representative learning design in springboard diving

This chapter is based on the following peer-reviewed journal article:

Barris, S., Davids, K., and Farrow, D., (2013). Representative learning design in springboard diving: Is dry-land training representative of a pool dive? *European Journal of Sport Science.* doi:10.1080/17461391.2013.770923

Representative learning design in springboard diving

Is dry-land training representative of a pool dive?

Two distinctly separate training facilities (dry-land and aquatic) are routinely used in springboard diving and pose an interesting problem for learning, given the inherent differences in landing (head first vs. feet first) imposed by the different task constraints. Although divers may practice the same preparation phase, take-off and initial aerial rotation in both environments, there is no evidence to suggest that the tasks completed in the dry-land training environment are representative of those performed in the aquatic competition environment. As such, the aim of this study was to compare the kinematics of the preparation phase of reverse dives routinely practiced in each environment. Despite their high skill level, it was predicted that individual analyses of elite springboard divers would reveal differences in joint coordination and board-work between take-offs completed in the dry-land and those performed in the pool. These differences were expected as a consequence of the constraints of the training environment, decoupling of important perception and action information and decomposition of the task (feet first vs. wrist first landing). The two-dimensional kinematic characteristics of the reverse somersault take-off phases (approach and hurdle) were recorded during normal training sessions and used for intra-individual analysis. Kinematic characteristics of the preparatory take-off phase revealed differences in board-work (step lengths, jump height, board depression angles) for all participants at key events. However, the presence of scaled global topological characteristics suggested that all participants adopted similar joint coordination patterns in both environments. These findings suggest that the task constraints of wet and dry training environments are not similar, and highlight the need for coaches to consider representative experimental and learning designs in high performance diving programmes.

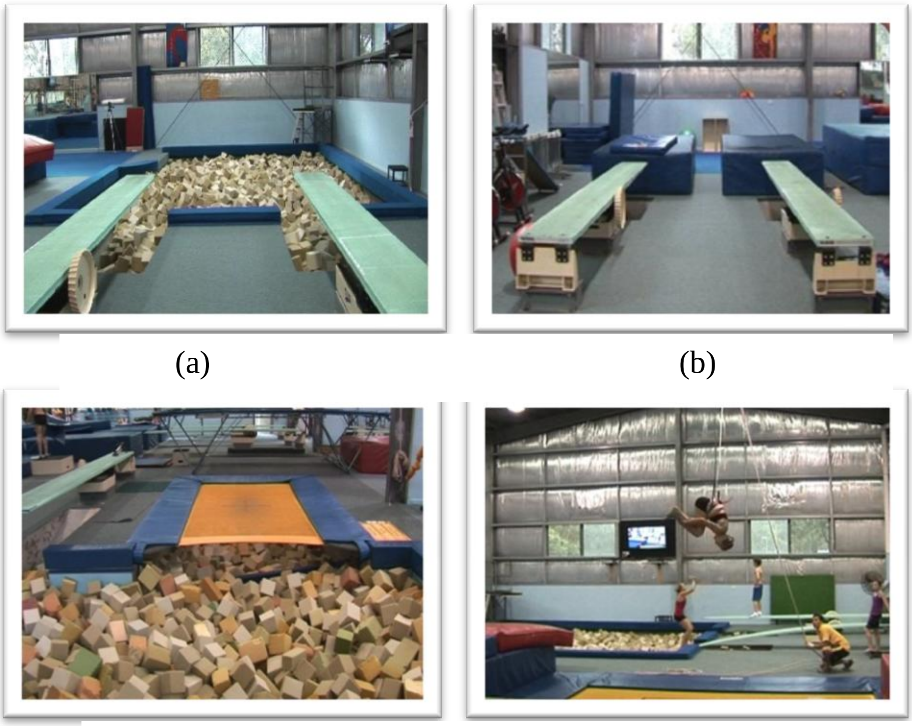
Ecological approaches to understanding motor performance have identified the importance of examining the physical and social environments in which activity occurs (Araújo & Davids, 2009; Araújo, et al., 2006; Araújo, et al., 2007; Davids, et al., 2008). *Representative design*, a concept introduced in psychology by Brunswik (1956), refers to the composition of experimental task constraints so that they *represent* the behavioural setting to which the results of an investigation are intended to be generalised (for detailed discussion see Pinder and colleagues (2011b), and Dhami, Hertwig & Hoffrage (2004)). Araújo and colleagues (Araújo, et al., 2007) contended that, without representative design, an experimental environment becomes a stand-alone environment, not representative of the performance environments to which the results might be generalised. Instead, it was proposed that scientists should understand how to represent those messy, irregular conditions in the design of empirical research and practice to discover how individuals overcome uncertainty in adapting to their natural performance environments (Araújo, et al., 2007; Brunswik, 1956). These valuable ideas highlight an important issue for applied sports science research and support, where there is potential for the resultant behaviours of an individual required to perform a task in a controlled laboratory or practice/training environment, to be influenced by this prior knowledge and associated expectations (Araújo, et al., 2007).

More recently, some ecological psychologists interested in learning and performance in sport have adapted Brunswik's original concept to generalise task constraints in learning or practice environments to the constraints encountered in a competitive performance context (Araújo, et al., 2007; Davids, et al., 2007; Davids, et al., 2003; Dicks, et al., 2008). Based on this work, the idea of *representative learning design* refers to ensuring that the task constraints employed in training environments *where learning occurs* (e.g. during practice) are representative of those encountered by athletes in a competitive performance context. These arguments suggest that representative design is also important in the context of practice and performance analysis in sport, where small changes in task constraints can lead to substantial changes in movement behaviours used to achieve specific performance goals (Hristovski, et al., 2006; Jobson, et al., 2007; Wilson, et al., 2008). Consequently, the design of sports science research and practice tasks need to allow performers to practice (and learn) the same movement responses as those which are functional in competitive performance environments (Pinder, et al., 2011a; Pinder, et al., 2009; Renshaw & Fairweather, 2000).

The degree of association between behaviour in an experimental task with that of the performance setting to which it is intended to generalise, is known as action fidelity (Araújo, et al., 2007; Lintern, et al., 1989). The purpose of action fidelity is to examine whether a performer's responses (e.g. actions or decisions) remain similar in two or more contexts (e.g. a flight simulator compared to flying a plane) (Pinder, et al., 2009; Stoffregen, et al., 2003). In this respect, practice, training and learning tasks in diving could also be viewed as simulations of the performance environment that need to be high in action fidelity. If the emergent actions are highly dissimilar, it is likely that differences in task constraints between simulations (training) and simulated (competitive) environments might indicate low levels of action fidelity with obvious consequences for athlete development. Here, the degree of fidelity was assessed by measuring practice performance (e.g. board-work, joint kinematics) in both the simulated training environment and the competitive performance context (Araújo, et al., 2007). Consequently, important questions exist regarding the extent to which behaviours in one context (practice), correspond to those in another context (competition) (Araújo, et al., 2007).

Biomechanical analyses of the dive take-off have shown that the preparatory movements in diving (approach and hurdle phases) are the precursors that facilitate the actual execution of dives (Miller, 1984; Slobounov, et al., 1997). These studies have revealed that preparation for aerial phase of the dive is most predictive of performance success in diving. In this work, efficient execution of these initial movements was observed to be vital for the overall achievement of the performance goal (a good approach and hurdle typically led to a good body position, sufficient height off the board, completion of the necessary somersault rotations and successful entry into the water).

Elite divers, currently train between 28-30 hours per week and use both aquatic and dry-land training environments. In the pool, they complete seven or eight repetitions of each dive with traditional wrist first entries into the water before moving on to the next skill. In contrast, the dry-land training environment is in a purpose-built gymnasium designed for land-based diving practice (see Figure 3-1 for examples of equipment and activities). The focus of this research is on those skills performed on the dry-boards, see Figure 3-1 (b). Dry-boards are springboards set up over large foam mats that allow divers to practice the early preparatory phase of the dive take-off with a feet first landing. Anecdotally, this training facility allows divers to experience a higher volume of dives during practice than they can achieve in the pool environment where time is lost exiting the water and climbing towers to the springboard (personal communication with the National Head Coach, Aug 2009). The motor learning strategy behind the use of a dry-land training environment is based on the assumed value of allowing athletes (directed by their coaches) to isolate small components of a dive coordination pattern and practice them independently. This motor learning approach has been termed task decomposition (Davids, et al., 2001). For example, the approach phase (initial steps, hurdle step, hurdle jump) and take-off can be isolated and practiced on dry-land springboards (see Chapter Two, Figure 2-4 for diagram of preparatory approach phase). However, the constraints of the practice environment prevent the same number of somersaults being performed in the dry-land as in pool practice or elite competition. Furthermore, athletes are required to perform variable landings in both areas. For example, in the dry-land, a diver can complete one or two somersaults before landing feet first on the mat or in the foam pit.



(a) (b)

(c) (d)

Figure 3-1 Dry- boards and trampolines in the AIS dry-land training facility

The use of these two distinctly separate training facilities in the elite diving training programme poses an interesting problem for motor learning, given the inherent differences in landing (head first vs. feet first) and the information sources imposed by the different practice task constraints. Although divers may practise the *same* preparation phase, take-off and initial aerial rotation in both environments, to date, there is no evidence to suggest that the task components completed in the dry-land training environment are representative of those performed in the competition environment. Although the rationale for dry-land training is to allow the athlete to isolate small manageable parts of the task, the constraints placed on the training tasks in the dry-land facility (fewer somersaults and a feet-first landing), may compel athletes to create new movement patterns that are neither functional for, nor representative of, performance in competitive environments. In order to investigate this critical issue, the aim of this study was to compare the kinematics of the preparation and take-off phases of two reverse dives routinely practised in each training environment: the reverse two and half somersault in the pool (3m) and the reverse somersault (with feet first landing) in the dry-land. Despite their high skill level, it was predicted that individual analyses of elite springboard divers' performance would reveal differences in joint coordination (i.e. kinematic differences evidenced by changes in coordination pattern size and shape), and board-work (e.g., divers' movements on the springboard, step lengths and jump heights) between take-offs completed feet first in the dry-land and those performed wrist first in the pool (3m). These differences were expected as a consequence of the distinct task constraints of the two training environments, and the decomposition of the task.

Method

Participants

Six elite springboard divers (5 female, 1 male mean age 18.3 ± 2.33) who were all National representatives, free from injury and currently in training were recruited for this study and provided written informed consent. Characteristics of this elite group of participants are presented in Table 3-1. The experimental protocols received approval from two local research ethics committees.

Table 3-1 Participant information

		Age	Exp (yrs)	Ht (cm)	Wt (kg)
P1	F	20	11	165	60
P2	M	20	7	167	72
P3	F	15	6	159	55
P4	F	21	11	161	61
P5	F	17	5	160	67
P6	F	17	8	158	63

Apparatus and procedures

Flat 14mm tape was fixed to twelve lower body limb landmarks on both the right and left sides of the body (anterior superior iliac spine; thigh, knee, shank, ankle, toe), ensuring an optimal position for minimising visual occlusion (Slobounov, et al., 1997). Additional markers were placed on the side of the springboard (at 0.5m, 1m, 1.5m and 2m from the oscillating end) in direct line with the camera for calibration of the filming environment and to assist with step and hurdle length measurements.

Divers participated in two testing sessions: One, in the dry-land training facility and a second in the aquatic complex. Divers performed the same springboard dive *take-off phases* (approach and hurdle steps, see Chapter 2, Figure 2-4) of the reverse take-off, where the diver faces forward and rotates backward towards the springboard, in each environment. However, in the dry-land condition divers only completed a partial dive (one somersault) and landed feet first on a foam mat, as they would normally do in practice to simulate aspects of a reverse 2 ½ somersault dive in the pool. In the pool-based protocol, divers completed traditional wrist first entries from a 3m springboard. No additional or specific instructions, corrections or comments were provided to the athletes by the researchers during data collection.

The preparation phase of five randomly selected reverse take-offs were captured in each environment using one stationary camera (Sony HDV-FX1 HDV 1080i, 60 frames per second, shutter speed 1/100s) positioned perpendicular to the side of the diving board in the sagittal plane (approximately 90°) and at heights of 1.5m and 4.5m in the dry-land and aquatic facilities respectively (Slobounov, et al., 1997). A sufficient focal length was chosen that permitted the recording of the whole dive movement and allowed the digitisation of the relevant body markers (Barris, et al., 2012; Slobounov, et al., 1997). The two-dimensional kinematic analyses of each take-off were achieved by manual digitisation of the key anatomical landmarks using PEAK Motus™ Motion Analysis Software (Oxford, United Kingdom). The data were filtered using a second order low-pass Butterworth digital filter with a cut-off frequency of 6Hz (Miller & Munro, 1984).

Data were separated and analysed in two phases: board-work and joint kinematics. The first phase examined the divers' movements on the springboard.

This analysis included: step lengths during the forward approach (two normal walking steps); the length of the hurdle step (long lunge like step), and the hurdle jump distance (two foot take-off - one foot landing). All step and jump lengths were measured as the distance in centimetres between heel-strike and toe-off. Additionally, hurdle jump height (distance (cm) between the tip of the springboard and toes), flight time (s) during hurdle jump and the maximum angle (°) of springboard depression during the hurdle jump landing were all recorded. The means and standard errors of each divers movements at key events during the preparation and approach phases of dive take-offs in the dry-land and aquatic training facilities are presented in Table 3-2.

The second phase analysed the participants' joint kinematics at the same key events (e.g., approach step, hurdle jump, flight time, and maximum board depression angle) during dives completed in the dry-land and aquatic environments. Joint angles were plotted against each other to create angle-angle diagrams (for example left ankle-left shank). Angle-angle diagrams were used to qualitatively assess the topological equivalence of the two tasks (See Chapter 2, Page 50, Quantifying movement patterns, Bartlett, 2007). Shapes are considered to be topologically equivalent if one can just be 'stretched' to form the other (Bartlett, et al., 2007). The topological characteristics of a movement describe the motions of the body segments relative to each other and changes in these patterns can provide evidence that specific aspects of coordination have changed (Anderson & Sidaway, 1994; Chow, et al., 2008).

The data were analysed with SPSS (version 18.0.0) for windows software (SPSS, Inc, USA).

Results

An intra-individual analysis examined differences in divers' movement patterns during take-offs completed in the dry-land and the pool with feet first and traditional entries respectively. Descriptive statistics revealed differences between dry-land and aquatic take-offs for all participants at various key performance milestones (for details see Table 3-2). The most noticeable differences in dive take-off between environments began during the hurdle (step, jump and height) where the diver generates the necessary momentum to complete the dive. Consequently, greater step lengths and jump heights resulted in greater board depression prior to take-off in the aquatic environment where the dives required greater amounts of rotation.

Paired sample t-tests showed significant differences ($p < .01$) at key events (approach step 2, hurdle step, hurdle jump height, and board angles during the hurdle and at landing) during the preparation phase of dive take-offs completed in dry-land and aquatic training environments (see Table 3-2). For example, participants displayed significantly less step length in the second approach step during take-offs completed in the dry-land area ($M = 47.2$, $SE = 1.51$), than those completed in the pool ($M = 51.5$, $SE = 1.60$, t (29) = -9.00, $p < .01$). Similarly, participants showed significantly less hurdle distance during take-offs completed in the dry-land area ($M = 68.8$, $SE = 3.29$), than those completed in the pool ($M = 81.7$, $SE = 3.19$, t (29) = -12.04, $p < .01$). Further, participants showed significantly less board angle depression at landing (from the hurdle jump) during take-offs completed in the dry-land area ($M = 14.27$, $SE = 0.24$), than those completed in the pool ($M = 15.99$, $SE = 0.26$, t (29) = -6.63, $p < .01$). There were no significant differences between conditions in the first approach step and the hurdle jump flight time.

Ankle-shank and shank-thigh angle-angle plots were constructed for both lower limbs to qualitatively depict any differences in intra-limb coordination between take-offs completed in the dry-land and those performed in the aquatic environment. Overall, qualitative angle-angle diagrams demonstrated similarities in joint coordination patterns between training environments for all participants (see Figure 3-2). However, large differences were observed in the scaling of the movement patterns between conditions at some joints throughout the movement. While data displayed in Figure 3-2 is for Participants One, Two, Three and Six, these findings were representative across all individuals in the study, where all divers demonstrated similar scaling of the movement patterns (e.g. smaller range of motion) during the dry-land task and greater range of motion during performance of the aquatic tasks.

Table 3-2 Means and standard errors at key events during the preparation and approach phases of dive take-offs in the dry-land and aquatic training facilities

P		*Approach Step 1 (cm)*	*Approach Step 2 (cm)*	*Hurdle Step (cm)*	*Hurdle Jump Dist (cm)*	*Jump Height (cm)*	*Hurdle Jump Flight (s)*	*Board Angle Hurdle (°)*	*Board Angle Landing (°)*
1	*Mean Dry*	49.2 (1.30)	46.2 (2.58)	9.6 (1.94)	96.2 (4.32)	81.2 (3.56)	0.86 (0.02)	10.64 (0.05)	13.84 (0.01)
	Mean Pool	49.0 (2.0)	49.8 (1.30)	11.0 (1.0)	106 (2.0)	93.4 (1.14)	0.88 (0.01)	12.76 (0.18)	15.8 (0.21)
2	*Mean Dry*	63.2 (2.05)	54.8 (2.59)	146 (3.24)	**	83.6 (4.28)	0.912 (0.02)	10.94 (0.04)	15.7 (0.04)
	Mean Pool	62 (2.0)	57.6 (2.51)	157.2 (1.48)	**	102.8 (2.95)	1.01 (0.02)	15.68 (0.18)	19.06 (0.15)
3	*Mean Dry*	43.2 (2.28)	48.2 (2.77)	9.8 (1.48)	88.0 (3.46)	54.3 (3.60)	0.592 (0.01)	9.82 (0.71)	13.3 (0.03)
	Mean Pool	41.4 (1.52)	52.8 (2.17)	10.6 (0.89)	94.2 (1.64)	62.6 (1.14)	0.728 (0.02)	11.68 (0.13)	14.8 (0.2)
4	*Mean Dry*	39.4 (2.07)	57.0 (1.58)	10.4 (1.14)	97.4 (2.07)	83.2 (1.92)	0.874 (0.01)	12.64 (0.05)	14.42 (0.24)
	Mean Pool	40.1 (1.52)	63.6 (0.02)	11.2 (0.02)	103.9 (0.04)	93.8 (0.07)	0.942 (0.08)	13.32 (0.30)	15.48 (0.35)
5	*Mean Dry*	21.0 (3.74)	32.8 (1.30)	20.2 (3.56)	89.0 (1.58)	73.4 (5.03)	0.804 (0.02)	11.4 (0.55)	15.2 (.055)
	Mean Pool	26.6 (1.52)	36.6 (1.51)	33.6 (0.07)	94.0 (1.0)	81.4 (1.51)	0.894 (0.02)	13.26 (0.23)	15.34 (0.27)
6	*Mean Dry*	46.2 (1.64)	44.0 (1.22)	9.2 (1.64)	63.0 (2.78)	47.4 (4.56)	0.622 (0.02)	9.8 (0.29)	13.2 (0.21)
	Mean Pool	50 (1.41)	48.6 (1.82)	11.4 (1.34)	70.3 (1.18)	56.0 (1.58)	0.732 (0.01)	12.24 (0.15)	15.5 (0.4)

▨ Indicates significant differences

** Diver does not do a small hurdle step and jump, instead performing one long hurdle lunge

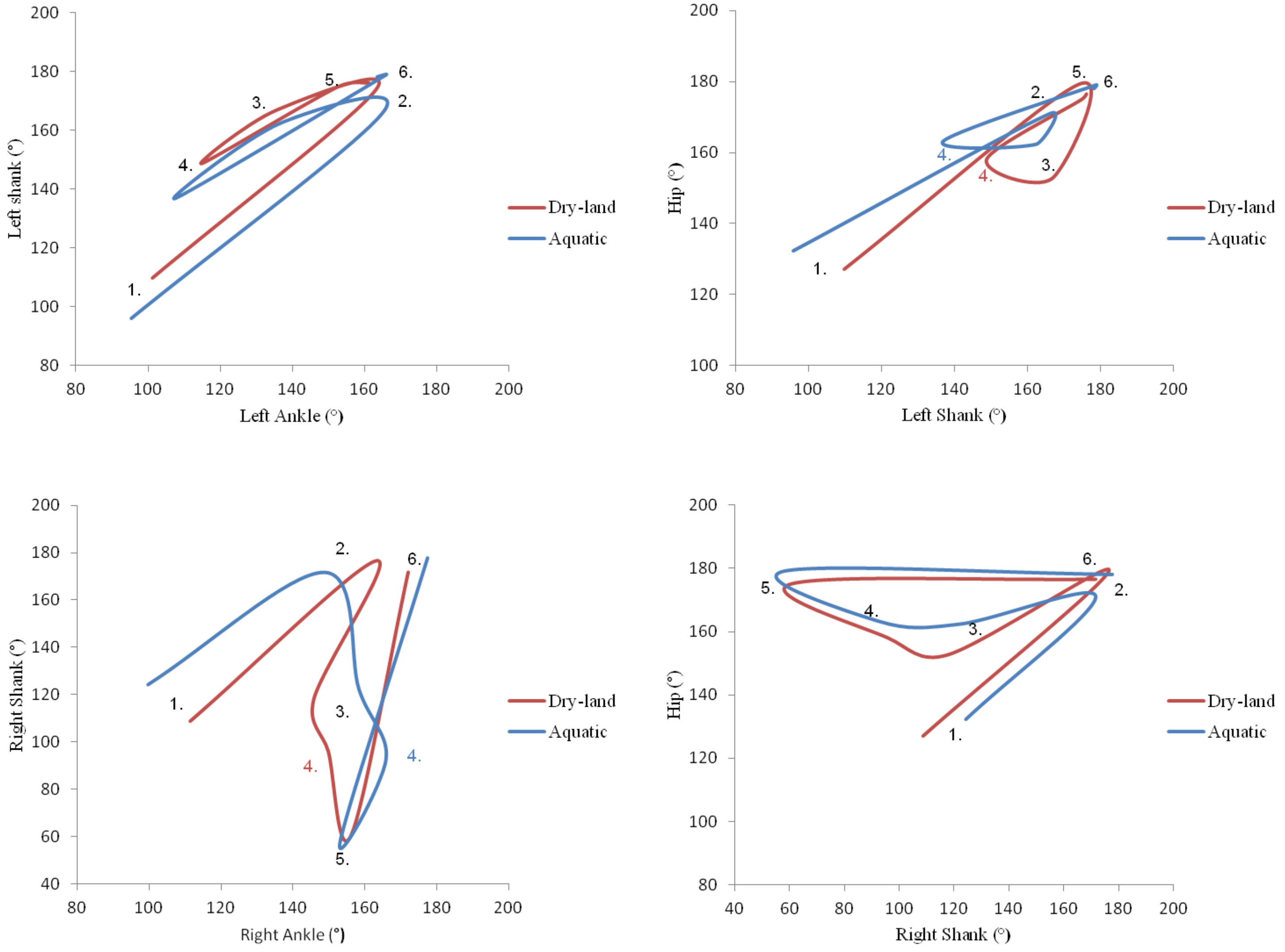


Figure 3-2 (a) Mean angle-angle plots for dives completed in the dry-land & aquatic environments for Participant One
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

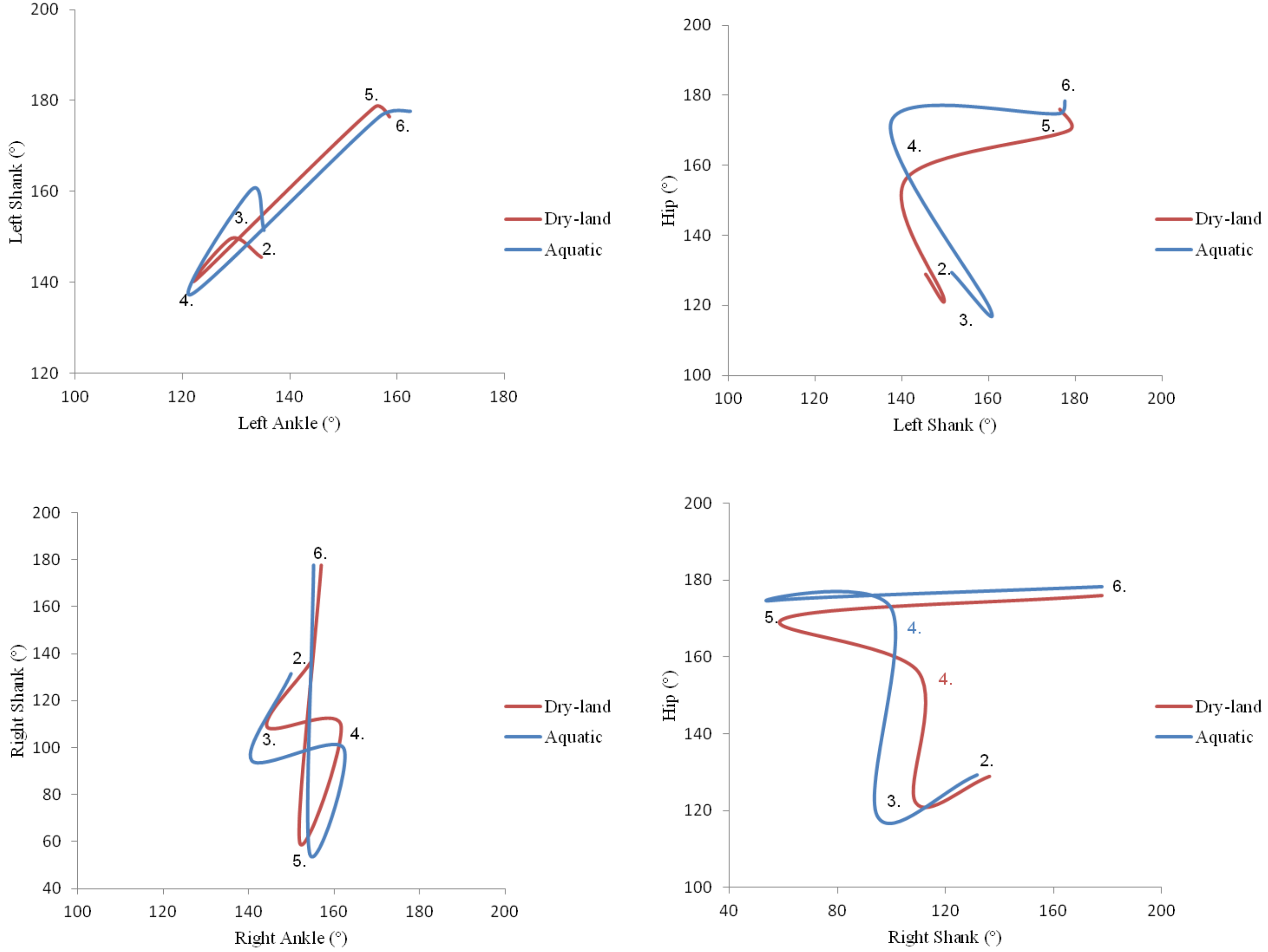


Figure 3-2 (b) Mean angle-angle plots for dives completed in the dry-land & aquatic environments for Participant Two
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

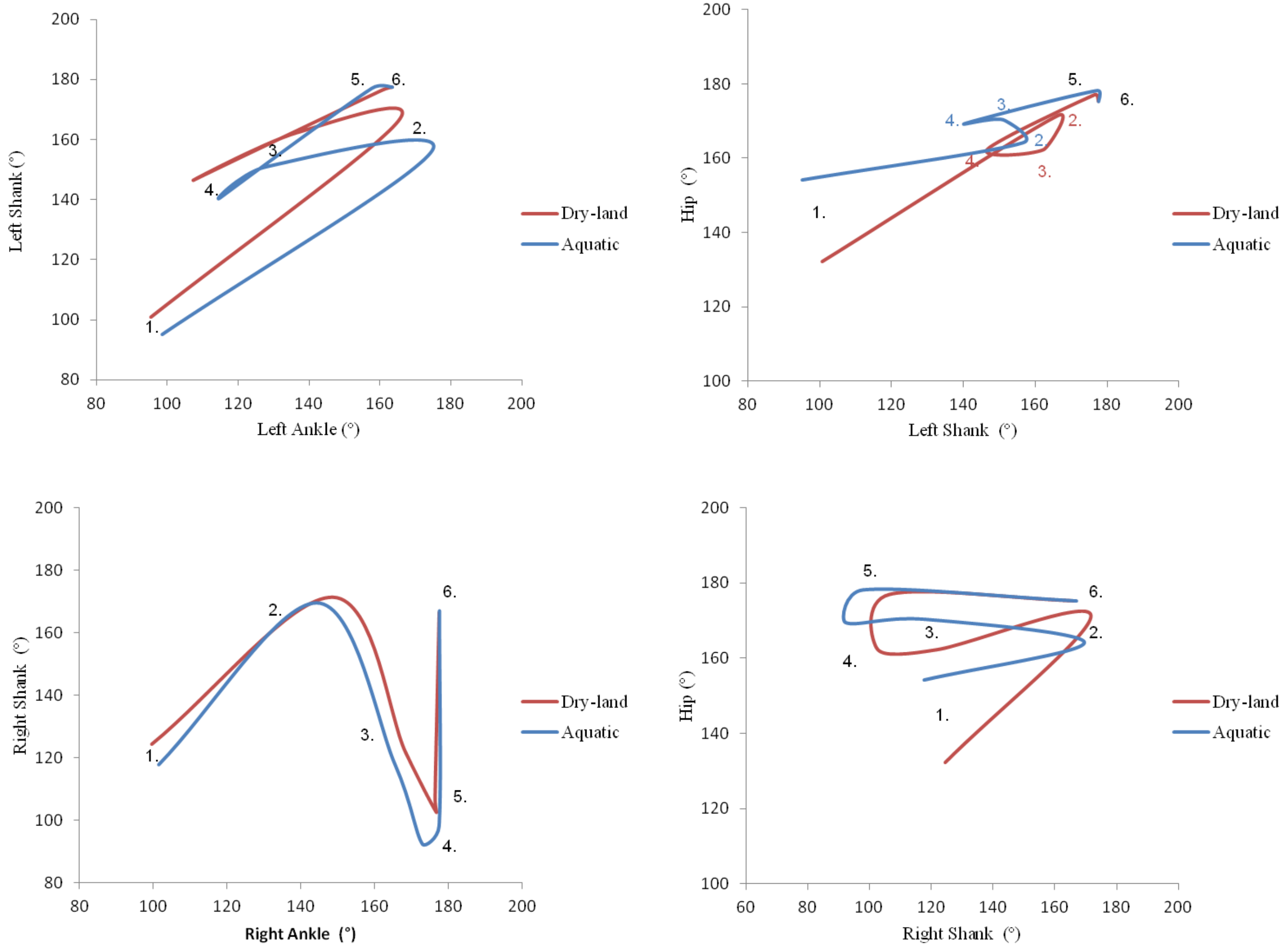


Figure 3-2 (c) Mean angle-angle plots for dives completed in the dry-land & aquatic environments for Participant Three (1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

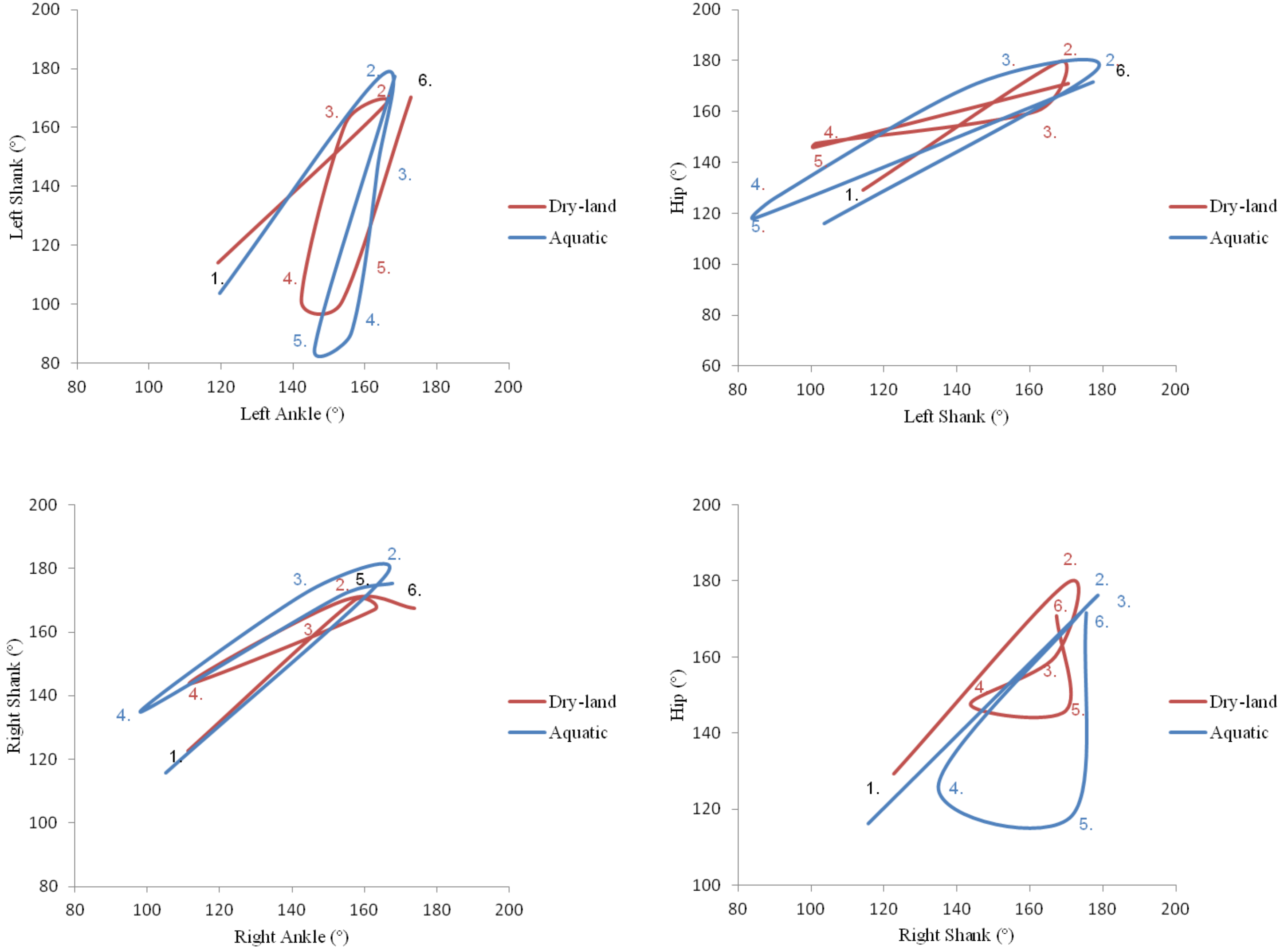


Figure 3-2 (d) Mean angle-angle plots for dives completed in the dry-land & aquatic environments for Participant Six
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

Discussion

This study investigated whether observable differences existed between the movement kinematics of elite divers in the preparation phases of dives completed in the dry-land and aquatic environments. Despite their high skill level, it was expected that differences would be observed in the movement patterns (i.e. kinematic differences evidenced by changes in coordination pattern size and shape) and board-work (e.g., divers' movements on the springboard, step lengths and jump heights) between take-offs completed feet first in the dry-land and those performed wrist first in the pool (3m).

Individual analyses revealed topological similarities in the shapes of the coordination plots between conditions for all participants. However, large differences were observed between conditions (evidenced by greater ranges of motion in the pool dives) at some joints at key events throughout the movement. This observation suggests that, although the movement patterns are not different between conditions, functional differences may exist at specific joints during coordination that determine whether the divers can create enough height and momentum to complete the necessary somersaults. These findings are further supported by data recorded at the key events (e.g., step lengths, jump height) during the approach and hurdle phases of the take-off, where participants showed significantly greater step lengths, jump heights and board depression angles (during the hurdle jump and at landing prior to take-off) in the aquatic environment compared to the dry-land.

These findings are in line with data reported by Pinder and colleagues (2009) who analysed the movements of cricket batters when responding to ball deliveries from a 'live' bowler and a ball projection machine. In this situation, the ball machine was used to simulate the bowler in the performance environment. Similarly, the differences observed between the movement patterns of reverse dive take-offs completed in the dry-land and aquatic training environments in this study are arguably the consequence of changes in task constraints, which are imposed by differences in the two training environments. Specifically, the height of the springboard, the foam landing mats and the limited number of somersaults that can be completed in the dry-land, results in the decomposition of the dive take-off task and changes the overall task execution (feet first vs. wrist first landing).

The conditions of practice are a fundamental issue for the acquisition of skill and optimisation of performance in sport. It has been regularly questioned whether a learner should practice the whole task from the beginning or whether the task should be decomposed into parts that are practiced separately (Newell, Carlton, Fisher, & Rutter, 1989). Intentionally or not, the process of task decomposition is common in diving practice where the environmental constraints force the diver to modify the skill to land feet first rather than wrist / head first as in the aquatic environment. Task decomposition techniques in sports training, which have dominated traditional pedagogical approaches, aim to make informational loads more manageable, reduce the attentional demands on the performer during skill acquisition and positively transfer learning of the component (e.g. a reverse dive take-off) to performance of the whole task (e.g. a reverse 2 ½ somersault dive) (Araújo, et al., 2004; Davids, et al., 2001; Naylor & Briggs, 1963). However, this pedagogical method also tends to rupture the link between information and movement, breaking up potential information-movement couplings which are used to regulate behaviours (Araújo, et al., 2004; Montagne, et al., 2000). Consequently, valuable information regarding the dynamics of the movement may be lost if each of these segments are practised in isolation or removed from the competitive performance context, potentially changing the task constraints, as observed in the current investigation (Hamill, et al., 2005). In this instance, the context becomes a stand-alone environment and not representative of the performance context to which the practice results are generalised (Araújo, et al., 2007).

Previous research has demonstrated how the nature of the task can greatly influence the value of the learning strategy (Frederiksen & White, 1989; Naylor & Briggs, 1963). In particular, tasks that have highly interdependent parts or complex coordination requirements, like diving or gymnastics, may not benefit from part-task or decomposition practice (Frederiksen & White, 1989; Naylor & Briggs, 1963). Instead, it has been suggested that practising a simplified version of the whole task is more effective for complex skills, than practising separate components, and then applying to them to a whole task at the end of training (Davids, et al., 2001; Dicks, et al., 2008; Gopher, Weil, & Seigel, 1989; Schneider, 1985; Wrightman & Lintern, 1985). The task simplification approach maintains the coherence of the task and the perception-action cycles remain intact during practice. This pedagogical approach ensures that key perceptual variables remain available to the performer to pick up and continuously use to support action (Dicks, et al., 2008). To exemplify, a coach might gently feed a ball to a tennis player early in learning, rather than designing a practice task for the learner to hit a ball projected from a ball machine. Similarly, in diving, task simplification may be exemplified by the completion of full dives, which can only be achieved in the pool, with take-off, rotation and entries intact, but manipulating the number of rotations in the air, and gradually increasing the dive complexity.

In summary, it has been argued that a *representative learning design*; the composition of practice task constraints so that they *represent* the performance setting, is crucial for the acquisition of skilled behaviours. Biomechanical analyses of the dive take-off have shown that the preparatory movements in diving (particularly the approach and hurdle phases) are the precursors that facilitate the actual execution of dives (Miller, 1984; Slobounov, et al., 1997). Consequently, divers routinely isolate components of the dive, practising the preparatory phase of the take-off in the dry-land training facility, in order to achieve an efficient, invariant take-off. However, the results of this investigation have highlighted the existence of key differences in the preparatory phases of reverse dive take-offs completed by elite springboard divers during performance of their typical training tasks in the dry-land and aquatic training environments. The data suggest that there may not be any performance advantages associated with practising the preparatory phase of the dive take-off in isolation as traditionally assumed. In this instance, task simplification may be a more beneficial approach to learning, rather than decomposition.

Finally, although the findings of this study displayed differences in the preparatory phase of the dive take-off in the dry-land and aquatic environments due to task decomposition, it is important to note that only one aspect (the preparatory phase) of the decomposed task was analysed. The extent to which other dry-land practice tasks, such as the aerial phase (somersaulting on the trampoline), or ‘come out’ phase (transition from somersaulting position to final water entry position), may contribute to the successful transfer of isolated phases into the whole task remains unknown and should be subject to further research.

CHAPTER FOUR – Movement kinematics in springboard diving

This chapter is based on the following peer-reviewed journal article:

Barris, S., Farrow, D., Davids, K. (2012). Do the kinematics of a baulked take-off in springboard diving differ from a completed dive? *Journal of Sport Sciences.* doi:10.1080/02640414.2012.733018

Movement kinematics in springboard diving

Do the kinematics of a baulked take-off in springboard diving differ from a completed dive?

Consistency and invariance in movements are traditionally viewed as essential features of skill acquisition and elite sports performance. This emphasis on the stabilisation of action has resulted in important processes of adaptation in movement coordination during performance being overlooked in investigations of elite sport performance. Unlike many other athletic events, springboard diving requires athletes to adhere to imposed movement criterion which dictate how the movement pattern should be performed, forcing athletes to satisfy strict judging criteria in their performance outcomes. Here we investigated whether differences existed between the movement kinematics displayed by five, elite springboard divers (17 ± 2.4 years) in the preparation phases of baulked and completed take-offs. The two-dimensional kinematic characteristics of the reverse somersault take-off phases (approach and hurdle) were recorded during normal training sessions and used for intra-individual analysis. All participants displayed observable differences in board-work at key events during the approach phase; however, the presence of similar global topological characteristics suggested that overall, participants did not perform distinctly different movement patterns during completed and baulked dives. These findings provide a powerful rationale for coaches to consider assessing functional variability or adaptability of motor behaviour as a key criterion of successful performance in sports like diving.

Historically, scientists have stressed the importance of understanding the mechanisms associated with optimising behaviour and how skilled individuals achieve repeatable movement performance outcomes (Glazier & Davids, 2009). Variability in movement can be described as the normal variations that occur in motor performance across multiple repetitions of a task (Stergiou, et al., 2006). It has been argued that a reduction in movement pattern variability is a characteristic of expert performance (Todorov & Jordan, 2002) which results in a decrease in performance variability as the learner becomes more skilful (Bootsma & van Wieringen, 1990; Higgins & Spaeth, 1972; O'Brien, 1992; Slobounov, et al., 1997). Based on these theoretical insights, some coaches, athletes and sport scientists believe that skilled performance in sport is characterised by a reduction of variability in movement patterns achieved through extensive training and practice over thousands of hours (Todorov & Jordan, 2002). Consequently, coaching practice has been dominated by highly repetitive training sessions which emphasise invariant repetition of a perceived optimal movement pattern (Brisson & Alain, 1996; O'Brien, 1992). This is particularly true of aesthetic sports, like gymnastics or diving, where movement form is a major task constraint. In these tasks, external environments can vary, yet great importance is placed on production of stable repeatable performance outcomes, which are judged subjectively using strict criteria-based guidelines for how actions should look (see the FINA handbook for detailed dive descriptions, (2009-2013). The existence of these performance criteria may further contribute to the athlete's desire to assemble a reproducible, invariant movement pattern, rather than allowing and encouraging functional variability in the performance of a dive or gymnastic skill. It is important to note, that although divers in particular may find changes to movement patterns alter the execution of the task, ultimately influencing the performance outcome (e.g. changes to foot placement on the springboard may influence final dive entry into the water), these variations are not directly assessed by the judges. Instead, judging focuses on the overall aesthetics of the movement and the resulting performance outcome.

Theoretical insights have since emerged from a number of empirical studies showing the potential of movement pattern variability to be functional (Arutyunyan, et al., 1968; Bootsma & van Wieringen, 1990). Movement pattern variability within expert individuals can be considered functional when it supports the performance flexibility needed to adapt to changing environmental constraints in order to achieve a consistent performance outcome. In sport performance, consistent performance outcomes can be achieved by different patterns of joint coordination available through the re-configuration of the joint's biomechanical degrees of freedom (DOF) (Bernstein, 1967; Davids & Glazier, 2010; Seifert, Button, & Davids, In Press). Movement pattern variability, therefore, should not necessarily be construed as a negative feature of expert performance in sport. Rather functional levels of movement adaptability require the establishment of an appropriate relationship between *stability* (i.e., persistent behaviours) and *flexibility* (i.e., variable behaviours). This relationship is essential to skilled performance in many different sports. Expert performance is characterised by relatively stable movement patterns, which lead to consistent outcomes over time, are resistant to perturbations and reproducible in that a relatively similar movement pattern may be assembled by athletes under changing task and environmental constraints. For example, it would be expected that experts could produce subtly nuanced performance behaviours, which are not at all stereotyped and rigid, but rather flexible and adaptive to environmental variations.

According to these theoretical ideas, although their movement patterns might exhibit some regularities and similarities within their structural components, elite athletes should not be fixed into a rigidly stable solution, but can be adapted in a functional way, since neurobiological complex systems can exploit inherent *degeneracy*. In the engineering of automated control systems, *redundancy* is built in to allow system components to take over processes when a specific component fails (Mason, 2010). In neurobiological systems, *degeneracy*, the ability of elements that are structurally different to perform the same function or yield the same output (Edelman & Gally, 2001), provides the conceptual basis to explain the functional role of movement pattern variability in sport performance. Essentially, degeneracy provides a strong expectation that performance outcome consistency should not require movement pattern consistency (Bartlett, et al., 2007).

Since skill adaptation is proposed to be the basis of performance expertise in dynamic environments (Araújo & Davids, 2011), the co-existence of various adaptive motor solutions within inherently degenerate neurobiological systems can be exploited to enable different system components to achieve the same performance outcomes, consistently (Seifert, et al., 2013). This crucial idea implies that a diversity of movement patterns may be functional in negotiating dynamic performance environments and may be particularly relevant in unpredictable environmental situations, such as controlling the bounce on an oscillating springboard (Araújo & Davids, 2011; Davids, et al., 2007).

Observations of the behaviours of high performance divers have revealed that, in attempts to practice only high quality dives and achieve invariant movement patterns, squad members ‘baulk’ frequently. A baulked dive is defined as a take-off where the diver completes the approach and hurdle steps (see Figure 4-1.), but aborts the intended movement before the take-off phase if he/she considers the preparation to be imperfect. Over a week of training, this approach can result in upwards of 100 baulks (per diver, approximately 20% of all dives attempted). This approach to training reduces the volume of practice achieved by an individual and can have detrimental effects in competition with a two-point baulking penalty or ‘no-dive’ result. Consequently, divers often attempt to complete dives in a competitive environment that they would not complete in training. Despite this common practice, currently, there is no empirical evidence to suggest the existence of differences (temporal, kinematic or kinetic) in the preparation phase of baulked and completed dives in high performance athletes. It is possible; therefore, that this training habit is predicated on the misconception that only the best dives must be practiced at all times in order to enhance skill in a sport like diving. Put simply, divers may be baulking in response to variations in their approach phase, essentially, stopping and restarting instead of trying to adapt and use a different strategy for solving the movement problem.

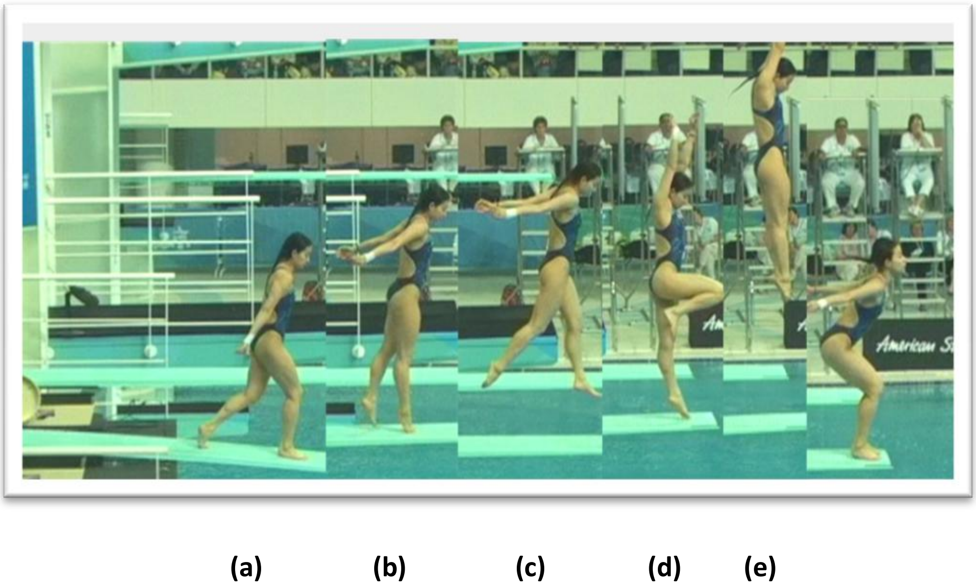


Figure 4-1 An example of the approach (a-b) and hurdle (c-d-e) phases of a reverse dive take-off.

Biomechanical analyses of the dive take-off have shown that the preparatory movements in diving (particularly the approach and hurdle phases) are the precursors that facilitate the actual execution of dives (Bergmaier, et al., 1971; Miller, 1984; Slobounov, et al., 1997). Specifically in the performance of springboard dives from either the forward or the reverse group, the diver begins with a minimum of three approach steps followed by a hurdle and take-off (see Figure 4-1). The major function of the approach and hurdle in running (forward and reverse) springboard dives is to establish optimal conditions for an effective take-off. The final approach step is defined as the period between toe-off of one foot and toe-off of the opposite foot immediately preceding hurdle flight. During the support phase following the final step the diver builds up horizontal and vertical velocity needed for the hurdle flight (see Figure 4-1(b)) (Miller, 1984). Efficient divers are lifted into the hurdle by the action of the board, not by jumping up themselves (Miller, 1984). Consequently, the foot placement of the third step is critical and serves to help push the board down. As the knee flexes, mass of the body moves down and the momentum starts depressing the board. At the same time the lifting of the arms and the other knee increase the downward force because, according to Newton’s third law, the reaction to these lifting movements is a downward press of the body against the board (Batterman, 1968).

In executing the hurdle, the diver steps off one foot and travels forward to the end of the board. The application of force by the diver to depress the board during hurdle support, and its subsequent release during hurdle flight, causes the board-tip to oscillate. Hurdle flight encompasses the airborne phase of the movement and occurs between last contact with the hurdle support foot and initial contact with both feet near the end of the board to begin the take-off (Miller, 1984). The process of generating the necessary vertical velocity for the flight phase of the dive begins during the support phase preceding the hurdle. While free in the air during the hurdle, the diver is influenced only by gravitational force. Consequently, vertical velocity decreases to a value of zero at the peak and then becomes progressively more negative during decent back to the board (Miller, 1983). The magnitude of the diver’s downward velocity at the end of the hurdle jump is determined by the peak height of the jump. The magnitude of the vertical velocity at touchdown is greater than at the beginning of the hurdle with men and women experiencing values of 4.2 m/s and 3.6 m/s respectively. The diver’s centre of gravity is shown to be considerably lower at touch-down than at the beginning of the hurdle, averaging 31 cm and 26 cm lower for men and women respectively (Miller, 1983).

With a long hurdle step, the diver can develop considerable forward momentum so that after the feet land and are stopped by friction, the body continues to move forward. Due to inertia, the momentum remains constant and the diver lands at the end of the board with no lean. The lean develops after the feet land, during the time the board moves up and down (Batterman, 1968). During the drop back to the board, the head is rotated down, eyes looking at the end of the board. The body is straight, and the diver falls back to the board, landing on the balls of their feet. As the diver falls, their arms circle back, down and around. This causes a downward force that is transmitted to the board with both feet to begin the take-off (Batterman, 1968).

Efficient execution of these initial movements is, therefore, vital for the overall achievement of the performance goal (a good approach and hurdle means good body position, good height off the board, good rotation and good entry into the water).

Recently, it has been argued that skill adaptation is the basis of performance expertise in dynamic environments (Araújo & Davids, 2011). It follows that, by only completing dives that follow an ideal preparation phase, skilled divers may not be affording themselves the opportunity to develop adaptive and flexible strategies to achieve a similar performance outcome goal (rip entry into the water with minimal splash), with a varied take-off movement pattern. Adaptive movement patterns may enable skilled performers to repeat attempts at the same skill, but with differing patterns of performance. This flexibility allows the exploration of different strategies to find the most proficient among the many available options, so that consistent performance outcomes can be achieved. The performance of true experts in sport warrants investigation since expertise is predicated on the adaptation of a performer's intrinsic dynamics (inherent performance tendencies) to cooperate with the task dynamics (Davids, et al., 2007). Davids and colleagues (2007) suggest that enhanced movement adaptability, can be trained during practice when the gap between an individual's pre-existing movement repertoire (the number of available solutions) and the demands of the task are low. Consequently, the aim of this study was to investigate whether observable differences actually existed between the movement kinematics displayed by elite divers in the preparation phases of baulked and completed take-offs. Due to their high skill level, it was predicted that individual analyses of elite springboard divers would reveal no differences in the movement patterns (i.e. no kinematic differences evidenced by no changes in coordination pattern shape) between completed and baulked take-offs. However, in light of the athletes' goal to eliminate take-off variations during training, it was expected that the movement patterns in the preparation phase for completed take-offs would display greater consistency than in those take-offs where the athletes baulked (e.g. variations in the size of angle-angle coordination plot). To summarise, in this study we expected to see no differences in movement patterns, evidenced by no change in coordination modes, because the observed athletes are highly skilled. We also expected that the completed dives performed by the athletes would show greater consistency, evidenced by lower levels of variability in the coordination plots, because the divers would typically try to deal with preparation variability by baulking to remove it during performance.

Method

Participants

Five elite Australian springboard divers (4 female and 1 male; mean age 17.2 years ±1.8) from the National and State high performance squads who were free from injury and currently in training (average 28 hours per week) were recruited for this study and provided written informed consent. Characteristics of this elite group of participants are presented in Table 4-1. The experimental protocols received approval from two local research ethics committees.

Table 4-1 Participant information

	Gender	Age	Experience (yrs)	Ht (cm)	Wt (kg)
P1	F	15	6	159	55
P2	M	20	8	165	75
P3	F	17	8	158	63
P4	F	17	5	160	67
P5	F	16	4	168	55

Apparatus and procedures

Flat 14mm tape was fixed to twelve lower body limb landmarks on both the right and left sides of the body (anterior superior iliac spine; thigh, knee, shank, ankle, toe), ensuring an optimal position for minimising visual occlusion (Slobounov, et al., 1997). Further markers were placed on the side of the springboard (at 0.5m, 1m, 1.5m and 2m from the oscillating end) in direct line with the camera for calibration of the filming environment and to assist with step and hurdle length measurements.

Video-recordings of divers successfully completing take-offs or baulking were captured during two training sessions in the athletes’ normal training environments; the aquatic centre and the diving dry-land training centre. A baulked dive was defined as a take-off where the diver completed the approach and hurdle steps, but did not complete the take-off phase of the dive. In the pool, each completed dive (those that displayed an approach, hurdle, take-off, and aerial phase) was assigned a score (out of ten) based on the perceived quality of the take-off, aerial somersaults and entry into the water by a national team coach who was naive to the aims of the study. Dives that scored between 7.0 and 10 were classified as successful dives and included in the study as the *completed dives*. Dives that scored between 4.0 and 6.5 were classified as unsuccessful and those that scored lower than 4.0 were considered incomplete. None of these dives were included in this study. In the dry-land area, coaches identified take-offs and aerial somersaults as ‘good’ or ‘poor’. No scores were assigned to baulked take-offs in either environment.

During data collection, participants were asked to follow their normal individual coach-prescribed training programmes and were informed that video recordings (similar to those made at most training sessions) would be taken at various stages during the session for technique analysis. No additional specific instructions, corrections or comments were provided to the athletes by the researchers during data collection, in order not to contaminate the data emerging from the athlete performances during these sessions. Information regarding the research interest in baulking kinematics was also withheld from participants to prevent positively or negatively influencing performance. Dives from all take-off groups (front, back, inward and reverse) were recorded during these sessions, however only those from the reverse take-off group were used for analysis (in the reverse dive group, the diver takes off facing forward and rotates backward towards the board). Specifically, in the pool, the approach and hurdle phases of a reverse two and a half somersault with wrist first entry was used for analysis. In the dry-land environment, the approach and hurdle phase of a reverse somersault with feet first landing was used. To prevent the training environment influencing the analysis, recordings of baulked take-offs in the dry-land were compared to completed take-offs in the same environment. For each participant, five completed dives that met the selection criteria (score) and five baulks from the same environment were chosen at random for analysis. The two-dimensional kinematic characteristics of these take-off phases (approach steps and hurdle) were captured using one stationary camera (Sony HDV-FX1 HDV 1080i, shutter speed 1/100s) positioned perpendicular to the side of the diving board in the sagittal plane (approximately 90°) in each environment and recorded movements at 60 frames per second (Slobounov, et al., 1997). A sufficient focal length was chosen that permitted the recording of the whole dive movement and allowed the digitisation of the relevant body markers (Slobounov, et al., 1997). Kinematic analyses of the approach and hurdle phases of baulked and completed dives were achieved by manual digitisation of the key anatomical landmarks using PEAK Motus™ Motion Analysis Software (Oxford, United Kingdom). The data were filtered using a second order low-pass Butterworth digital filter with a cut-off frequency of 6Hz Analysis (Miller & Munro, 1984).

Data in this investigation were separated and analysed in two phases: board-work and joint kinematics. The data were analysed with SPSS (version 18.0.0) for windows software (SPSS, Inc, USA).

Board-work

Due to the limited number of expert participants available, traditional inferential statistics are not reported. Only descriptive statistics are presented. The mean and standard error values between completed dives and baulked take-offs for each participant were determined at all key phases during the dive preparation. The first phase examined the divers’ movements on the springboard. This analysis included: step lengths during the forward approach (two normal walking steps); the length of the hurdle step (long lunge like step); and the hurdle jump distance (two foot take-off - one foot landing). All step and jump lengths were measured as the distance between heel-strike and toe-off. Additionally, hurdle jump height (distance between the tip of the springboard and toes), flight time during hurdle jump and the maximum angle of springboard depression during the hurdle jump landing were all recorded. The means and standard errors of each divers movements at key events during the preparation and approach phases of dive take-off are presented in Table 4-2.

Joint kinematics

The second phase analysed the participants' joint kinematics at the same key events (e.g., approach step, hurdle jump, flight time, and maximum board depression angle) during baulked and completed dives. Joint angles were plotted against each other to create angle-angle diagrams (for example left ankle-left shank). Angle-angle diagrams were used to qualitatively describe performance variability and assess the topological equivalence of two different skills (See Chapter 2, Page 50, Quantifying movement patterns, Bartlett, 2007). The topological characteristics of a movement describe the motions of the body segments relative to each other and changes in these patterns can provide evidence specific aspects of coordination change (Anderson & Sidaway, 1994; Chow, et al., 2008). If the two shapes are topologically equivalent, then it can be assumed that the same skill is being performed (Bartlett, et al., 2007). However, if one diagram has to be folded, stretched or manipulated to fit the other, it can be assumed that two separate skills are being performed. Previous investigations have used angle-angle plots to depict qualitative changes in intra-limb coordination as a function of practice, and normalised root mean square error (NoRMS) to assess variability in the relationship between joint angles (Button, et al., 2010; Chow, et al., 2007; Chow, et al., 2008; Mullineaux, 2000; Sidaway, et al., 1995). The root mean squared error is totaled for the number of trials collected and normalised with respect to the number of trials. This method has been recommended for small trial sizes and normalised techniques (Mullineaux, 2000), and has successfully detected changes in stability of coordination in both linear and non-linear data (Chow, et al., 2007; Chow, et al., 2008; Sidaway, et al., 1995). Results were interpreted based on the assumption that, a higher index for NoRMS is indicative of greater variability in joint coordination over trials, whereas a lower NoRMS index will indicate lower levels of variability in intra-limb coordination (Chow, et al., 2007).

Finally, one video sequence was selected at random and digitised by the same observer on five occasions to ensure that reliable results were obtained through the digitising process (Hopkins, 2000). Intraclass correlation coefficient values ranged between r = 0.970 and r = 0.999 indicating strong correlations between the repeatedly analysed trials.

Results

Board-work

An intra-individual analysis was used to examine differences in divers' movement patterns during baulked and completed dive take-offs. Descriptive statistics showed the existence of small differences between baulked and completed dives for all participants at various key performance milestone events (see Table 4-2). For example, Participant One showed very similar average step lengths between baulked and completed dives, demonstrating only 1cm- 1.4cm differences between conditions during the initial three steps. The largest differences between baulked and completed take-offs were observed in Participants Two and Five, who showed differences of 18.8cm in hurdle step length and 9.6cm in approach step 1, respectively. Four participants showed large differences (5cm – 8cm) in the average jump height between conditions. Small differences were observed in the angle of board depression at landing between baulked and completed take-offs in all participants (2.5° – 4.8°).

Joint kinematics

Ankle-shank and shank-thigh angle-angle plots were constructed for both lower limbs to depict qualitative changes in intra-limb coordination between completed and baulked take-offs. Qualitative angle-angle diagrams demonstrated the presence of individual differences in movement pattern coordination (see Figure 4-2). No topological differences were observed within participants, suggesting that the same movement coordination pattern was being organised in both baulked and completed dive take-offs (see Figure 4-3). However, differences were observed in the amount of variability between patterns with angle-angle plots displaying greater variability in the approach and hurdle phases of baulked take-offs and less variability in completed dive take-offs (see Figure 4-2). This performance feature was further highlighted by the presence of higher NoRMS indices for baulked dives relative to the completed dives. An example of NoRMS indices for each participants right shank-thigh intra-limb coordination during five completed and five baulked dive trials is presented in Figure 4-4.

Table 4-2 Means and standard errors for completed and baulked dives at key events during take-off

P		Approach Step 1 (cm)	Approach Step 2 (cm)	Hurdle Step (cm)	Hurdle jump Dist (cm)	Jump Height (cm)	Hurdle Jump Flight (ms)	Board Angle Hurdle (°)	Board Angle Landing (°)
1	Mean Completed	39.6 (.005)	40.8 (.004)	11.6 (.005)	52.8 (.007)	55.4 (.012)	6.34 (.006)	6.68 (.097)	7.9 (.212)
	Mean Baulk	41 (.007)	42 (.004)	12.6 (.007)	61.2 (.004)	50.4 (.016)	6.52 (.005)	6.72 (.058)	10.4 (.150)
2	Mean Completed	66.4 (.004)	62 (.008)	127.2 (.200)	34.6 (.019)	75.6 (.157)	8.24 (.010)	10.24 (.103)	13.16 (.238)
	Mean Baulk	63.2 (.009)	54.8 (.012)	146 (.012)	39.6 (.012)	83.6 (.019)	9.12 (.008)	10.94 (.163)	15.7 (.279)
3	Mean Completed	52.2 (.009)	42.6 (.016)	42.2 (.021)	32.8 (.016)	63.8 (.017)	7.38 (.005)	9.6 (.243)	9.66 (.194)
	Mean Baulk	50 (.006)	48.6 (.008)	39.2 (.007)	37.4 (.011)	56 (.007)	7.32 (.005)	9.8 (.130)	13.2 (.095)
4	Mean Completed	25.6 (.021)	37.2 (.014)	26.2 (.023)	46.2 (.013)	74 (.019)	7.60 (.025)	11.4 (.354)	11.9 (.319)
	Mean Baulk	21 (.017)	32.8 (.005)	20.2 (.016)	45.4 (.009)	73.4 (.022)	8.01 (.009)	11.4 (.245)	15.2 (.247)
5	Mean Completed	40.2 (.034)	51.6 (.008)	36.6 (.017)	39.2 (.018)	65.8 (.020)	8.14 (.018)	12.26 (.093)	11.96 (.186)
	Mean Baulk	49.8 (.017)	52.8 (.012)	31 (.020)	35.6 (.017)	71 (.013)	8.12 (.008)	12.1 (.274)	16.78 (.301)

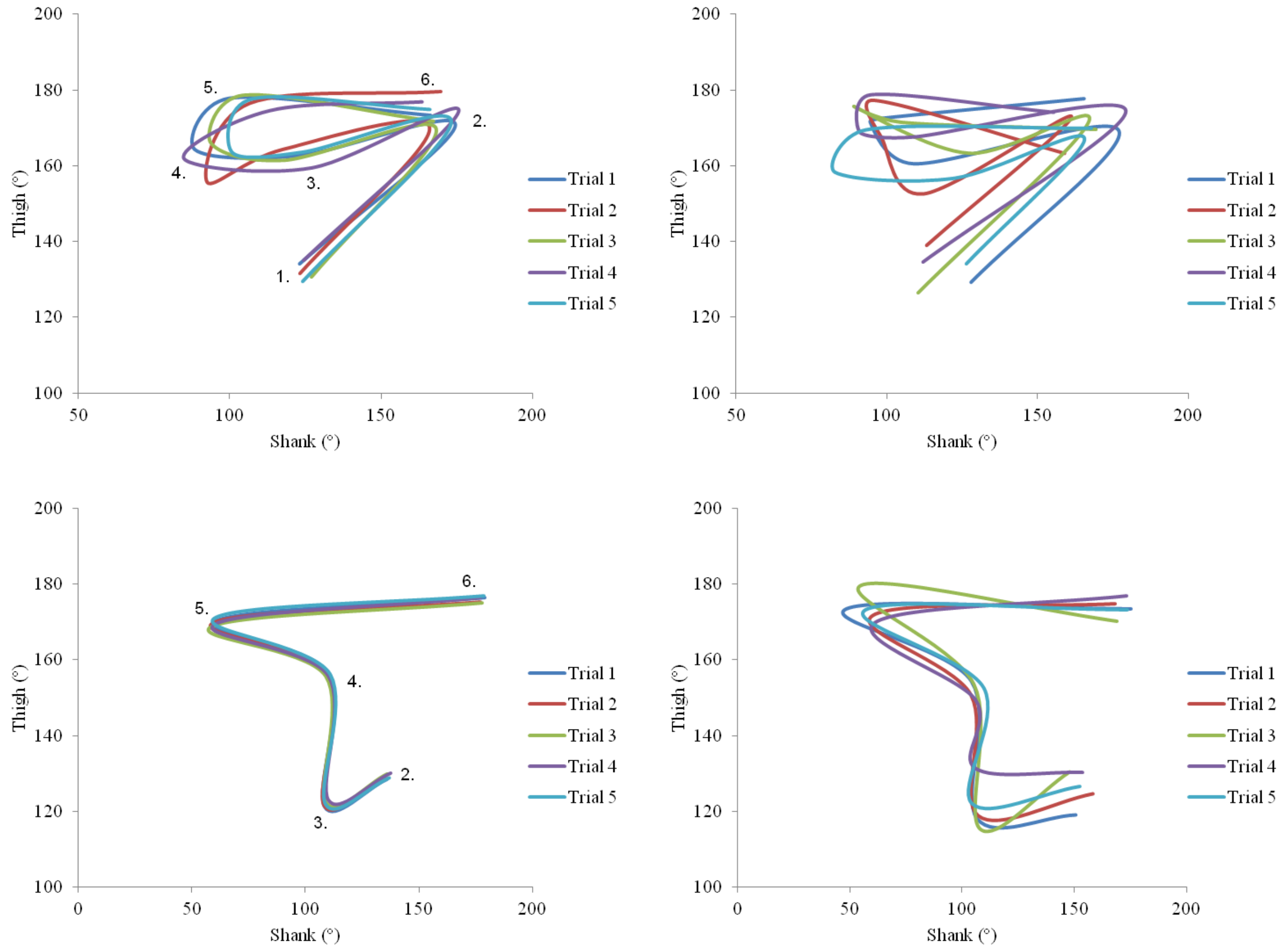


Figure 4-2 Right shank-thigh angle-angle plots for completed (left) and baulked take-offs (right) for Participant One (top) and Participant Two (bottom) (1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

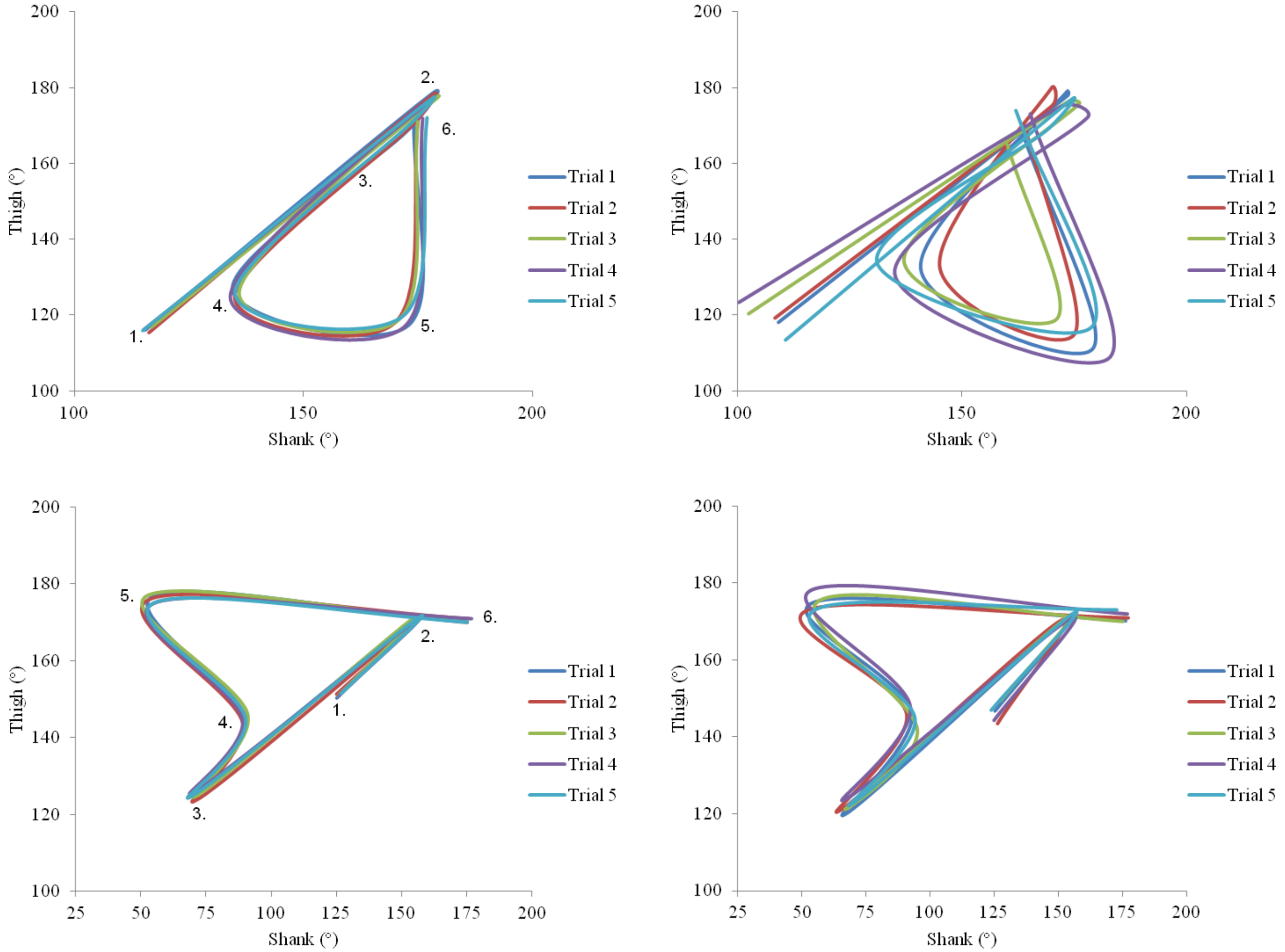


Figure 4-2 Right shank-thigh angle-angle plots for completed (left) and baulked take-offs (right) for Participant Three (top) and Participant Four (bottom) (1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

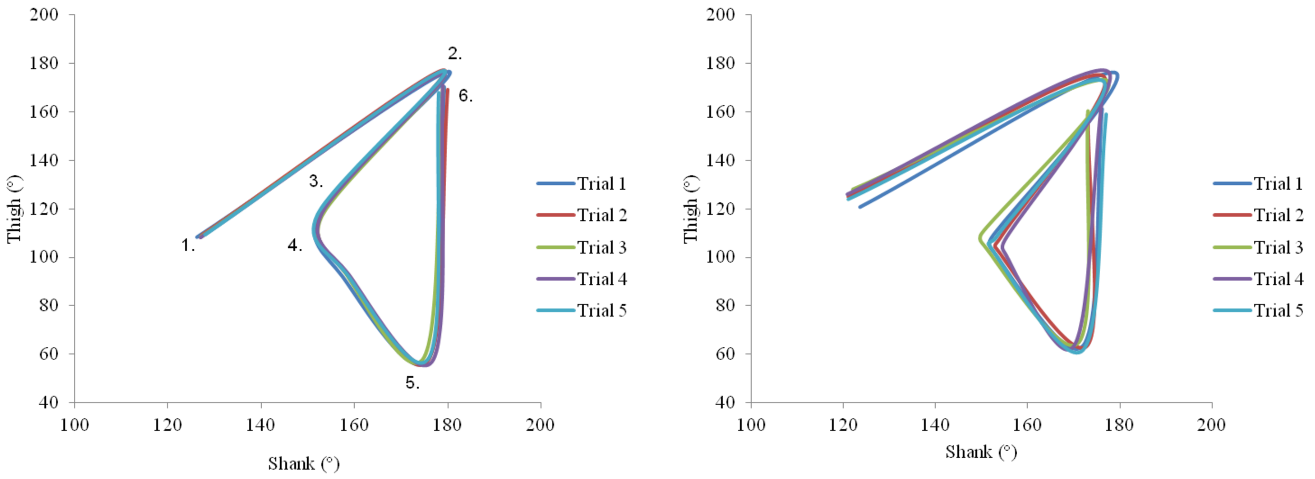


Figure 4-2 Right shank-thigh angle-angle plots for completed (left) and baulked take-offs (right) for Participant Five
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

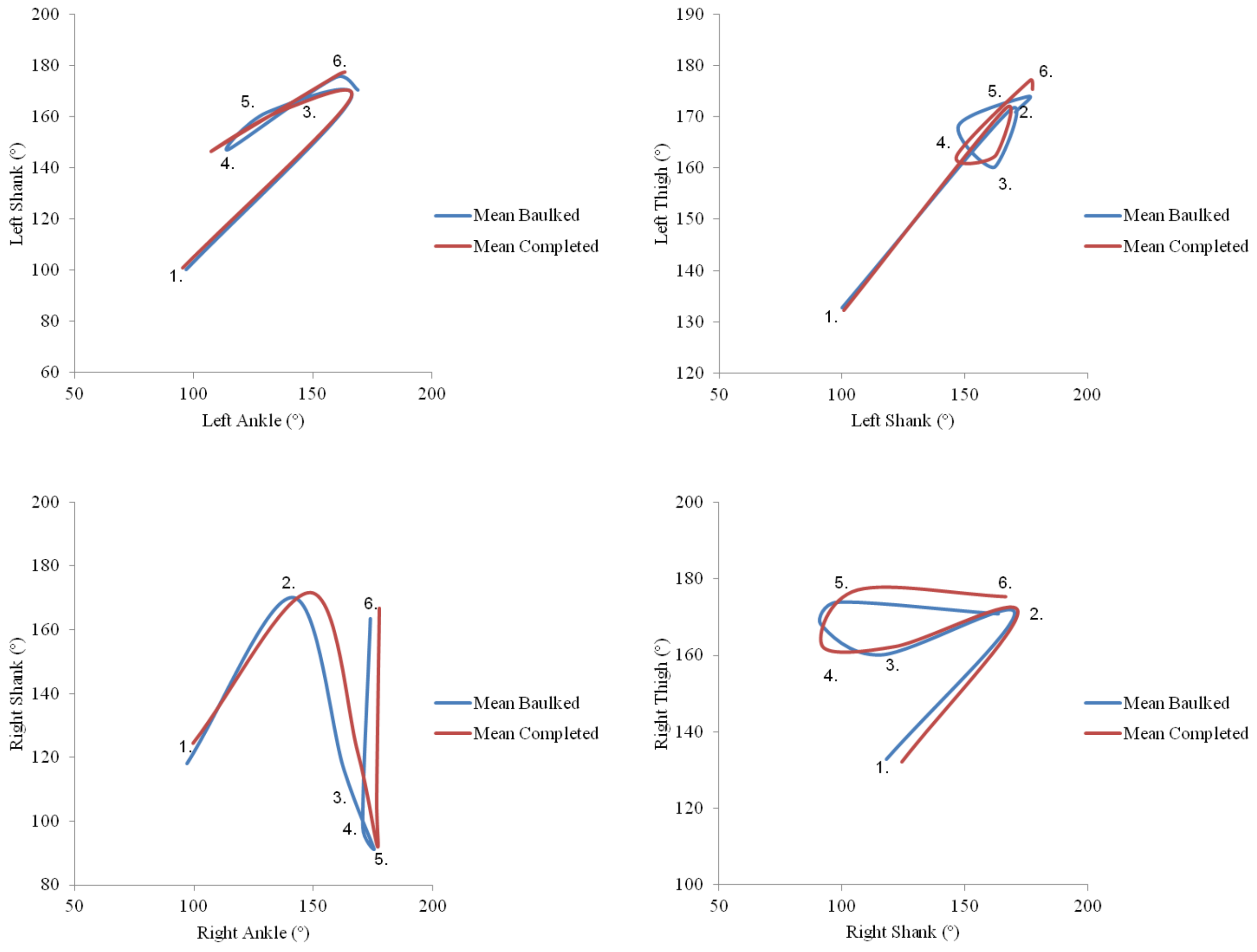


Figure 4-3 (a) Mean completed and mean baulked angle-angle plots for Participant One
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

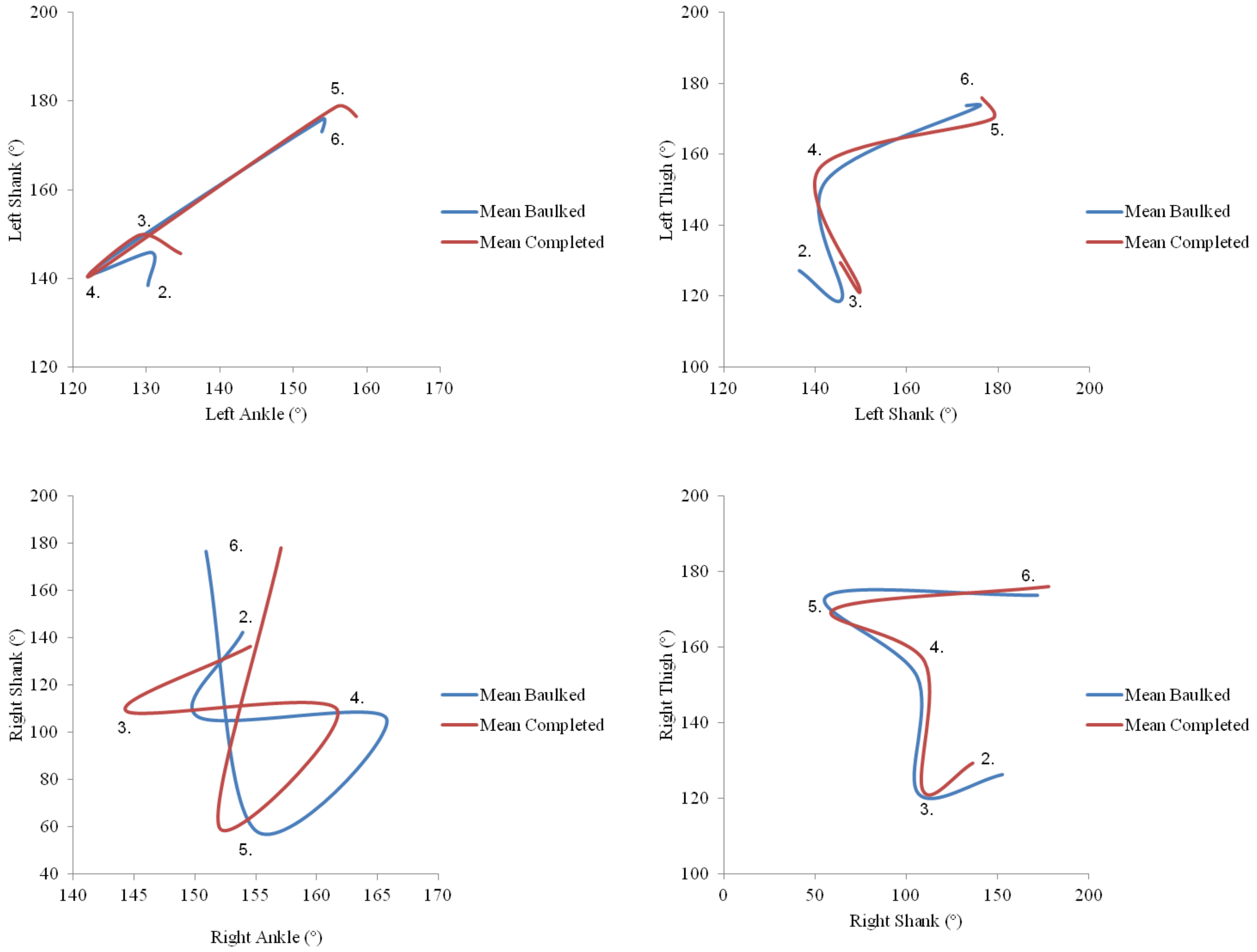


Figure 4-3 (b) Mean completed and mean baulked angle-angle plots for Participant Two
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

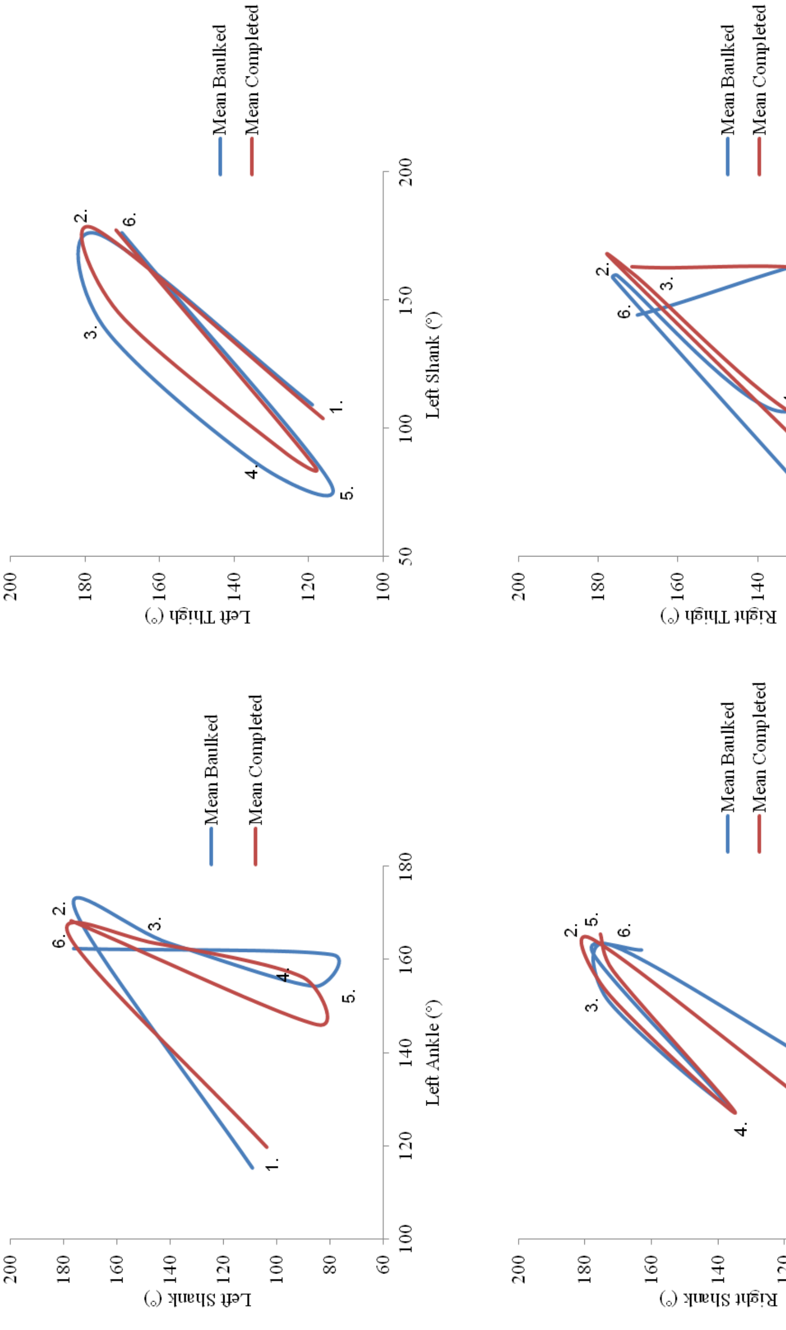


Figure 4-3 (c) Mean completed and mean baulked angle-angle plots for Participant Three
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

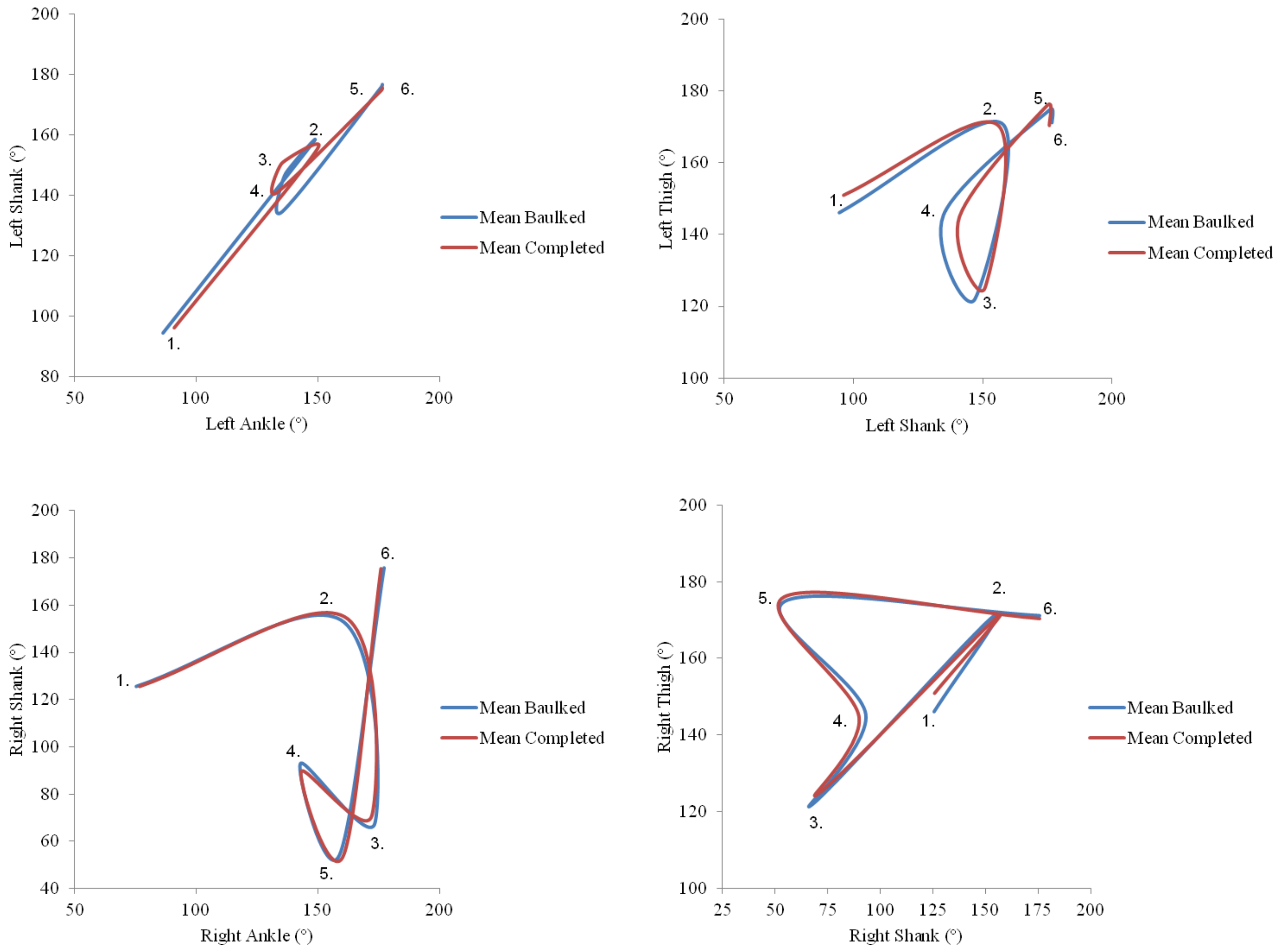


Figure 4-3 (d) Mean completed and mean baulked angle-angle plots for Participant Four
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

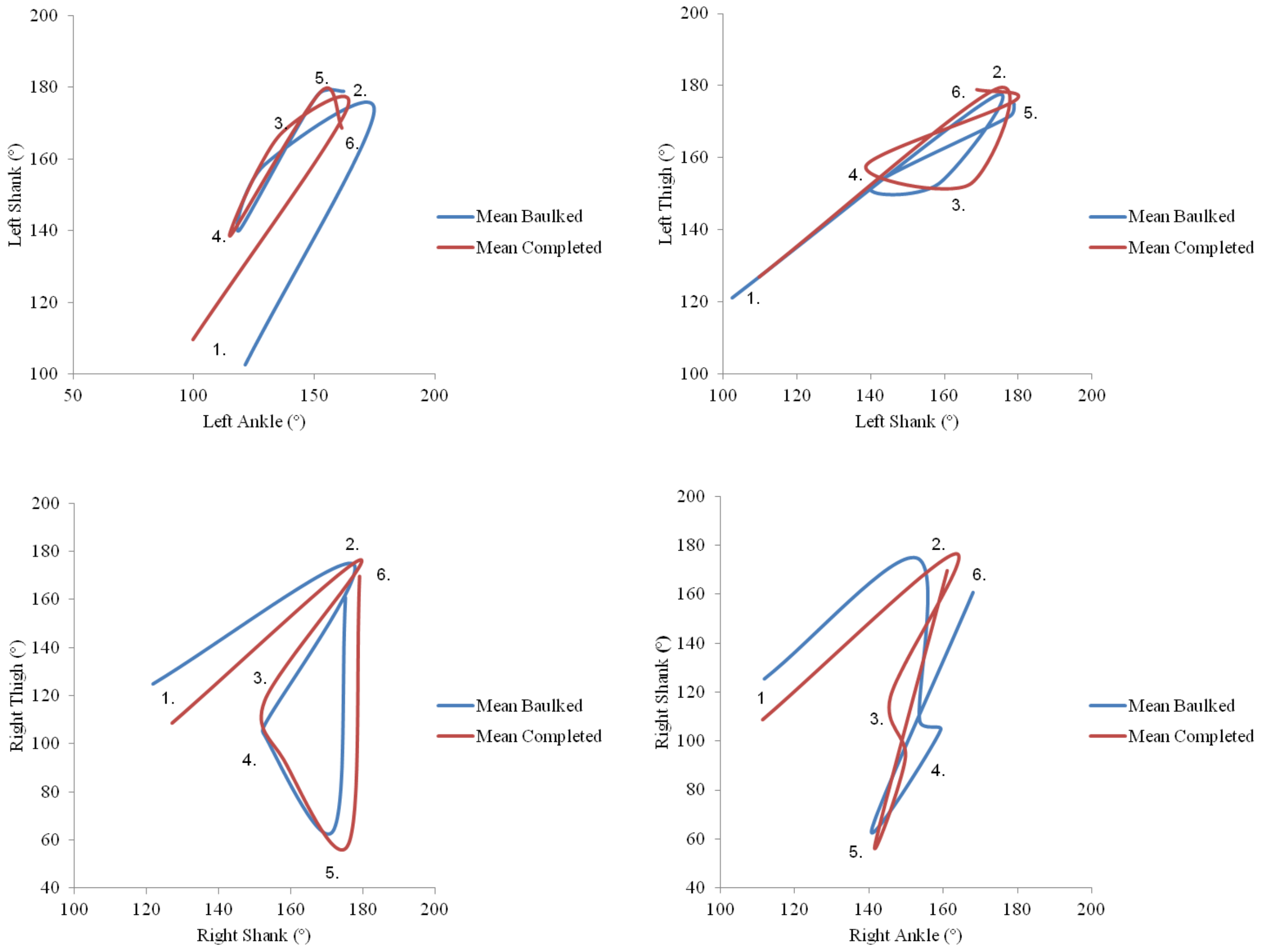


Figure 4-3 (e) Mean completed and mean baulked angle-angle plots for Participant Five
(1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

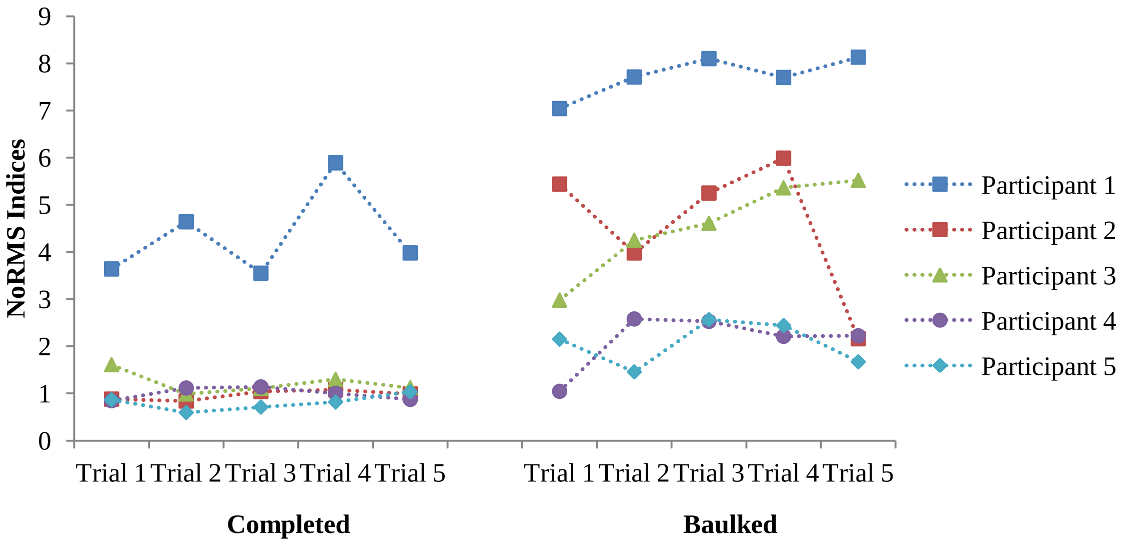


Figure 4-4 NoRMS indices of right shank-thigh intra-limb coordination for all participants during five completed and five baulked dive trials

Discussion

This study aimed to investigate whether observable differences existed between the movement kinematics of elite divers in the preparation phases of baulked and completed take-offs. As predicted, no differences in movement patterns were observed between completed and baulked take-offs. Specifically, individual analyses revealed no changes in the shape of the angle-angle plots between conditions for any of the participants (see Figure 4-3 a-e), suggesting that no differences in movement pattern coordination existed between baulked and completed dives that might justify the abortion of an intended dive. In attempting to only practice high quality dives, many athletes have traditionally tried to eliminate take-off variations during training. Consequently it was expected that, because of this approach to training, the movement patterns of completed take-offs would display greater consistency than those take-offs where the athletes baulked. Quantitative analyses of variability within conditions, revealed greater consistency and lower variability amongst completed dives, and greater variability amongst baulked dives for all participants as evidenced by the NoRMS indices (see Figure 4-4).

An examination of key events (e.g., step lengths, jump height) during the approach and hurdle phases of the take-off revealed observable differences between performance conditions for all participants. However, these differences were not observed in all participants at all key events suggesting that, overall, the hurdle and approach phases of completed dives were not completely different from those of baulked take-offs. Furthermore, it is possible that athletes will choose to abort a planned take-off when they detect variation from the highly practiced movement pattern of the comfortable completed dives. Wilson and colleagues (2008) suggested that each phase of a skill may be affected by the preceding phases. For example, Participant Five displayed large differences between completed and baulked take-offs in the distance of first approach step (9.6 cm). A slightly shorter or longer step than the athlete considers ideal, may affect subsequent phases of the take-off, creating perceptions of discomfort and resulting in the athlete baulking. Further, Wilson et al., (2008) propose that the ability of coordinative units to adapt to performance perturbations (e.g. variations in step lengths or foot placements on the springboard in diving) is crucial if the performer is to consistently achieve successful performance outcomes. Additionally, the results of this study suggest that there may not be a single key event that causes all divers to abort the take-off. For example; Participant One showed the largest difference between conditions in the average hurdle jump distance (8.4 cm). Participant Two showed the largest difference between conditions in the average hurdle step distance (18.8 cm). Participant Three showed the largest difference between conditions in the average hurdle jump height (7.8 cm).Participants Four and Five showed the largest differences in average hurdle step (6.0) and first approach step (9.6 cm) respectively.

An important characteristic of skilled performance is the precise tuning of an action to the changing circumstances of the environment captured by the information properties available (Van der Kamp, et al., 2008). With repetition in practice, the strength of the coupling of environmental information to action may increase the stability of the movement outcome observed (Van der Kamp, et al., 2008). By only practising dives with good quality take-offs, divers may only be affording themselves the opportunity to develop strong couplings between information and movement under very specific performance circumstances. Consequently, in situations where the divers do not perform an ideal take-off (often in competition); they are unable to adapt ongoing movements to achieve performance outcome stability (rip entry into the water with minimal splash). By encouraging divers to minimise baulking during training and attempt to complete every dive, athletes may be able to strengthen the information and movement coupling in all circumstances, widening the basin of performance solutions and providing alternative couplings to solve a performance problem even if the take-off is not ideal (Higgins & Spaeth, 1972). Slobounov and colleagues (1997) argued that skilful diving performance was characterised by significant variability of movement patterns in preparatory phases preceding the actual execution of the dive itself. Of particular interest was their finding that dives that are more complex showed less variability than simple dives. The authors argued that this finding may have been an indication of an expert diver’s ability to efficiently reduce the number of controlled elements that need to be regulated during difficult dives (Slobounov, et al., 1997). An alternative interpretation of these results, however, could attribute the observed variability in the simple dives to the athlete’s ability to complete simple tasks under variable conditions. In this example, divers were asked to complete dives without somersaults. The simplistic nature of these tasks (and the extensive training history) may have meant that the divers were more willing to complete a dive with an ‘uncomfortable’ take-off. Because of this, they may have already developed skills allowing the successful completion of the dive under varied take-off conditions. Conversely, with more complex skills (dives with multiple somersaults), athletes may fear that they will not complete the required number of rotations without an ideal preparatory phase; and baulk; ultimately reinforcing the notion that a good dive can only be achieved from a good take-off. Unfortunately, the number of baulks that occurred during the data collection phase in that study was not reported.

Although previous research has shown that functional variability increases with task expertise (Araújo & Davids, 2011; Arutyunyan, et al., 1968; Bernstein, 1967; Manoel & Connolly, 1995), the current investigation is unique since the sample of elite divers had actively attempted to phase out or minimise functional variability during training. These findings have shown that no differences exist between baulked and completed take-offs and provide a powerful rationale to encourage coaches to consider functional variability or adaptability of motor behaviour as a key criterion of successful performance in diving; rather than the ability of all performers to replicate an ideal movement template. This perspective is in line with suggestions that skill acquisition might be better understood as skill adaptation. How changes to training practices might include or integrate functional variability in performance, and how this may affect movement form, and ultimately performance outcomes in the form of judges’ scoring, remains an issue for future work. However, the benefit of achieving performance outcome consistency during competition (and any minor point deductions associated with deviation from the movement criteria guidelines) would outweigh the severe penalties imposed for either baulking or executing a poor dive from an uncomfortable, unpractised take-off.

In summary, it has been argued that variability is a necessary prerequisite to adaptation whether genetic or behavioural, and that the sources of variability are intrinsic to a neurobiological system (Klingsporn, 1973). The results of this investigation on lower limb degrees of freedom provided no evidence to suggest that different movement patterns existed between baulked and completed dives that might justify the abortion of an intended dive. Consequently, with no major differences in coordination patterns, and the potential for a negative performance outcome in competition, there appears to be no training advantage in baulking on unsatisfactory take-offs during training, except when a threat of injury is perceived by an athlete. The observation of similar movement patterns in baulked and completed dives is an interesting finding. Prior to this study it was not known whether the preparation phase differed between baulked and completed dives and the data reported here indicate that there were no clear reasons, from a movement kinematics perspective, for the elite divers to baulk. However, it may be possible that other components of this complex system, those not measured here may be responsible for baulking tendencies, for example head stability. This is an issue that needs to be investigated in follow-up work. However, since the results show that there are no performance advantages for the elite divers to baulk (indeed there are clear competitive *disadvantages* for this behaviour), the implication is that enhancing their movement adaptability would be far more beneficial.

A future training programme, where participants continue with normal training practice but are not allowed to baulk, may be advantageous for developing skills to adapt to variability in the movement patterns of the approach and hurdle phases or environmental changes (e.g. an oscillating board) (see Chapter Five). Specifically, divers should aim for an optimal performance outcome (quality dive entry) on each dive; continuing with the dive approach and take-off regardless of the perceived quality of the preliminary lead-up.

CHAPTER FIVE – Adaptive movement patterns in springboard diving

This chapter is based on the following peer-reviewed journal article:

Barris, S., Farrow, D., and Davids, K., (2013). Increasing functional variability in the preparatory phase of the take-off improves elite springboard diving performance. *Research Quarterly for Exercise and Sport.*

Adaptive movement patterns in springboard diving

Functional variability in the preparatory phase of the take-off and performance in elite springboard diving

Previous research demonstrating that performance outcome goals can be achieved in different ways is functionally significant for springboard divers whose performance environment can vary extensively. Despite this evidence, elite divers have traditionally endeavoured to achieve stable, invariant movement patterns by baulking (aborting the take-off) during practice. In a twelve-week training programme (2x day; 6.5 hours per day), four elite female springboard divers were encouraged to adapt movement patterns under variable take-off conditions and complete intended dives, rather than avoiding variability by baulking. Intra-individual analyses revealed small increases in variability in the board-work of each diver's pre- and post-training programme reverse dive take-offs. No topological differences were observed between movement patterns of dives completed pre- and post-training program. However, differences were noted in the amount of movement variability within the different training conditions (evidenced by higher NoRMS indices post-training program). An increase in the number of completed dives (from 78.91 – 86.84% to 95.59 – 99.29%) and a decrease in the frequency of baulked take-offs (from 13.16 – 19.41 % to 0.63 – 4.41%) showed that all four athletes were able to adapt their behaviour during the training programme. These findings coincided with greater consistency in the divers' performance as scored during judged events. Results suggested that, at the completion of this training programme, the athletes were capable of successfully performing skills under more varied take-off conditions and displayed greater consistency and stability in performance outcomes.

A large body of work has theoretically modelled the functional role of movement variability in skill performance from a range of perspectives including optimal control theory (Todorov & Jordan, 2002), the uncontrolled manifold hypothesis (Scholz & Schöner, 1999), and ecological dynamics (e.g. Davids, et al., 2003). These approaches acknowledge that some action parameters can be allowed to vary during performance, whilst others are more tightly constrained. They share a commonality in advocating that a range of deterministic and variable processes contribute to observed fluctuations in regulated and unregulated motor system degrees of freedom during task performance. Riley and Turvey (2002) described this process as 'piecewise determinism' in which particular combinations of variable and deterministic behaviours emerge when performers attempt to satisfy different task constraints by allowing variability in redundant biomechanical degrees of freedom, and minimizing it in other parts of the motor system.

These ideas are aligned with theories of skill acquisition proposing that a functional relationship between consistency and variability is required for successful sport performance (Newell & Corcos, 1991). It has been argued that elite athletes' actions should not be considered automated or stereotyped, but rather they can be subtly varied and coordinated to sudden changes in the performance environment (Davids, Bennett, et al., 2006; Davids, et al., 2003). The capacity of skilled performers to achieve performance outcome consistency occurs as a result of an individual's greater use of functional movement pattern variability (Arutyunyan, et al., 1968). In this study we adopted an ecological dynamics perspective to investigate whether elite divers could be trained to harness adaptive movement variability to achieve consistent performance outcomes.

Movement pattern variability within individuals is considered functional when it affords performers flexibility to adapt goal-directed actions to satisfy changing performance constraints (Davids, Handford, & Williams, 1994). It has been shown that consistent performance outcomes can be achieved by different patterns of coordination available through the re-configuration of a joint's biomechanical degrees of freedom (DOF) (see especially Bernstein, 1967; Davids & Glazier, 2010; Newell & Corcos, 1991). From this perspective, functional levels of movement adaptability require the establishment of an appropriate relationship between *stability* (i.e., persistent behaviours) and *flexibility* (i.e., variable behaviours) Experts can produce subtly nuanced performance behaviours which exhibit some structural regularities and similarities, but are not fixed into rigidly stable solutions. Neurobiological system degeneracy, the ability of elements that are structurally different to perform the same function or yield the same output (Edelman & Gally, 2001), provides a conceptual basis to explain the functional role of movement pattern variability in sport performance (Barris, et al., 2012). We sought to understand whether elite performers could adapt behaviours in a functional way by exploiting inherent system degeneracy.

Evidence for these ideas has emerged from studies of performance in a range of tasks including triple jumping (Wilson, et al., 2008), basketball shooting (Button, et al., 2003), table tennis (Bootsma & van Wieringen, 1990), locomotion (Hamill, et al., 1999) throwing (Bartlett, et al., 1996) (Bauer & Schöllhorn, 1997), and pistol shooting (Arutyunyan, et al., 1968; Scholz, et al., 2000). These investigations have demonstrated that individual performers are capable of discovering different ways to achieve specific task goals, even under similar performance constraints, through the coordination and control of a variety of functional movement patterns (Chow, et al., 2008; Edelman & Gally, 2001).

The theoretical possibility that specific performance goals can be achieved by organizing different or variable execution parameters is clearly of significance to performance in sports such as springboard diving where the external environment can be highly variable (Barris, et al., 2012; Kudo, et al., 2000). Appreciating the characteristics of the springboard are particularly important for understanding the variable environment within which divers train and compete. For example, small increases in the oscillation of the board (resulting from changes in location and magnitude of force application by athletes during contact in dive preparation) can lead to large increases in the variability of the performance environment (the board oscillates more quickly or slowly depending on the nature of contact by the athlete).

This performance challenge has practical implications for understanding divers' training behaviours. For example, during dive preparation, if a diver lands back from the edge of the board, the capacity to generate enough height to complete the required rotations to complete the dive successfully may be constrained (Kooi & Kuipers, 1994; Miller, et al., 1998; O'Brien, 1992). These insights are important since biomechanical analyses of preparatory movements in diving have highlighted the significance of the approach and hurdle steps for the successful execution of the complete dive. That is, the actions of divers *after* take-off are largely dependent on their *preparatory* actions on the board (Jones & Miller, 1996; Miller, 1984; Miller, et al., 1998; Slobounov, et al., 1997). Despite such potential variations in the performance environment, elite divers and their coaches typically strive during practice to achieve a stable, highly reproducible and invariant movement pattern (Barris, et al., 2012). For example, in his manual for coaches, O'Brien (1992) stressed the importance of "consistent preparatory postural movements on the springboard" which he claimed should be the coach's primary concern, regardless of the type of dive and the diver's level of skill.

To contend with the variability generated in interactions with the springboard, current training practices in springboard diving allow elite athletes to baulk (abort the take-off), if they believe their preparation is imperfect. A baulked dive occurs when a diver completes the preparatory phase on the board (approach and hurdle steps), but does not take-off to complete the aerial somersaulting phase of the dive (see Figure 5-1). The implication of this strategy is that divers tend to reduce the number of practice trials they undertake and only practice the execution of dives from what they perceive to be an 'ideal' approach and hurdle phase. This 'template-driven' approach to training is somewhat dysfunctional since it can have detrimental effects in competition, where a two-point baulking penalty or 'no dive' judgment (score of zero from all judges) can result for baulking. The result is that elite divers often attempt to complete dives in a competitive performance environment that they would choose to baulk on in training. Anecdotal evidence in the form of experiential knowledge from an elite diver supports the idea that baulking should be avoided (Lowery, 2010):

(a) (b) (c) (d) (e)

Figure 5-1 An example of the approach (a-b) and hurdle (c-d-e) phases of a reverse dive take-off

> “He stressed the importance of quality training and making every dive count in practice. The athletes took notice when [four time Olympic Gold medallist Greg] Louganis mentioned he rarely baulked in training, instead seeing a poor take-off as an opportunity to challenge himself. Stanley said he has found himself making adjustments in his workouts after listening to Louganis. “His comment about baulking; to go no matter what; really stood out to me. I think I’ve baulked maybe once since then,” Stanley said. “Before, I would baulk over and over again until I got a good take-off” (2010, p. 9).”

Although divers typically baulk when they detect slight deviations from an optimal take-off routine, a movement analysis by Barris and colleagues (2012) refuted this practice tendency. In this study, no topological differences were observed between the movement patterns of baulked and completed take-offs for any of the elite participants, suggesting that similar movement coordination patterns were being organised in both baulked and successful take-offs (see Chapter Four Figures 4-2 & 4-3). Differences were noted, however, in the amount of variability within the different take-off conditions, with angle-angle plots demonstrating more variability in the approach and hurdle phases of baulked take-offs than in completed dive take-offs. This finding was further supported by the presence of higher normalized root mean squared (NoRMS) indices for baulked dives relative to the completed dives (Barris, et al., 2012). As such, it was concluded that individual movement coordination patterns during baulked take-offs were not different enough from those that were completed to justify the abortion of a planned dive.

Consequently, with the potential for a negative performance outcome in competition (a 2-point penalty) there appears to be no advantage in baulking on unsatisfactory take-offs during training, except when a threat of injury is perceived by an athlete. Rather, it seems advantageous for elite athletes to gain experience in compensating for variability in their take-off movements or environmental changes (e.g. an oscillating board), and attempt to complete a quality dive under varying take-off conditions. While previous research has theoretically and empirically supported the notion of functional variability in performance, there have been no attempts to introduce this important idea into an elite sport performance training program. The aim of this training program, therefore, was to introduce the notion of functional variability to an elite high performance squad which had traditionally aimed to remove variability from performance through constant practice.

This study aimed to investigate whether a sample of elite divers were able to adapt their movement patterns regardless of the perceived quality of their preparatory movements on the springboard. We sought to design task constraints for an elite athlete training program which were *representative* of the competitive performance environment (Brunswik, 1956). The concept of representative design implies a high level of specificity between a training environment and competitive performance conditions (Pinder, et al., 2011b), induced by encouraging divers to practice movement adaptation because it is functional during competitive performance.

In line with previous research (Arutyunyan, et al., 1968; Hamill, et al., 1999; Wilson, et al., 2008), it was expected that elite divers would be able to successfully reduce the amount of baulking in training and, like other highly skilled athletes, become more capable of completing their dives under varied take-off conditions at the end of the training programme. As a result of the training programme, it was anticipated that greater levels of variability would be observed in the hurdle and approach phases of the take-off after the training programme, but that greater stability would be observed in key performance outcomes (i.e. a rip entry into the water with minimal splash from a varied take-off movement pattern).

Method

Participants

Five elite female springboard divers (mean age 19.4 ± 2.88); who were free from injury and currently in training (average 28 hours per week); were recruited for this study and provided written informed consent. The sample represented 100% of the elite female springboard divers in Australia at the time of the study. The performance level of the sample was truly elite with participants having experience of performing at world championship and Olympic level. One athlete withdrew at week six due to injury. Participant characteristics are presented in Table 5-1. The experimental protocols received approval from two local research ethics committees.

Table 5-1 Participant information

	Age	Exp (yrs)	Ht (cm)	Wt (kg)
P1	19	7	159	63
P2	20	11	165	60
P3	17	5	160	67
P4	24	10	156	48
P5*	17	8	158	63

* participant withdrew

Pre- and post training programme observation

Prior to commencing the training programme, participants were observed during all training sessions (aquatic and dry-land training) for one week to record baseline measurements of baulking frequency. The number of baulked and completed dives were recorded for each individual and presented as a percentage of dives attempted. At the completion of the training programme, the divers were observed for one further week to record behaviour retention. To avoid unduly influencing training behaviours, these recordings were completed without the diver's direct knowledge of the research question.

Training programme design

The design of this investigation involved a twelve-week, single-group training programme with an elite athlete population who were analysed performing complex multi-articular skills in their normal practice environment. As such, this naturalistic, unique, observational training programme did not provide opportunities to follow traditional laboratory-based intervention methods: with large sample sizes, control groups, learning and detraining periods and follow-up retention tests. For this reason, a dive not included in the training programme, but practiced as much, was used as a within-participant control condition. In a backward somersaulting dive, the diver takes-off from a standing start on the springboard with their back to the water and rotates backwards. Back dives (with two and a half somersaults) were included as a control measure, as they received the same amount of coaching and training time as reverse dives, but were not included in the training programme as they do not begin with the 'walking' hurdle approach. Similarly, since the movement patterns of each elite participant were subjected to individualised analyses, it was decided not to examine group-level data, decreasing the need to include a separate control group.

The performance of each elite athlete was monitored throughout all training sessions (10 per week), to record any baulks that occurred in both the aquatic and dry-land environments (springboards set up over foam pits and crash pads in a gymnasium). Divers were encouraged to continue with their coach-prescribed individual training programmes, but to avoid baulking except in instances where they felt unsafe or where injury may have occurred.

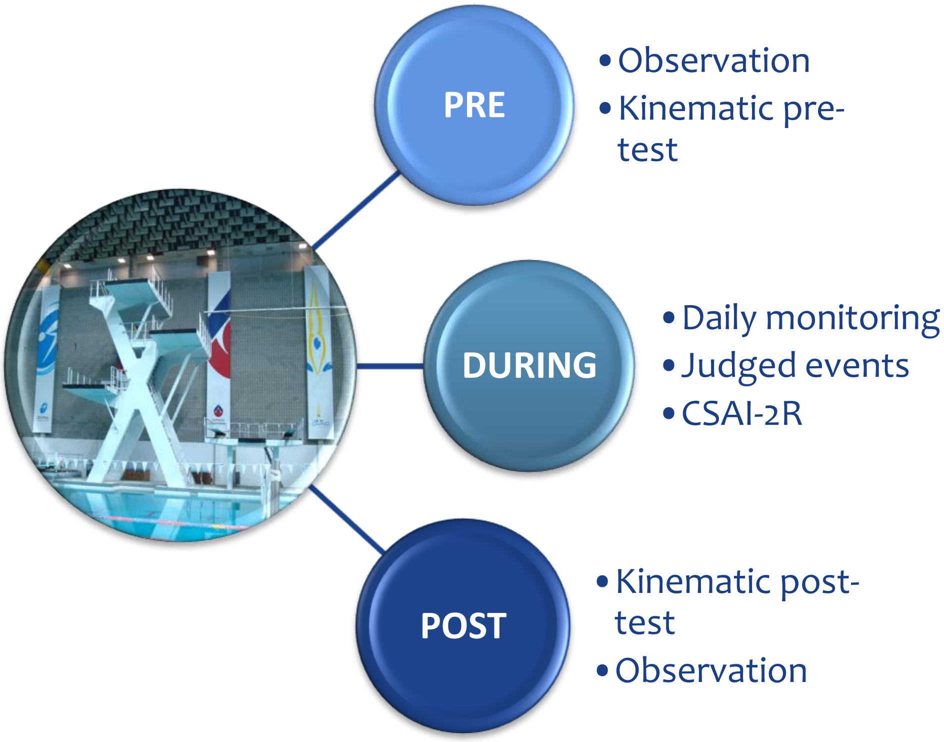


Figure 5-2 Diagram of training programme testing schedule

Testing periods

Pre- and post training programme kinematics

The testing periods during this training programme occurred in multiple parts (see Figure 5-2). Kinematic analyses were conducted before and after the training programme to compare the amount of variability present in the preparatory phase of the take-off. It was hypothesised that a post- training programme analysis of movement kinematics would reveal greater variability between trials than those recorded prior to the initiation of the training programme. Two-dimensional kinematic characteristics of the approach and hurdle phases were captured using one stationary camera (Sony HDV FX1 HDV 1080i, shutter speed 1/100s) positioned perpendicular to the side of the 3m diving board (at a height of 4m and distance of 15m) in the sagittal plane (approximately 90°) and recorded movements at 60 frames per second (Barris, et al., 2012; Slobounov, et al., 1997). A sufficient focal length was chosen that permitted the recording of the whole dive movement and allowed the digitisation of the relevant body markers (Slobounov, et al., 1997). Divers completed five repetitions of one dive (a reverse two and a half somersaults pike) to measure their ability to perform consistently. Participants were informed that their performances would be recorded for technique analysis and were asked to perform as best they could, according to the normal competitive judging criteria. No additional or specific instructions, corrections or comments were provided to the athletes by the researchers during data collection, in order not to contaminate the data emerging from the athlete performances during these sessions.

Flat 14mm tape was fixed to twelve lower body limb landmarks on both the right and left sides of the body (anterior superior iliac spine; thigh, knee, shank, ankle, toe), ensuring an optimal position for minimising visual occlusion (Slobounov, et al., 1997). Further markers were placed on the side of the springboard (at 0.5m, 1m, 1.5m and 2m from the oscillating end) in direct line with the camera for calibration of the filming environment and to assist with step and hurdle length measurements (Barris, et al., 2012). The kinematic analysis of the approach and hurdle phases was achieved by manually digitising the identified lower limb anatomical landmarks using PEAK Motus™ Motion Analysis Software (Oxford, United Kingdom). The data were filtered using a second order low-pass Butterworth digital filter with a cut-off frequency of 6Hz (Miller & Munro, 1984). One video sequence was selected at random and digitized by the same observer on five occasions to ensure that reliable results were obtained through the digitizing process (Hopkins, 2000). Intraclass correlation coefficient values ranged between $r = 0.950$ and $r = 0.999$ indicating strong correlations between the repeatedly analyzed trials.

Each diver's movements on the springboard prior to take-off were analysed during all ten trials (five before and five after the training programme) including: step lengths during the forward approach; (two normal walking steps), the length of the hurdle step (long lunge like step), and the hurdle jump distance (two foot take-off one foot landing). All step and jump lengths were measured as the distance between heel strike and toe off. Additionally, hurdle jump height (distance between the tip of the springboard and toes); flight time during the hurdle jump and the maximum angle of springboard depression (the maximum angle the springboard moves below its horizontal resting position) during the hurdle jump landing, were also recorded (Barris, et al., 2012). The means and standard errors of each divers movements at key events during the preparation and approach phases of dive take-offs pre and post training programme are presented in Table 5-3.

Further, each participant's joint kinematics were analysed at the same key events (e.g., approach step, hurdle jump, flight time, and maximum board depression angle). Angle-angle diagrams were used to qualitatively describe performance variability and assess the topological equivalence of pre- and post training programme dives (See Chapter 2, Page 50, Quantifying movement patterns, Bartlett, 2007). The topological characteristics of a movement describe the motions of the body segments relative to each other and changes in these patterns can provide evidence that specific aspects of coordination have changed (Anderson & Sidaway, 1994; Chow, et al., 2008). If the two shapes are topologically equivalent, then it can be assumed that the same skill is being performed (Bartlett, et al., 2007). However, if one diagram has to be folded, stretched or manipulated to fit the other, it can be assumed that two separate skills are being performed. Previous investigations have used angle-angle plots to depict qualitative changes in intra-limb coordination as a function of practice, and normalised root mean square error (NoRMS) to assess variability in the relationship between joint angles (Button, et al., 2010; Chow, et al., 2007; Chow, et al., 2008; Mullineaux, 2000; Sidaway, et al., 1995). The root mean squared error is totaled for the number of trials collected and normalised with respect to the number of trials. This method has been recommended for small trial sizes and normalised techniques (Mullineaux, 2000), and has successfully detected changes in stability of coordination in both linear and non-linear data (Chow, et al., 2007; Chow, et al., 2008; Sidaway, et al., 1995). Results were interpreted based on the assumption that, a higher index for NoRMS is indicative of greater variability in joint coordination over trials, whereas a lower NoRMS index will indicate lower levels of variability in intra-limb coordination (Chow, et al., 2007).

A post- training programme kinematic analysis was conducted at the conclusion of the training programme, one week after the last training session.

During training programme: Athlete self monitoring

During every training session during the training programme, as athletes attempted to adapt their movement behaviour, the divers were asked to record their perceptions of each dive (attempted or completed) in chronological order in one of three columns (completed, uncomfortable, baulk). Dives where the athlete felt comfortable and completed the intended skill were recorded in the completed column. Uncomfortable dives were classified as those where the athlete would previously have baulked but instead attempted a dive (regardless of whether it was the intended dive or not). Finally, baulked dives were those where the athlete aborted the take-off. For example; if a diver completed five dives and the first two were completed successfully, the third one was a baulk and the fourth and fifth were uncomfortable, the athlete would record '1, 2' in the completed column; '3' in the baulk column and '4, 5' in the uncomfortable column. These records allowed each athlete's progress throughout the training programme to be monitored and permitted the identification of potential patterns associated with baulking behaviour (e.g., higher numbers of baulks towards the end of a session might suggest fatigue as a cause; early baulking a lack of mental preparation). Individual athlete performances throughout the training programme are presented as line graphs in the following section (see Figure 5-5).

Performance measure (judged tests)

Each diver completed a full 3m springboard competition 'round' (a simulated competition performance with one attempt at each dive in order of competition performance); on 16 occasions throughout the training programme period. These simulated competitions were held during the first and last training sessions during weeks 1, 2, 3 & 12; and during the last training session of the remaining weeks). Each simulated competition performance was completed under FINA competition conditions. One Sony HDV FX1 HDV 1080i camera was placed in an elevated positioned perpendicular to the side of the diving boards (similar to the judges' seating locations at actual competitions) and recorded the event (60Hz) for retrospective analysis. The video images were viewed independently by qualified experts, who were also blind to the research question, in a randomised order. Judging reliability was achieved by cross checking the experts' scores with those of a second competition judging panel (n=5). Intraclass correlation coefficient values ranged between $r = 0.870$ and $r = 0.999$ indicating strong correlations between judging panels on all dives. Each diver selected test dives specific to her individual ability and performed these same dives at each testing session. Divers were informed of the judging component of the testing sessions and reminded that competition rules and conditions applied (e.g. penalties in the form of point deductions for baulking).

Although divers performed each of the five different types of dives in the simulated competitions and all five dives were awarded a score, the scores from only two dives will be reported here. The average score for each participant's reverse and back[2] dives are presented in Figure 5-6. The average back dive score is reported as a control; because it was practiced as much as the other dives (front and reverse); but was not included in the training programme as it does not have a hurdle take-off. Lastly, a Wilcoxon Test was conducted on the first five and last five competitions to evaluate whether divers showed greater stability in performance after the 'no baulking' training programme.

Representative environment (anxiety testing)

Competitive State Anxiety Inventory 2 Revised (CSAI-2R) questionnaires were completed by each participant on three separate occasions to determine the level of representativeness of the simulated competition training environment (Dhami, et al., 2004; Riley & Turvey, 2002). Participants were asked to indicate how they felt 'right now' in relation to each item for example; 'I am concerned about performing poorly' and 'I feel jittery'. Each item was scored on a 4 point Likert scale (*1= not at all, 2= somewhat, 3= moderately, 4= very much so*). The inventory consisted of three subscales: Cognitive anxiety, somatic anxiety and self-confidence. The item responses were averaged and multiplied by ten to provide one score for each subscale (Cooke, Kavussanu, McIntyre, & Ring, 2010). This method provided subscale scores of 10 to 40. Data on each athlete's self reported perception of anxiety levels were collected immediately prior to performance of complex skills at; a regular training session, a simulated competition during training and the Australian open diving championships.

Results

Observations

The pre-training programme observations of athlete baulking behaviour showed that all participants baulked more in the pool (18.08 – 25.91% of all dives)

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[2] In the back dive group, the diver takes off with their back to the water and rotates backward

than in the dry-land training centre (7.11 – 16.86% of all take-offs), see Table 5-2. Overall, athletes baulked on approximately 13.16 – 21.09% of all dives attempted. At the completion of the training programme, observation of the athletes performances at training showed that all divers had reduced the number of baulked take-offs to between 0.63 – 4.41% of all dives attempted. However statistical analyses reveal no significant differences.

Pre- and post training programme kinematics

Board-work

An intra-individual analysis was used to determine the amount of variability in divers' movements during pre- and post-training programme reverse dive take-offs. Descriptive statistics showed the existence of very small amounts of variability within pre- and post-training programme dives for all participants (see Table 5-3). However, more variability was observed after the training programme in almost all measures (as evidenced in higher standard deviation values) for all participants. For example, Participant One showed more variability in the post-training programme tests in all measures except the board angle at landing (pre: 13.5° (.234), post: 15.3° (.212)). In contrast, Participant Three showed more variability in the post- training programme tests in all measures except jump height (pre: 73.4 cm (2.112), post: 74.4 (1.965)). These findings were further supported by Wilcoxon tests, which indicated significant differences (pre- and post training program) in springboard depression during the hurdle, $z = -2.845$, $p < .01$ and at jump landing, $z = -2.845$, $p < .01$.

Joint kinematics

Ankle-shank and shank-thigh angle-angle plots were constructed for both lower limbs to depict qualitative changes in intra limb coordination between pre- and post-training training programme take-offs. Qualitative diagrams revealed the presence of individual differences in movement pattern coordination. No topological differences were found to exist between the movement patterns of dives completed before- and after the training programme, for any of the elite participants, suggesting that similar movement coordination patterns were being organised in both conditions (see Figure 5-3). However, differences were observed in the amount of variability within conditions, with angle-angle plots demonstrating greater variability in the approach and hurdle phases of take-offs completed post- training programme and less variability in pre- training programme dive take-offs. Data displayed in Figure 5-3 are examples of one joint coordination plot from each Participant however, these findings were representative for all coordination plots in the study. This performance feature was further highlighted by the presence of higher NoRMS indices for dives completed post-training programme relative to those completed pre-training programme. An example of these NoRMS indices, for each participant's intra-limb coordination, is presented in Figure 5-4 (Right ankle-shank Participants 1 & 2; Left ankle-shank Participants 3 & 4).

During training programme: Athlete self monitoring

All athletes showed an increase in the number of completed dives during the twelve-week training programme (see Figure 5-5 a-d). In the first week, athletes decreased the number baulks from their pre- observation values (13 21% of all completed dives) and reported a high number of uncomfortable dives as they attempted to minimise baulking in training. Each athlete then adapted to the training programme slightly differently. Participant One (Figure 5-5 a) gradually decreased the number of uncomfortable dives from week one to week six, but increased the number of baulked dives until week ten. Participant Three (Figure 5-5 c) adapted very quickly and managed to reduce both the uncomfortable and baulk dives keeping them under 10 per week. Participants Two (Figure 5-5 b) and Four (Figure 5-4 d) responded to the training programme as expected, simultaneously showing a decrease in baulked dives and an increase in uncomfortable take-offs. Each diver's ability to adapt to uncomfortable take-offs throughout the twelve-week training programme was mirrored by an increase in the number completed dives recorded (see Participants Two and Four for example). The total number of baulks recorded each week gradually decreased for all participants during the training programme to 1–4% of all completed dives at. The daily monitoring of sessions did not reveal any observable patterns in baulking behaviour for any participant throughout this training programme, with baulked and uncomfortable dives randomly distributed throughout the training sessions and across each week.

Performance measure (judged tests)

Video recordings of 16 different simulated competitions conducted throughout the training programme period were analysed retrospectively (according to FINA judging rules (FINA, 2009-2013). The average score (out of ten) for each participant’s reverse and back dives are presented in Figure 5-6. None of the participants baulked during any of the simulated competition events. The average scores for each participants reverse dives showed less variation between competitions as the training programme progressed (competitions 8 16). For example, scores for Participant One’s reverse dives fluctuated between 4.0 and 7.0 in competitions 1 to 7 before becoming stable around competition 8, consistently scoring between 7.0 and 8.0. Similarly, Participant Four showed large fluctuations in performance in the early competitions, scoring between 5.5 and 8.0 in competitions 1 to 8, before showing consistent performances in later events (average scores 7.0 8.5). These findings were further supported by a Wilcoxon test which indicated a significant difference, $z = -3.73$, $p < .01$, in the consistency of reverse dives performed at the start of the training programme and those performed at the end. Conversely, the average scores reported for each athlete’s back dives, recorded in the same sessions, showed no consistency in performance between pre and post training programme conditions, $z = -1.92$, $p > .05$.

Table 5-2 Diver's pre and post training programme completed and baulk dive frequencies and percentages

Pre Intervention Observation

	Dry-land		**Pool**		**Dry-land**	**Pool**	**Weekly**	**DRY-LAND**		**POOL**		**OVERALL**	
								%	%	%	%	**%**	**%**
P	*Completed*	*Baulk*	*Completed*	*Baulk*	TOTAL	TOTAL	TOTAL	*Completed*	*Baulk*	*Completed*	*Baulk*	***Completed***	**Baulk**
1	87	17	104	29	104	133	237	83.65	16.35	78.2	21.8	**80.59**	**19.41**
2	143	29	235	72	172	307	479	83.14	16.86	76.55	23.45	**78.91**	**21.09**
3	196	15	213	47	211	260	471	92.89	7.11	81.92	18.08	**86.84**	**13.16**
4	115	9	163	57	124	220	344	92.74	7.26	74.09	25.91	**80.81**	**19.19**

Post Intervention Observation

	Dry-land		**Pool**		**Dry-land**	**Pool**	**Weekly**	**DRY-LAND**		**POOL**		**OVERALL**	
								%	%	%	%	**%**	**%**
P	*Completed*	*Baulk*	*Completed*	*Baulk*	TOTAL	TOTAL	TOTAL	*Completed*	*Baulk*	*Completed*	*Baulk*	***Completed***	**Baulk**
1	102	2	134	6	104	140	244	98.08	1.92	95.71	4.29	**96.72**	**3.28**
2	164	0	256	3	164	259	423	100.00	0.00	98.84	1.16	**99.29**	**0.71**
3	114	4	168	9	118	177	295	96.61	3.39	94.92	5.08	**95.59**	**4.41**
4	205	1	268	2	206	270	476	99.51	0.49	99.26	0.74	**99.37**	**0.63**

Table 5-3 Pre and post training programme means and standard errors at key events during the preparation and approach phases of a dive take-off

P		*Approach Step 1 (cm)*	*Approach Step 2 (cm)*	*Hurdle Step (cm)*	*Hurdle jump Dist (cm)*	*Jump Height (cm)*	*Hurdle Jump Flight (t)*	*Board Angle Hurdle (°)*	*Board Angle Landing (°)*
1	*Pre practice*	36.8 (0.663)	46.4 (0.749)	52 (0.945)	62 (1.140)	69.2 (1.562)	0.826 (0.014)	9.34 (0.157)	13.5 (0.234)
	Post practice	34.6 (1.364)	47.2 (1.655)	58.4 (1.887)	68.2 (2.245)	71.2 (2.200)	0.826 (0.024)	9.94 (0.304)	15.3 (0.212)
2	*Pre practice*	30 (0.707)	26.8 (0.663)	28.6 (1.166)	82.8 (1.393)	64 (0.707)	.65 (0.014)	13.46 (0.163)	15.98 (0.287)
	Post practice	32 (1.000)	30.4 (1.721)	31.6 (1.631)	79.6 (2.502)	71 (2.191)	.71 (0.017)	13.52 (0.159)	15.58 (0.235)
3	*Pre practice*	26 (1.38)	37.6 (1.030)	26.4 (1.288)	113.2 (1.068)	73.4 (2.112)	.716 (.001)	11.4 (.123)	14.1 (.187)
	Post practice	26.4 (2.56)	35.4 (1.536)	23.8 (1.985)	113.6 (2.337)	74.4 (1.965)	.822 (.002)	11.7 (.154)	15.3 (.241)
4	*Pre practice*	33.2 (0.800)	40.0 (0.316)	34.2 (0.583)	24.6 (0.510)	54.2 (0.583)	0.946 (0.001)	8.36 (0.214)	12.86 (0.103)
	Post practice	30.8 (1.428)	38.6 (0.510)	33.6 (0.927)	35 (1.095)	54.2 (1.020)	0.862 (0.001)	9.6 (0.228)	13.36 (0.317)

▨ Indicates significant differences

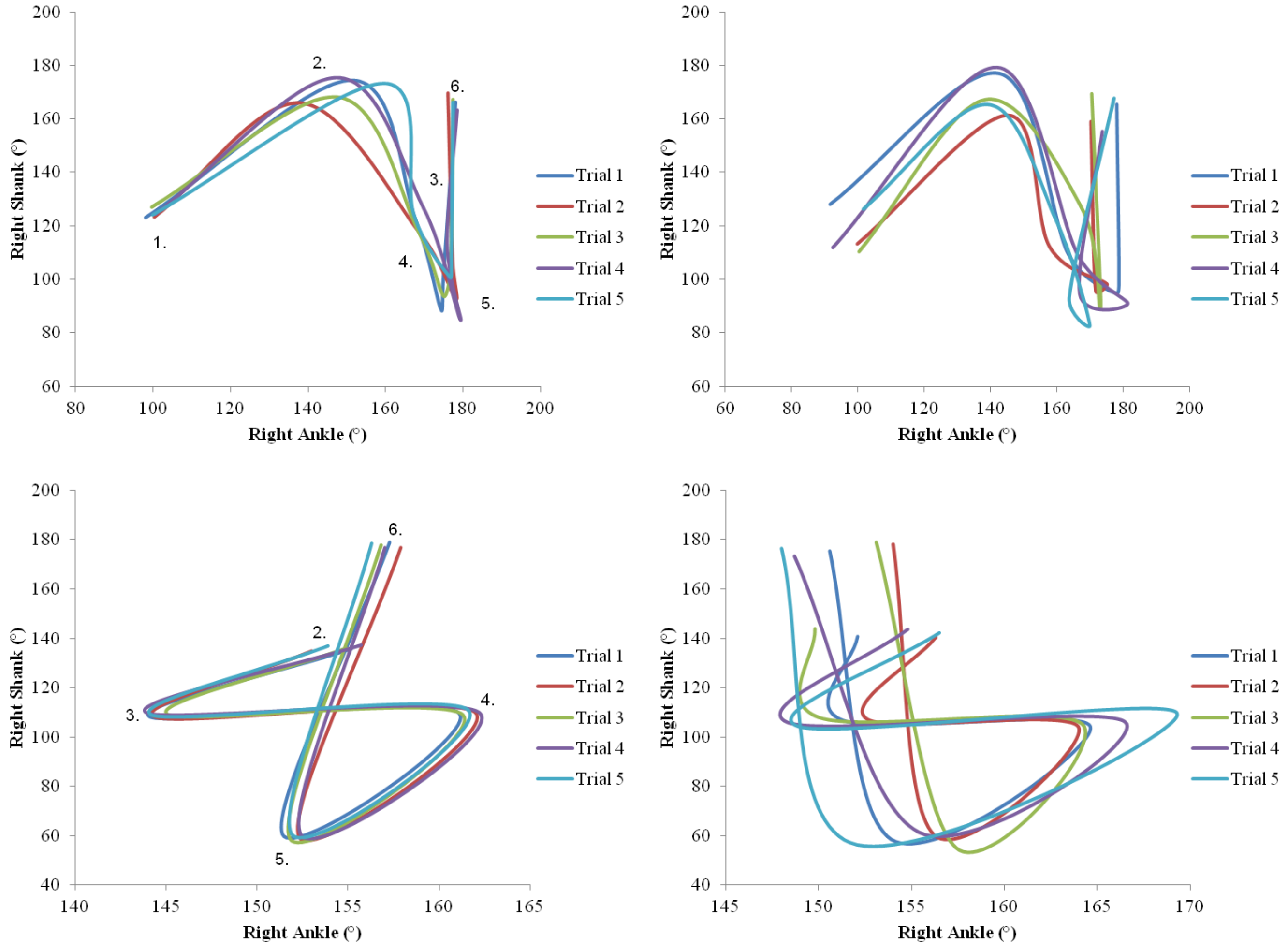


Figure 5-3 Examples of pre- and post-training programme angle-angle plots for two participants (Top- Participant One & Bottom- Participant Two) (1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

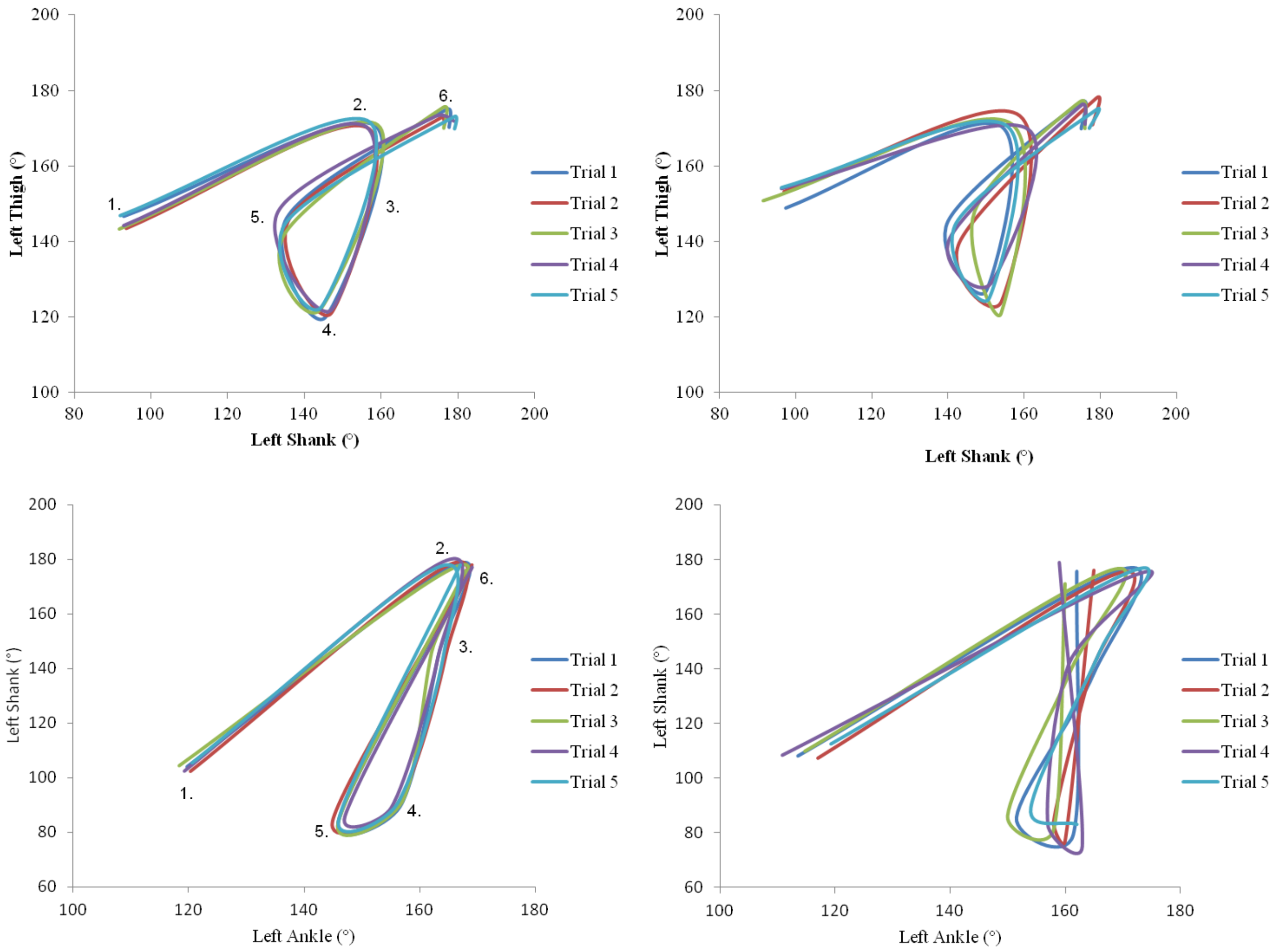


Figure 5-3 Examples of pre- and post-training programme angle-angle plots for two participants (Top- Participant Three & Bottom- Participant Four) (1) Max knee flexion (2) Toe-off pre hurdle (3) Hurdle jump (4) Max board depression (5) Toe-off hurdle (6) Peak jump height

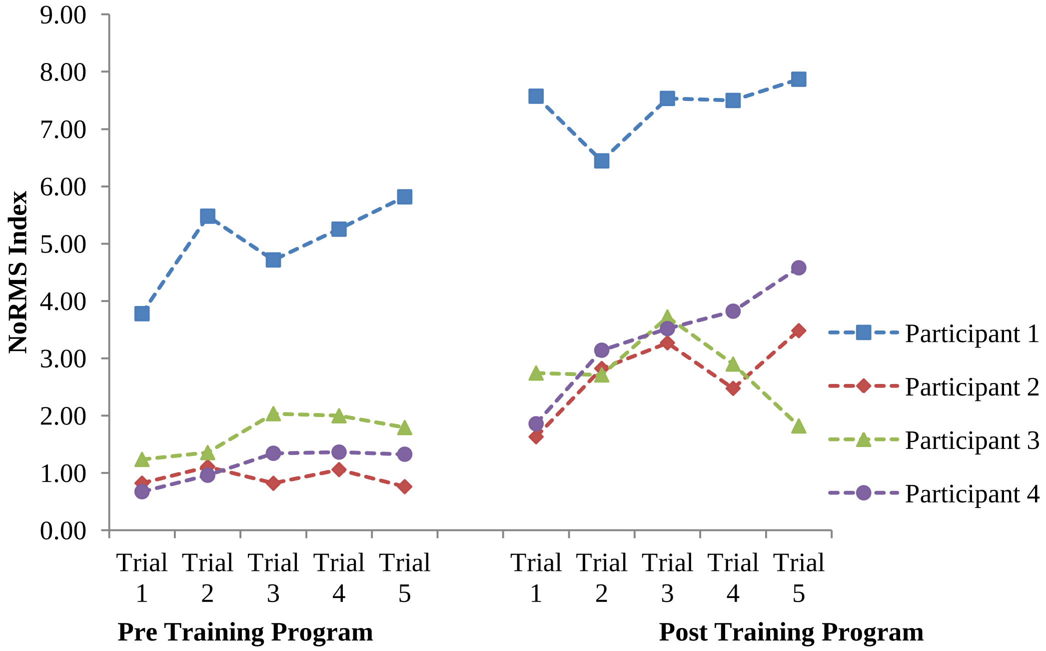
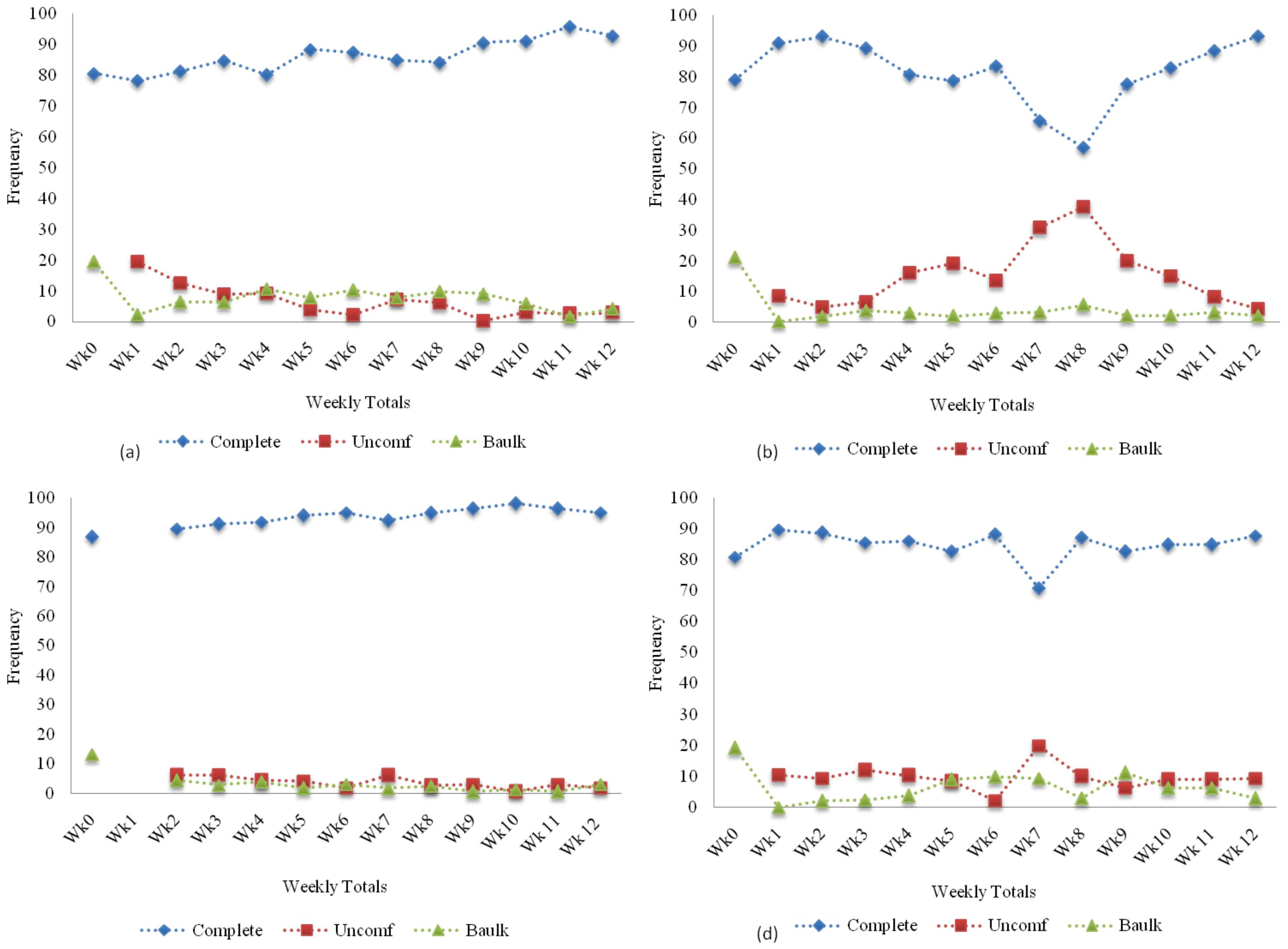


Figure 5-4 Corresponding NoRMS indices for each participant's intra-limb coordination plot displayed above in Figure5-3 (Right ankle-shank Participants 1 & 2; Left ankle-shank Participants 3 & 4).



(a)

(b)

(d)

Figure 5-5 Each diver's progress throughout the training programme

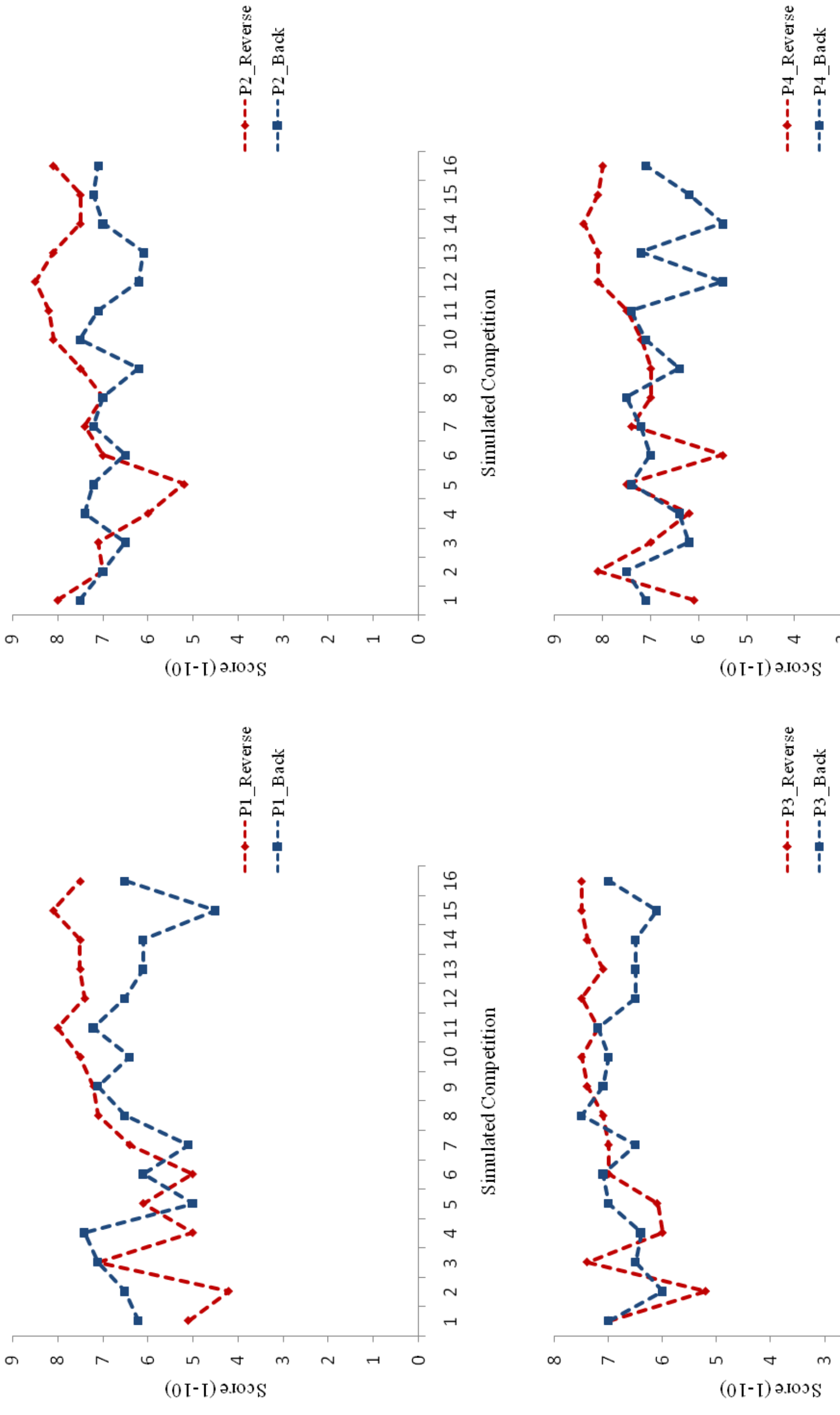


Figure 5-6 Average judged performance scores for each diver's reverse and back dive take-offs during simulated competitions

Representative environment (anxiety testing)

The mean (± standard deviation) cognitive and somatic anxiety and self confidence values reported at each test occasion were calculated for Participants One-Four respectively: 26 ± 0; 26 ± 0 and 22 ± 2 for Participant One; 34 ± 2; 31.6 ± 2.1 and 20.6 ± 1.2 for Participant Two; 19.6 ± 2.9; 12.3 ± 0.6 and 20 ± 0 for Participant Three and 26 ± 2; 13 ± 1 and 20.6 ± 1.2 for Participant Four. None of the three subscales of the CSAI-2R showed differences between the three test occasions for any of the participants, suggesting that they considered the simulations to be a close approximation to what is experienced in the competitive setting (i.e. the representativeness of the simulations was verified) .

Discussion

Throughout this training programme, attempts were made to change traditional training behaviours, and supplant the desire to perform a high quality, invariant preparatory phase, with a goal to achieve stability in a key performance outcome (entry into the water). Over a twelve-week period, this training programme determined that elite athletes were able to adapt their movement patterns during this complex task (the approach and hurdle phases of a multi-somersault springboard dive take-off) and stabilise performance outcomes (e.g., entry into the water). These adaptations were exemplified post-training by a reduction in the incidence of baulking, an increased variability in the preparatory phase of the take-off and greater stability of the performance outcome.

As predicted, after the training programme, observations of the athletes' performance showed that all divers had reduced the number of baulked take-offs during training sessions, suggesting that the divers were able to adapt their movement patterns during complex multi-articular springboard dives. The ability to solve the same motor problem by exploiting different or variable execution parameters becomes especially important when the external environment is dynamic, as skilled performance emerges from the dynamic relationship between the performer, environment and task (Newell, 1986). In this instance, a diversity of movement patterns may be functional in unpredictable environmental situations, e.g.

bouncing on an oscillating springboard (Araújo & Davids, 2011; Davids, et al., 2007).

A contemporary dynamical systems perspective suggests that movement coordination variability typically plays a functional role in the performance of athletic tasks (Hamill, et al., 1999). However, unlike other athletic tasks such as running and jumping, skills performed in diving and gymnastics must adhere to strict aesthetic performance criteria. These competitive performance constraints may have forced elite divers to try to actively avoid experiencing movement variability during their performances by baulking (Barris, et al., 2012). Investigations in other sports have shown how increasing levels of skill can lead elite performers towards harnessing compensatory (or functional) movement variability, affording greater flexibility in task execution (Arutyunyan, et al., 1968; Bradshaw, Hume, Calton, & Aisbett, 2010; Davids, et al., 2003; Scott, et al., 1997). In line with these findings, this investigation examined whether compensatory variability would enable elite divers to perform repeated attempts at the same skill, but with the emergence of different movement patterns.

Individual analyses of each individual diver’s preparatory phase revealed no changes in the shape of the angle-angle plots between conditions (pre- and post training program). This finding suggests that similar movement coordination patterns were being organised in both conditions. However, quantitative analyses of variability within the different conditions revealed greater consistency and lower levels of variability in dives completed prior to the training program and greater variability in dives completed at the completion of the training program, as evidenced by the NoRMS indices. This result demonstrates flexibility in the athlete’s performance. By practicing without baulking, the divers were able to develop the capacity to adapt their performances, exploring different strategies and exploiting the most functional performance behaviours (Davids, et al., 2007).

Functional variability in performance may be interpreted as the flexibility of the system to explore different strategies to find the most proficient one among many available. During the learning process, the stability of certain attractors can be strengthened at the expense of others to increase the probability that the movement system will return to that pattern over extended periods. From an ecological perspective, it has been suggested that the coordination variability in a system provides the required flexibility to adapt to perturbations in the movement pattern (Hamill, et al., 1999).This flexibility allows for learning a new movement or adjusting the already known one by gradually selecting the most appropriate pattern for the actual task (Preatoni, et al., 2010). For example, the performance of a complex multi-articular springboard dives after practising under a no-baulking condition. The ability to solve the same motor problem by different or variable execution parameters becomes especially important when the external environment is dynamic, as skilled performance emerges from the dynamic relationship between the organism, its environment and the task. In this instance, a diversity of movement patterns can be functional in negotiating dynamic environments and may have specific importance in unpredictable environmental situations, e.g. bouncing on an oscillating springboard (Araújo & Davids, 2011; Davids, et al., 2007).

The representativeness of the simulated competitions was established using the Competitive State Anxiety Inventory-2 Revised Questionnaire (Riley & Turvey, 2002) and revealed no differences between the three test occasions. These results suggest that simulated competitions in training were representative of an actual competition, and, therefore, provided an accurate measure of performance outcomes. Similarly, an investigation by Cottyn et al. (2004) examined competitive anxiety during balance beam performances in gymnastics. Competitive anxiety was assessed continuously by heart rate monitoring and retrospective self-report of nervousness (CSAI-2) in eight female level gymnasts during their balance beam routine during one competition and two training sessions. Cottyn and colleagues (2004) reported no differences in balance beam performance, or self reported feelings of nervousness, between the competition and training sessions, despite a significant increase in heart rate during the competition session. They concluded that performance of the balance beam routine caused the gymnasts anxiety, which was related to the complexity of the skill and was not altered by the perceived importance of the event (Dhami, et al., 2004). This may also be true in diving, where athletes report feeling nervous when performing complex skills regardless of the performance context.

The use of performance measures (judged competitions) were included in this study to observe whether competitive performance could be improved by removing baulking from the training environment. Although no improvements were made in the *quality* of movement pattern execution (e.g. magnitude of scores did not improve), all athletes became more *consistent* in their reverse dive execution, which was reflected in the consistent scoring by the experts (even though they did not view the diving events sequentially). The divers were asked to consider these simulated competitions as they would an actual performance event, where competition rules would apply (including penalties for baulking). No baulks were recorded for any of the participants, which may account for the fluctuations initially seen in the judged scores, where athletes attempted to execute dives from take-offs where they would normally have baulked in practice (similar to actual competition behaviour). Towards the end of the training programme, as the athletes became more confident diving from uncomfortable hurdles, the performance scores became more stable. Conversely, the judged scores for the four participants' back two and half somersault dives were inconsistent and fluctuated greatly from test to test throughout the training programme. Back dives were included as a control measure, as they received the same amount of coaching and training time as reverse dives, but were not included in the training programme as they have a different approach and take-off phase. The ability of the athletes to execute both dives well, may be attributed to the large training volume, high repetition of skills and expert coaching. However, it is possible that the *consistency* in execution of the reverse dive may have been the result of the training programme, where the divers, like skilled athletes in other studies, were able to demonstrate stability in performance outcomes by compensating for variability detected in the take-off.

Importantly, the introduction of functional variability in diving performance during practice appears to have had little impact on the emergent movement form and the experts' scoring. Consequently, it seems that the benefit of achieving performance outcome consistency during competition (avoiding any minor point deductions that may be associated with deviation from the movement criteria guidelines) outweighed the severe penalties imposed for either baulking or executing a poor dive from an uncomfortable, unpractised take-off.

Comments made by the athletes during training sessions prior to the training programme, provided an insight into their attitude towards baulking; "I baulked four times in training, then in comp ("competition") I was too far forward, but I had to go...I would have baulked again if it was training." (Personal communication, Participant One, Aug 2011). Additionally, Participant Four shared her feelings about baulking in training:

> I know it’s wrong but it seems like a waste to go on a bad hurdle, I have to get out and dry myself; it takes longer, so it’s easier to baulk while you are on the board and start again.....It makes sense to me that I should only go off good hurdles, I only want to practice the good ones.
>
> (Personal communication, Participant Four, Sept 2011).

In the early stages of the training programme, athletes tried to use their poor hurdles to complete any dive. This was observed in all participants during the first four weeks; where the number of uncomfortable dives recorded was greater than the number of baulks (see Figure 5-4). During this time the athletes reported feelings of nervousness and discomfort but also greater concentration and awareness. “It makes me feel more cautious, like I am in competition” (Personal communication, Participant Three, Oct 2011). This feeling was supported by Participant Two, who added; “I feel so tired after training...I think it’s because I have to think so much, I’m concentrating so much harder now” (Personal communication, Participant Two, Oct 2011).

Although each participant responded differently to this training programme, the tracking of the athlete’s weekly performances illustrated that this group of highly skilled divers were all clearly capable of adapting to the training programme and completing multi rotation somersaults off uncomfortable hurdles. The gradual increase in completed dives across the training programme suggested that as the athletes adapted to the training programme, experiencing movement variability within the preparatory phases no longer made them feel uncomfortable and they could comfortably complete the intended dive. The few baulks that did still occur were largely for safety reasons. In the final week of the training programme, the athletes were asked how they felt about the training programme they had been participating in. “It works; sometimes I forget and then I baulk, and then I remember after that I’m supposed to not baulk; and I don’t know why I did it, but I know I should try harder; because it does work.” (Personal communication, Participant Four, Dec 2011). Additionally, Participant Two reported greater feelings of confidence because “Good or bad, I know I can go on a good hurdle now” (Personal communication, Participant Two, Dec 2011). Finally, Participant One described her feelings in an actual competition:

> It was such a bad hurdle, I was hanging ten (toes over the edge of the board) and in the corner, but I knew what to do, it had happened in practice before, so I didn't panic, I just waited for the board and squeezed (into a really tight pike) (Personal communication, Participant One, Dec 2011).

In summary, elite springboard divers displayed greater consistency and stability in a key performance outcome (dive entry) at the end of a twelve-week training programme, which increased their exposure to functional movement variability. The data suggested that they were able to adapt their movements in the preparatory phase and displayed the flexibility required to complete good quality dives under more varied take-off conditions. This finding signals some significant practical implications for athletes in training and competition, improving training quality, reducing anxiety and enhancing feelings of self-confidence. As such, it is recommended that coaches take care when designing practice tasks since the clear implication is that athletes need to practice adapting movement patterns during ongoing regulation of multi-articular coordination tasks. For example, triple jumpers need to practice adapting to earlier perturbations in the run-up, volleyball servers need to adapt to small variations in the ball toss phase, long jumpers need to visually regulate gait as they prepare for the take-off, cricket bowlers need to adapt the bound phase to their run-up variations and springboard divers need to practice adapting their take-off from the hurdle step.

CHAPTER SIX – Epilogue

Epilogue

The overarching aim of this programme of work was to evaluate the effectiveness of the existing learning environment within the Australian Institute of Sport (AIS) elite springboard diving programme, using an ecological dynamics framework. The experimental studies in this thesis not only contribute to the advancement of theoretical understanding of human behaviour in elite performance, but provide methodological implications for sports science research, and practical guidance for diving training programmes.

As outlined in the introduction (Chapter One), this programme of work used conceptual, theoretical and methodological approaches that aimed to enhance the understanding of existing motor learning theories. Although empirical evidence exists to support current motor learning and control theories relating to practice structure and design, these traditional motor learning studies have largely been conducted under laboratory conditions with novel tasks, novice participants and short term learning intervention designs with long periods of detraining before retention tests (Araújo, et al., 2006; Goode & Magill, 1986; Hodges, et al., 2005; Shea & Morgan, 1979; Wulf & Shea, 2002), limiting the extent to which the results can be interpreted and applied to understanding performance in elite sporting populations. Unique to the current research programme, therefore, is the application of established theories of motor learning to an applied high performance training environment. In this thesis, an applied high performance springboard diving environment was used as a vehicle to represent complex sports skills in general. Here, springboard diving was examined as a complex system, where individual, task, and environmental constraints are continually interacting to shape performance. Elite, internationally successful athletes participated in these studies and were investigated in their normal training environments (dry-land and aquatic), without large sample sizes, control groups or lengthy periods of detraining. As a consequence, this research programme has presented some unique insights into movement adaptations, representative of elite populations, in what has traditionally been considered a ‘closed’ skill (Gentile, 1972).

Previous biomechanical analyses of the dive take-off have shown that the preparatory movements in diving (particularly the approach and hurdle phases, see Chapter Four, Figure 4-1) are the precursors that facilitate the actual execution of dives (Bergmaier, et al., 1971; Miller, 1984; Slobounov, et al., 1997). The major function of the approach and hurdle in running (forward and reverse) springboard dives is to establish optimal conditions for an effective take-off. Therefore, achieving efficient execution of these initial movements is vital for the overall success of the performance goal. For example, a good approach and hurdle means good body position, good height off the board, good rotation and good entry into the water. Consequently, the preparatory phase of the reverse dive take-off, and its important contribution to the overall dive, was selected for analysis throughout this programme of work. Specifically, movement adaptations that occurred during these phases were examined as a function of changes in learning design and practice in elite sport training environments. The questions examined in this programme of work relate to how best to structure practice, which is central to developing an effective learning environment in a high performance setting. Here, the contribution made at each stage of this thesis is reviewed and the important theoretical, methodological and practical implications of the PhD programme are re-iterated.

Chapter Three: Representative learning design in springboard diving

Study One (Chapter Three) provided important insights for the application of a representative learning design in elite training environments. Theoretical understanding of representative design, has largely been developed with, and applied to experimental research protocols in psychological science; although, more recently there have been discussions regarding its potential application to sports practice and performance contexts (Pinder, et al., 2011b). This study makes one of the first attempts to apply Brunswik’s theoretical ideas (1956) on representative design to elite performance where tasks are routinely practiced in two different training environments. The degree of association between behaviour in an experimental task with that of the performance setting to which it is intended to generalise, is known as action fidelity (Araújo, et al., 2007; Lintern, et al., 1989). Here, the degree of fidelity has been assessed by measuring practice performance (e.g. board-work, joint kinematics) in both the simulated training environment and the competitive context. This investigation determined the extent to which behaviours in one context (dry-land practice), correspond to those in another context (pool performance) (Araújo, et al., 2007).

In diving, the dry-land training environment is a purpose-built gymnasium designed for land-based practice (see Chapter Two, Figure 2-2). However, the constraints of the dry-land environment prevent the completion of the same number of somersaults that are possible in the aquatic environment and force the diver to land feet first. For example, in the dry-land training area the diver can only complete one or two somersaults before landing feet first on the mat or in the pit. Although it is widely accepted within the diving community that divers are able to practice the same preparation phase, take-off and initial aerial rotation in both environments (personal communication with athletes and coaches), until now, there has been no evidence to suggest that the two tasks follow the same movement patterns during the preparation phase.

Individual athlete analyses from this study revealed topological similarities in the shapes of the coordination plots between conditions for all participants. However, the topological patterns showed scaling throughout the movement. This suggested that, although the joint coordination patterns were not different between conditions, functional differences were present at specific joints during coordination that allowed the divers to create enough height and momentum to complete the necessary somersaults. These findings were supported further, by data recorded at the key events (e.g., step lengths, jump height) during the approach and hurdle phases of the take-off, where participants showed significantly greater step lengths, jump heights and board depression angles (during the hurdle jump and at landing prior to take-off) in the aquatic environment compared to the dry-land. The most noticeable differences in dive take-off between environments began during the hurdle (step, jump and height) where the diver needs to generate the necessary momentum to complete the dive. Greater step lengths and jump heights, therefore, resulted in greater board depression prior to take-off in the aquatic environment where the dives required greater amounts of rotation. It was concluded that the results observed during this investigation were the consequence of changes in task constraints, which were imposed by the two training environments. Specifically, the height of the springboard, the foam landing mats and the limited number of somersaults that can be completed in the dry-land, caused decomposition of the dive take-off task and changed the overall task execution (feet first vs. wrist first landing).

Theoretically, this investigation contributes empirical evidence to support the application of Brunswik's (1956) notion of representative design to a motor learning programme in sport and makes a first attempt at applying these theoretical ideas into an applied training environment. Further, this study makes one of the first attempts to apply the theoretical notions of action fidelity to training in a sport context. Here the practice environment was viewed as a simulation of the competition environment and examined the degree of association between behaviour in both environments (Araújo, et al., 2007; Lintern, et al., 1989). Practically, the examination of training behaviours and environments in this study highlight the importance of designing training tasks that are representative of the performance context and which have a high action fidelity (similar action or behavioural response).

Although the findings of Study One (Chapter Three) displayed differences in the preparatory phase of the dive take-off in the dry-land and aquatic environments due to task decomposition, only one aspect (the preparatory phase) of the decomposed task was analysed. The extent to which other dry-land practice tasks, such as the aerial phase (somersaulting on the trampoline, see Chapter Three, Figure 3-1 (c)) or 'come out' phase (trampoline with coach manipulated harness, see Chapter Three, Figure 3-1 (d)), may contribute to the successful transfer of isolated phases into the whole task remains unknown. Consequently, the diving community may still consider the dry-land training environment an important tool for skill development and learning. One way to maintain the inclusion of dry-land training would be to scale the athletes' exposure to this facility according to individual task proficiency. For example, a skilled performer learning a new dive (front 4 ½ somersaults), might initially commit up to 80% of the time spent practising *this* task, in the dry-land (e.g. trampoline somersaults, feet first dives into the foam pit, standing somersaults). As task proficiency improves, the time spent in the dry-land practising *this* task should decrease, with a simultaneous increase in pool practice time (see Figure 6-1). A scaled approach for each practice task, would allow for the safe learning and development of new skills during the control and coordination phases of learning. Once these initial learning stages have been achieved, it may be more beneficial to increase the amount of practice time in the pool, to allow mastery of the skill in the performance context, where the movement can be practiced in its entirety.

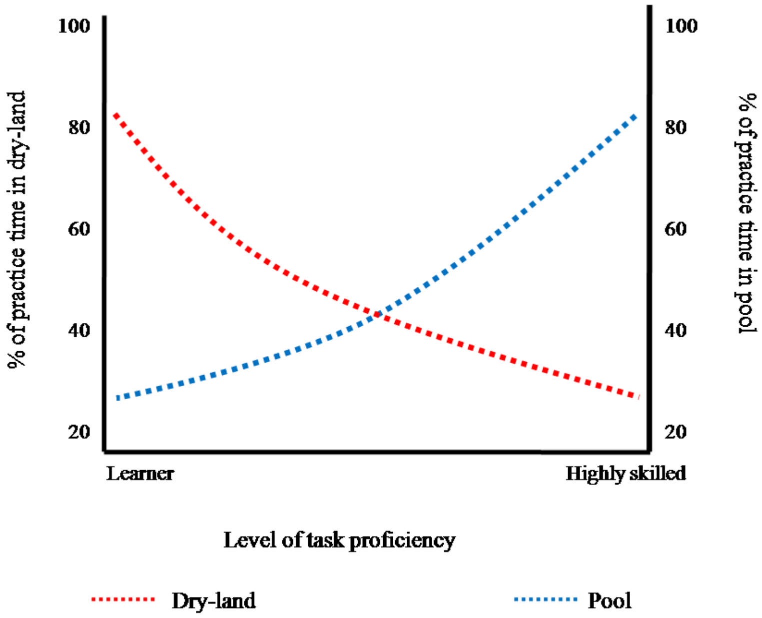


Figure 6-1 Example of a scaled approach for practising tasks in different training environments

Chapter Four: Movement kinematics in springboard diving

Study Two (Chapter Four) examined existing athlete training behaviours in normal diving practice environments. Observations of athlete training behaviour revealed that in an attempt to practice only high quality dives and achieve invariant movement patterns, elite divers baulk frequently- aborting planned take-offs. This traditional approach to training implies athletes and coaches believe that only the best dives must be practiced at all times in order to enhance skilled performance in diving. This conception of practice fits, intentionally or not, with the notion of the existence of a common optimal movement pattern, towards which all athletes should aspire (Brisson & Alain, 1996; Davids, Button, et al., 2006). Study Two, therefore, determined whether kinematic differences existed between baulked and completed take-offs, that would justify the abortion of a planned dive.

The results of this investigation did not reveal any differences in movement patterns between completed and baulked take-offs. Specifically, individual analyses revealed no changes in the topology of the angle-angle plots between conditions for any of the participants (see Chapter Four, Figure 4-3), and only small differences were observed in board-work between conditions. As such, it was concluded that no differences in movement pattern or joint coordination existed between baulked and completed dives that might justify the abortion of an intended dive. Of particular interest though, was the amount of variability present between trials. This was evidenced by the greater consistency and lower variability amongst completed dive trials, and greater variability amongst baulked dives take-offs. Although previous research has demonstrated that functional variability increases with task expertise (Araújo & Davids, 2011; Arutyunyan, et al., 1968; Bernstein, 1967; Manoel & Connolly, 1995), the current investigation can be considered unique since the sample of elite divers actively attempted to phase out or minimise functional variability during training. These findings reinforce the belief held by divers and coaches that only the best dives must be practiced at all times in order to enhance skilled performance in diving, where comfortable, completed dive take-offs showed very similar patterns of coordination. Conversely, movement patterns that deviated from the perceived optimal routine, resulted in an aborted take-off; suggesting the athletes were trying to remove this variability from the take-off by baulking and restarting the preparatory phase.

An important characteristic of skilled performance is the precise tuning of an action to the changing circumstances of the environment captured by the information properties available (Van der Kamp, et al., 2008). With repetition in practice, the strength of the coupling of environmental information to action may increase the stability of the movement outcome observed (Van der Kamp, et al., 2008). This is further supported by Wilson et al., (2008) who proposed that the ability of coordinative units to adapt to performance perturbations (e.g. variations in step lengths or foot placements on the springboard in diving) is crucial if the performer is to consistently achieve successful performance outcomes. Consequently, with no major differences in coordination patterns, and the potential for a negative performance outcome in competition, there appears to be no theoretical or practical training advantage in baulking on unsatisfactory take-offs during training, except when a threat of injury is perceived by an athlete. As such, this study concluded, that by only practising dives with good quality take-offs, divers may only be affording themselves the opportunity to develop strong couplings between information and movement under very specific performance circumstances (evidenced by the consistent patterns seen during the completed take-offs). This approach to training, means that in situations where divers do not perform an ideal take-off (often in competition); they are unable to adapt ongoing movements to achieve performance outcome stability (rip entry into the water with minimal splash). To this end, the practical implications of this study ultimately resulted in the development and design of a training programme (Study Three, Chapter Five) that encouraged divers to minimise baulking during training and attempt to complete every dive. This was considered achievable as, unlike Study Once (Chapter Three) which showed *dys*functional variability between patterns, caused by the decomposition of the task, the variability between baulked and completed tasks is functional (similar joint coordination and board-work movement patterns). In this way, it was expected that athletes could strengthen the information and movement coupling in all circumstances, widening the basin of performance solutions and allowing the development of alternative couplings to solve a performance problem even when the take-off is not perceived to be ideal (Higgins & Spaeth, 1972).

Chapter Five: Adaptive movement patterns in springboard diving

A twelve-week training programme was conducted in Study Three (Chapter Five), in response to the findings of Study Two, which showed no differences in movement patterns or joint coordination between baulked and completed dive take-offs. Throughout this training programme, attempts were made to change traditional training behaviour, and replace the desire to attain a high quality, invariant preparatory phase, with a goal to achieve stability in the performance outcome (entry into the water). From an ecological perspective, it has been suggested that the functional variability within a system provides the required flexibility to adapt to perturbations in the movement pattern (Hamill, et al., 1999). This flexibility can assist a learner in negotiating a new movement or a skilled performer in adjusting an existing skill to new conditions by selecting the most appropriate pattern for the actual task (Preatoni, et al., 2010). In this instance, the performance of a familiar complex multi-articular springboard dive, under new, no-baulking conditions. The ability to solve the same motor problem by different or variable execution parameters is especially important when the external environment is dynamic, as skilled performance emerges from the dynamic relationship between the organism, its environment and the task. Here, a diversity of movement patterns can be functional in negotiating dynamic environments and may have specific importance in unpredictable environmental situations, e.g., bouncing on an oscillating springboard (Araújo & Davids, 2011; Davids, et al., 2007).

Over a twelve-week period, this training programme determined that elite athletes were able to adapt their movement patterns during a complex task (the approach and hurdle phases of a multi-somersault springboard dive take-off) and stabilise the performance outcome (entry into the water) rather than removing variability in the performance by baulking (Study Two, Chapter Four). Joint coordination patterns, showed greater variability within trials in the post-training programme preparatory phases, similar to those seen in the baulked trials in Study Two. Although each participant responded differently (time taken to adapt) during their adaptation to the training programme, the data suggested that these highly skilled athletes were all able to adapt their movements and adjust to the variability in the preparatory phase, and displayed the flexibility required to complete good quality dives under more varied take-off conditions. These adaptations were exemplified by changes in the number of reported uncomfortable dives (increase in uncomfortable dives as they attempt to stop baulking, followed by an increase in completed dives, as the uncomfortable take-off's become easier). Of interest, was a temporary regression in feelings of comfort (observed as a decrease in completed dives and increase in uncomfortable reported dives) by Participants Two and Four during weeks seven and eight. This regression coincided with the final week of preparation before the National Championships (a National Team selection event), suggesting that although elite athletes were able to modify their behaviour during the training programme, perturbations, such as additional stress or anxiety can cause athletes to revert back to their original perception of what constitutes an uncomfortable dive.

Although no improvements were observed in the *level* of movement pattern execution (e.g. magnitude of scores did not improve); importantly for performance, all athletes became more *consistent* in their reverse dive execution. These findings showed that elite divers were able to functionally adapt their behaviour during this specific task to achieve a stable performance outcome, highlighting the degenerate ability of skilled human movement systems. These results are in line with previous research from other sports, and demonstrate how functional movement variability can afford greater flexibility in task execution (Bartlett, et al., 1996; Bootsma & van Wieringen, 1990; Button, et al., 2003; Schöllhorn & Bauer, 1998; Wilson, et al., 2008).

This investigation addresses a perceived imbalance in the motor behaviour literature on the practical relevance of the theoretical issue of functional adaptive movement variability. While there are clear theoretical insights provided in the motor behaviour literature on the conceptual nature of movement pattern variability, as well as an abundance of empirical data emerging in experimental research, leading to new perspectives on movement coordination, there have been no attempts to investigate applications of these ideas in a high performance skills training programme. This is an important and necessary addition to our understanding of the role of adaptive movement variability in sport. It is extremely challenging to persuade the designers of training programmes to allow their typical practical activities to be modified in the way described in this study.

To date, this study represents one of the first attempts to theoretically, empirically and practically integrate ideas of functional adaptive movement variability in a high performance training programme with a sample of truly elite athletes. It has provided some useful insights on how functional adaptive movement variability might benefit highly skilled individuals in performance contexts such as elite sport. Although the sample size might be considered small, by the standards considered typical in traditional laboratory-based experimental studies of motor behaviour, these participants represented 100% of all elite Australian female springboard divers. They provided a coherent sample to study from a single unified training programme, therefore reducing possible inter-individual variations due to background training experiences and cultural differences.

In addition, there have been some significant practical implications for participants in training and competition. This study was initially designed as a five-week training programme, however, the duration was extended by the head coach as the athlete’s showed improvements in their ability to adapt to poor quality take-offs.

Consequently, at the Australian Olympic Team Trial, two participants successfully performed dives from uncomfortable preparatory phases, which resulted in both of them qualifying for the 3m Springboard events at the London 2012 Olympics (see foot positioning in Figure 6-2). Participant One described her feelings the competition;

> It was such a bad hurdle, I was hanging ten (toes over the edge of the board) and in the corner, but I knew what to do, it had happened in practice before, so I didn't panic, I just waited for the board and squeezed (into a really tight pike) (Personal communication, Participant One, Dec 2011)

This training programme has now been integrated into daily training practice and extended to include members of the wider training squad. Further, the methodology of this training programme has been developed into a National protocol and presented to, and distributed amongst, the Australian diving network, where similar results are being seen with younger less skilled members of the Western Australia Institute of Sport (WAIS) diving squad (Personal Communication with the WAIS, Psychologist, September 2012).

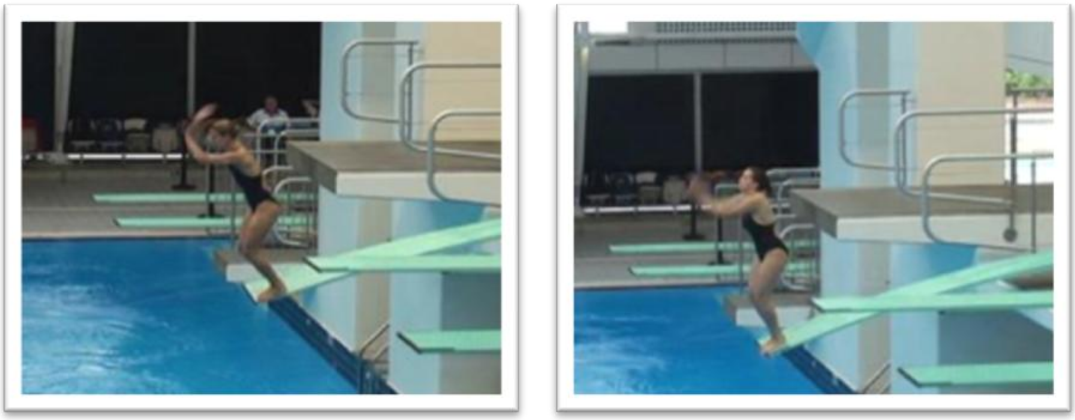


Figure 6-2 Examples of uncomfortable take-offs at the Olympic Team qualification event

As such, this investigation provides a powerful rationale for coaches to reconsider the traditional focus on invariant movement patterns and instead see functional variability or adaptability of motor behaviour as a key criterion of successful performance in sports like diving. Based on these findings it is recommended that care be taken by coaches, particularly those with younger developmental athletes, when designing practice tasks since the clear implication is that athletes need to practice adapting movement patterns during ongoing regulation of multi-articular coordination tasks. The implications of this study, however, are not limited to springboard diving alone. Previous research has suggested that each phase of a skill may be affected by the preceding phases (Wilson, et al., 2008), and subsequently, these finding may be applied to many types of sports skills. For example, volleyball servers can adapt to small variations in the ball toss phase, long jumpers can visually regulate gait as they prepare for the take-off, cricket bowlers can adapt the bound phase to their run-up variations and springboard divers need to continue to practice adapting their take-off from the hurdle step.

Ultimately, this study recommends that the traditional coaching adage ‘perfect practice makes perfect”, be reconsidered; instead advocating that practice should be, as Bernstein (1967) suggested, “repetition without repetition”.

Limitations

This thesis has argued that, in order to achieve a movement pattern or a behavioural response in an experimental or practice context that is representative of the performance environment, it is important to accurately sample and simulate task conditions that are high in action fidelity. However, it is still necessary for researchers to provide an acceptable degree of control over the experimental design. Attempts to balance these two notions resulted in the following limitations.

Environment and task limitations

The aquatic diving environment is particularly challenging and created a number of limitations to this research. First, a large capture volume (size of the performance area required to record the movement or skill) is required to adequately analyse the complete diving movement. For example, to also measure the take-off and somersaulting phases of the dive, the capture volume must be large enough to include the distance from the water to the 3m springboard, the individuals jump height and horizontal displacement. Second, most commercially available 3-Dimensional motion analysis systems are unsuited to an aquatic environment, where there are high levels of ambient light, high humidity and water. Third, traditional light reflective markers cannot be used, as impact with the water can cause significant discomfort to the athlete. Consequently, the series of studies in this research programme were limited to the preparatory phase of the dive take-off, which required a smaller capture volume and allowed for manual 2-Dimensional analysis. However, the 2-D analysis placed further limitations on the study, restricting the analysis to the lower limbs. As such, it is acknowledged that this initial exploration was restricted to simple performance and movement assessments due to the nature of the capture and performance environment. A more comprehensive and detailed analysis may strengthen and extend the findings of this programme. However, this thesis provides an initial attempt to apply motor learning theories to an elite population in a challenging, but representative performance context, a rich area for future research.

Participant sample

The participant sample, although small, constituted 100% of the elite springboard divers with international competitive experience in Australia. Although a larger sample was considered, an increased sample size would have diluted the skill level, therefore, eliminating one of the unique contributions made by this programme of work. To minimise the impact of the small sample, individualised analyses were undertaken and consequently, provided some unique insights into how truly elite individuals behave. However, further work is needed with a larger sample of similarly skilled athletes before more general conclusions can be drawn.

Conclusion

Collectively, the studies of this PhD programme extend the understanding of motor learning principles by applying established theoretical notions to a population of highly skilled athletes, performing complex multi-articular movements. Theoretically, this research programme presents a broad critique of previous experimental designs, and provides empirical evidence to demonstrate the importance of high action fidelity between practice and performance contexts in a representative learning environment (Chapter Three). Further it provides justification for, and execution of, integrating functional movement pattern variability into complex skill performance (Chapters Four and Five respectively). Practically, the examination of training behaviours and environments provides significant implications for elite sport programmes, such as diving, and advocates changes to the existing practice and learning designs. For example, the use of a training programme to reduce baulking in practice or scaling the amount of time spent in the dry-land environment to minimise the negative effects of task decomposition on performance.

APPENDIX

Appendix

Barris, S., (2012). Not making a splash- The anatomy of a perfect Olympic dive. Article for theconversation, https://theconversation.edu.au/not-making-a-splash-the-anatomy-of-a-perfect-olympic-dive-8082

Harrison, S., Cohen, R., Cleary, P., Barris, S., & Rose, G., (2012). *Forces on the body during elite competitive platform diving.* Ninth International Conference on CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, December 2012

Not making a splash: the anatomy of a perfect Olympic dive

https://theconversation.edu.au/not-making-a-splash-the-anatomy-of-a-perfect-olympic-dive-8082

Diving is one of the most graceful and spectacular sports in the world, and every four years it captures the attention of audiences worldwide. It is physically demanding, requiring stamina and strength as well as speed, agility and flexibility to perform an incredible range of somersaults, pikes, and twists. Many changes have occurred in competitive diving since its inclusion in the modern Olympics in 1904. Springboards which were once rigid wooden planks sloping upwards have undergone a radical transformation into tapered and perforated aluminium alloy boards mounted level and fitted with moveable fulcrums. Training methods have become more sophisticated with an emphasis on dry-land exercises and drills. The difficulty of dives performed in competition have also steadily increased during the past 30 years, where, once only few elite competitors were capable of performing a forward 1 ½ somersault, dives like a forward 4 ½ somersault are now being performed routinely. But just how do these athletes launch themselves from towers or springboards and disappear beneath the water with almost no splash?

At the moment of take-off from the platform or springboard, two critical aspects of the dive are determined, and cannot subsequently be altered during the execution. One is the trajectory of the dive, and the other is the magnitude of the angular momentum. Because the initial conditions of the flight, specifically, the angle of projection at take-off, velocity of the centre of mass, and angular momentum, are established during the take-off, this phase plays a major role in determining the outcome of the dive. During the take-off, divers must produce sufficient vertical momentum for the flight of the dive, adequate horizontal momentum to clear the take-off surface and enough angular momentum to execute the required number of twists and /or somersaults. The success of the dive is determined by a combination of the divers' position at last contact with the take-off surface and the magnitude and direction of the forces and that have been applied during the take-off phase. Consequently, the success of a dive is largely dependent on the actions of the diver before they leave the take-off surface.

In the air, most dives are performed in a tucked or piked position. The tucked position is the most compact (body folded up in a tight ball, hands holding the shins and toes pointed), and as such, gives the diver the most control over rotational speed. Dives in this position, are therefore, easier to perform. In a piked position the moment of inertia is larger (as the body has an increased radius) and consequently, the dives tend to have a higher degree of difficulty.

As the diver completes the required number of somersaults or twists, they open the body out ready for entry into the water. The action of opening out and changing body position does not stop the diver's rotation, but merely slows it down. The vertical entry achieved by expert divers is largely an illusion created by starting the entry slightly short of vertical, so that the legs are vertical as they disappear beneath the surface. A good entry into the water in competitive diving is one which appears to be ‘*splash-less*’, is accompanied by a characteristic ‘*rip*’ sound, and simulates the sound of tearing paper. The rip entry, considered the ‘*hallmark of a master’* looks to a viewer as if the diver is being sucked into the water without a splash.

To achieve a rip entry, the diver’s arms must be extended forwards in line with the ears, the elbows must be locked and the stomach and back of the diver must be tight. One hand grabs the other with palms facing down to strike the water with a flat surface. Impact with the water creates a vacuum between the hands, arms and head which, as the diver enters vertically, pulls any splash down and under the water with the diver until they are deep enough (1-2m) to have minimal effect on the surface of the water.

To be successful at international competitions, divers must be able to perform high degree-of-difficulty dives with reasonable consistency. To develop these skills, Australia’s top divers train 28-30 hours per week and split their time between the dry-land facility and the pool. The dry-land training environment is a purpose built gymnasium next to the aquatic centre designed for land-based diving practise. The divers use this centre to warm up, for strength and conditioning skills, and to part-practise diving skills, where, they can isolate small parts of the skill and practise them independently. For example, the take-off and initial somersault before landing feet first on the mat or in the pit. In the pool, divers complete both feet first and traditional wrist first entries into the water. Training programmes are written for each individual diver for each training session and cover basic water entries (to correct technique), take-off skills, compulsory dives (lower degree of difficulty dives performed in the preliminary rounds at competitions) and optional dives (dives with a higher degree of difficulty performed in competition). Between each repetition, the athletes receive external feedback from the coach and delayed video replays of their performance from multiple angles, allowing them analyse their dives and constantly fine tune the execution of these complex skills.

But these athletes don’t do it alone. Behind the divers are a team of dedicated coaches and support staff (trainers, psychologists, dieticians and analysts), who equally commit as many hours to training, sharing their experience and expertise to help these athlete in the pursuit of gold in London.

Videos

http://www.youtube.com/watch?v=YG-BAx93Emg (3m Ethan Warren front 4 ½ somersault London 2012)
http://www.youtube.com/watch?v=Az4w32d20SY (1:55 / 2:41) Platform Matthew Mitcham’s Final dive Beijing 2008)

FORCES ON THE BODY DURING ELITE COMPETITIVE PLATFORM DIVING

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ABSTRACT

Impact with the water during a 10 m platform dive imparts large forces onto the diving athlete. Wrist and back injuries are common and are thought to be related to cumulative damage from many overload events, rather than one acute high loading event. Experimental measures of forces on the body are impractical and instead computational simulation is appropriate to estimate this loading. A coupled Biomechanical-Smoothed Particle Hydrodynamics (BSPH) model is applied to a reverse pike dive performed by an elite athlete. The skin surface is represented by a mesh that deforms in response to measured skeleton kinematics. Calculations of the impact forces and the transmission of torque through the skeleton are made. The sensitivity of the results of the model to water entry angle is explored. The simulation framework presented shows promise as a tool for coaches to evaluate the performance and safety of diving technique.

INTRODUCTION

Most competitive platform diving injuries occur during water entry (Rubin, 1999). Injuries sustained during diving can either result from catastrophic overloading of joints during a poorly executed dive or, more commonly, from repetitive loading at lower levels of force, such as during a successful dive. An understanding of how these injuries occur will require detailed information about the mechanical loading of the joints during impact with the water. Biomechanical analysis of the loading on the body during water impact is sparse (Rubin, 1999; Sanders and Burnett, 2003), because direct experimental measurement of loading on the joints and bones is not possible.

Computational biomechanical modelling of sporting activities has previously elucidated the causation of injury through calculation of the mechanical loading of joints, bones, muscles and connective tissue (e.g. during a fall, Keyak et al., 1997; and during running, Schache et al. 2010). Computational simulation provides measures of experimentally immeasurable quantities such as net joint torque; joint power; joint, muscle and tendon forces; and articular stresses. High levels of joint torque are a useful (and easily calculated) indicator of large internal forces, and are highly correlated to injury risk in many activities (e.g. Hewett et al., 2005).

Simulations of the flight phase of platform diving have been recently been used to understand and evaluate flight phase performance (e.g. Koschorreck and Mombaur, 2012), but no models of dynamic fluid interactions with the body during platform diving presently exist.

Computational simulation of platform diving presents significant modelling challenges. The athlete is travelling at very high speed at the time of impact with the water and the pose of the athlete’s body changes significantly and rapidly during interaction with the water. The free surface of the water also experiences large displacements and fragmentation/splashing during entry by the athlete’s body. Smoothed Particle Hydrodynamics is a Lagrangian particle method that is well suited to transient problems with complex free surface behaviour, and moving and deforming boundaries of complicated shape. Recent work in swimming (Cohen and Cleary, 2010; Cohen et al., 2011; Cohen et al., 2012) has shown the viability and usefulness of this method for water-based sports.

A computational modelling framework for competitive platform diving using a coupled Biomechanical-SPH model is proposed. The purpose of this study is to explore the following issues:

1. What are the magnitudes of forces imparted onto different body segments during water entry for a reverse pike dive?
2. What is the torque generated in the wrists and back during water entry?
3. How does this torque loading change when the angle of entry is rotated by 5 and 10 degrees?

To answer these questions, the kinematic motion of an Australian Olympic athlete was digitised during a reverse pike dive. This motion was used to deform a boundary representation of her body during a computational simulation of the dive. Simulations using 5 and 10 degree variants to the angle of entry were performed. Whole body motion, fluid forces on the body joint segments and net torques about the joints were calculated.

COMPUTATIONAL MODEL

Smoothed Particle Hydrodynamics

Smoothed Particle Hydrodynamics (SPH) is a mesh-free Lagrangian particle method for solving partial differential equations. Fluid dynamics applications of the method are detailed in Monaghan (1994), Monaghan (2005) and Cleary et al. (2007). Volumes of fluid are represented by a moving set of particles, over which the Navier Stokes equations can be reduced to the following ordinary differential equations:

$$\frac{d\rho_a}{dt} = \sum_b m_b \mathbf{v}_{ab} \cdot \nabla_a W_{ab} \tag{1}$$

where □$_a$ is the density of particle *a*, *t* is time, m_b is the mass of particle *b* and $\mathbf{v}_{ab} = \mathbf{v}_a - \mathbf{v}_b$, where $\mathbf{v}_a$ and $\mathbf{v}_b$ are the velocities of particles *a* and *b*. *W* is a cubic-spline interpolation kernel function that is evaluated for the distance between particles *a* and *b*.

$$\frac{d\mathbf{v}_a}{dt} = -\sum_b m_b \left[\left(\frac{P_b}{\rho_a^2} + \frac{P_a}{\rho_a^2} \right) - \frac{\xi}{\rho_a \rho_b} \frac{4\mu_a \mu_b}{(\mu_a + \mu_b)} \frac{\mathbf{v}_{ab} \cdot \mathbf{r}_{ab}}{\mathbf{r}_{ab}^2 + \eta^2} \right] + \mathbf{g} \tag{2}$$

where P_a and □$_a$ are the local pressure and dynamic viscosity for particle *a*, □ is a small number to mitigate singularities, □ is a normalisation constant for the kernel function and **g** is the gravitational acceleration.

A quasi-compressible formulation of the SPH method is employed. The equation of state for such a weakly compressible fluid relates the fluid pressure, *P* to the particle density, □:

$$P = P_0 \left[\left(\frac{\rho}{\rho_0} \right)^{\gamma} - 1 \right] \tag{3}$$

where P_0 prescribes the overall dynamic pressure scale and the reference density is given by □$_0$. □ is a material constant, which is equal to 7 for fluids with properties similar to water.

Nodes of boundary objects are represented as boundary SPH particles, which are repositioned at every time step as a result of the any rigid body motion and deformation of the boundary. The boundary of the athlete's body (described below) was allowed to move dynamically in all six degrees of freedom during simulation. The moments of inertia of the athlete were calculated from the athlete's mass and volume, assuming a homogeneous distribution of density.

SPH model of the pool

A stagnant pool of water 5 m deep, 2 m wide and 4 m long was modelled. The water was represented by 13.2 M SPH particles with separations of 15 mm. Periodic boundary conditions were used in both horizontal directions.

Biomechanical model of the diving athlete

Surface mesh of the athlete's body

The athlete's body was represented in the computational model by a deforming surface mesh. The mesh of 51,000 nodes, spaced at an average separation of 10 mm, was constructed from 3D laser scans (VITUS Smart XXL machine; Human Solutions GmbH, Kaiserslautern, Germany) of one Australian Olympic athlete. The mesh was rigged to a virtual skeleton using the dual quaternion method (Kavan et al., 2008). This rigged mesh was deformed by manipulation of the virtual skeleton to produce specific poses that matched video footage of platform dives by the laser scanned athlete.

Kinematics digitisation

Footage from four temporally-synchronised, fixed position cameras was supplied for a reverse pike dive. The rigged surface mesh of the athlete's body was positioned using Autodesk Maya software (Autodesk Inc., San Rafael, CA, USA), to simultaneously match top, side (one above the water and one below) and rear views of each dive, at each frame of the video footage. Two of the views are show in Figure 1. The athlete kinematics were used to deform the skin mesh at each time in the simulation.

Kinetic analysis

Linear forces and torques exerted onto the diver boundary mesh predicted by interactions of boundary particles with fluid particles were calculated for the whole body and for individual joints. The linear force, $\mathbf{f_{obj}}$, acting on an object of interest was calculated by summing the individual boundary forces, $\mathbf{f_i}$, that act on all parts of that body.

$$\mathbf{f_{obj}} = \sum_{i=1}^{N} \mathbf{f_i} \tag{4}$$

Similarly the net torque, $\mathbf{T_{obj}}$, about an object was calculated as the vector sum of the cross product of each boundary force, $\mathbf{f_i}$, with the position vector of the boundary particle, $\mathbf{u_i}$, in the reference frame of the object:

$$\mathbf{T_{obj}} = \sum_{i=1}^{N} \mathbf{u_i} \times \mathbf{f_i} \tag{5}$$

Sensitivity analysis

To understand the sensitivity of predictions to model inputs, the following cases were simulated:

- Case 1. As digitised
- Case 2. Sagittal plane rotation (pitch angle) increased by 5 degrees prior to water impact
- Case 3. Sagittal plane rotation (pitch angle) increased by 10 degrees prior to water impact

The sensitivities of body forces and distal arm joints to these variations were calculated. Cases 2 and 3 represent poorly executed dives with over-rotation.

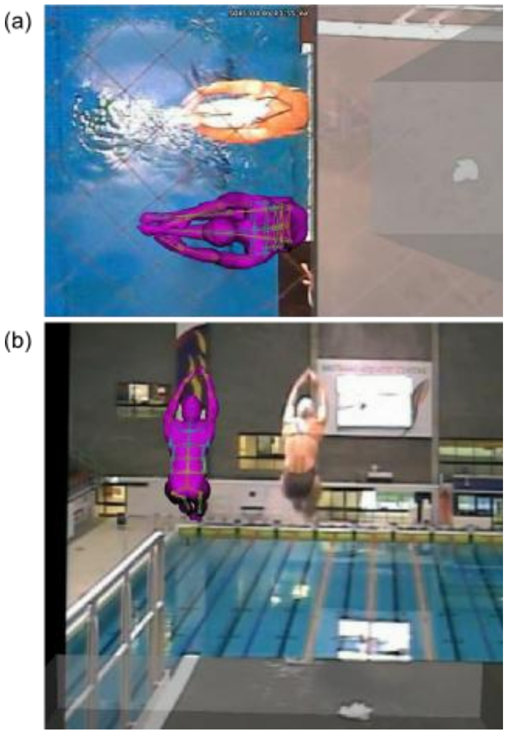

Figure 1: Digitisation of the athlete for the reverse pike dive. Top (a) and rear (b) viewing angles are shown.

RESULTS AND DISCUSSION

The simulated motion of the athlete during the reverse pike is shown in Figure 2. The reverse pike involves a forwards leap (0.0 s to 1.0 s), followed by a backwards rotation whilst the hands touch the legs near the feet (until 1.07 s), and then a straightening of the body as the half backwards somersault is completed (1.33 s onwards). The body then enters the water (at 2.36 s) in an approximately vertical orientation with the hands held flat as they impact the water. After water entry the body continues to translate and rotate in the same directions, albeit at a slower pace due to slowing effect of the water drag.

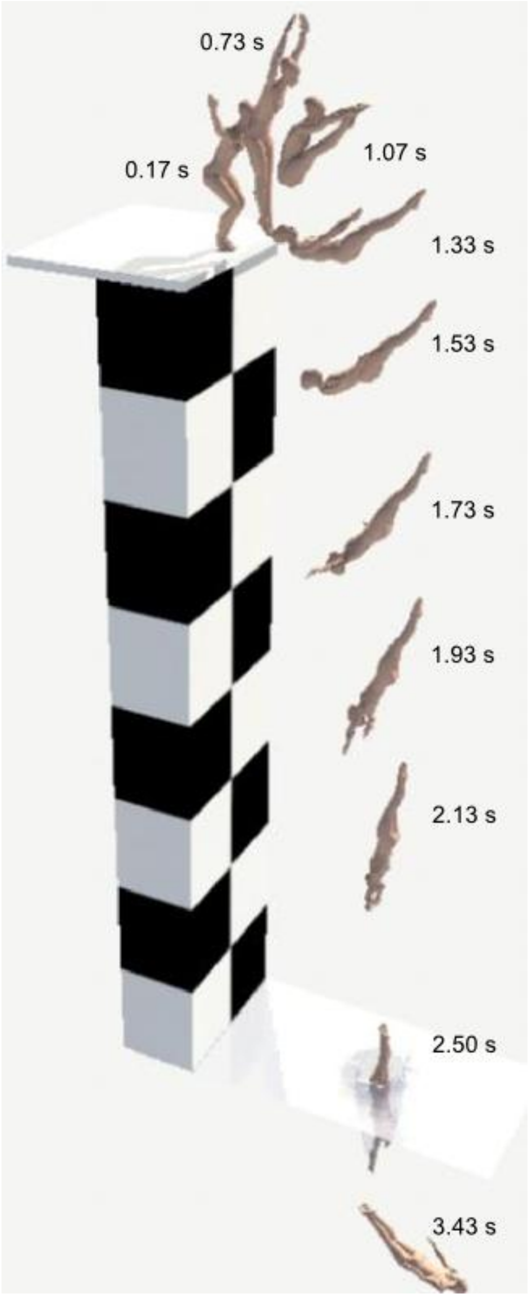

Figure 2: Motion of the athlete for the digitised reverse pike dive.

Figure 3 shows the magnitude of force exerted on each major body segment and the total magnitude of force exerted on the body. Peaks of force occur as each body segment first makes contact with the water. The hand forces are the largest and their peak occurs almost immediately after water impact. The hand forces then decline in magnitude until 2.76 s, when a small peak occurs as the arms sweep from a position above the head to a position beside the torso. Total body forces peak once all body segments have made contact with the water (2.57 s) representing the period of maximum drag by the fluid on the diver. This peak coincides with high levels of force in the forearms, shoulders and head, lower back and legs. Forces decline once complete immersion of the body has occurred (at 2.69 s), but increase again as skin drag between the water and the completely immersed body of the diver (2.70 s onwards) is at a maximum.

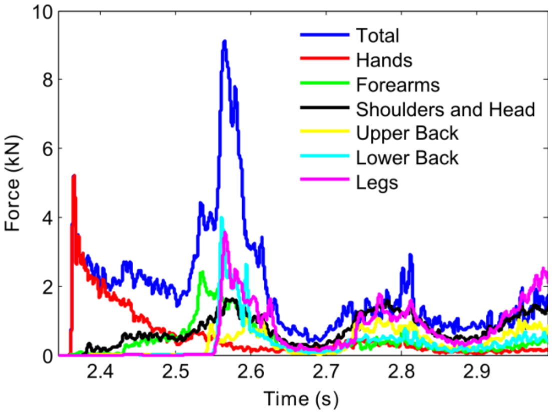

Figure 3: Magnitudes of fluid force on the segments of the body after water entry at *t* = 2.36 s.

Sensitivity analysis

The motion of the athlete and the athlete-water interactions change when the entry pitch angle is altered. Figure 4 shows the pitch angle, the vertical speed and the vertical position of the diver from the time of water entry. During the as digitised dive (Case 1) the body does not pitch significantly before 2.53 s (Figure 4a). After this the pitch angle decreases quickly over 200 ms and then gradually decreases further. However, as the entry pitch angle is increased (Cases 2 and 3 respectively), the body pitches further earlier and to a larger degree. The vertical speed decreases more quickly with increasing initial pitch angle (Figure 4b). As a result the dive trajectory becomes progressively shallower (Figure 4c).

The athlete's position, the fluid free surface, and the 3D vortex structures are shown in Figure 5 for all three cases. For Case 1 the body is approximately vertical until almost fully immersed (2.53 s). The area of the diver projected into the horizontal plane (which is orthogonal to the motion of the diver and controls the drag) is minimal. The fluid free surface near the body has been displaced downwards into a cavity (see Brown et al., 1984; in approximate forwards-rear symmetry about the body). The presence of the cavity delays interactions between the water and the body below the shoulders, even though the entire body is below the initial water level. At 2.67 s all the body below the lower legs is fully immersed and at 2.80 s the body becomes completely immersed in the water. Vortex structures are progressively shed from the hands, arms, torso and legs as the energy is transferred to the fluid and the body is decelerated.

As the initial pitch rotation increases the behaviour of the fluid and the athlete changes significantly. For Case 2 the body pitch increases strongly and quickly and the water cavity left behind by the body is larger in the forwards-rear direction (see Figure 5, at *t* = 2.53 s). The volume of water displaced is larger than for Case 1. The front side of the body from hands to shins have made contact with the water, changing the timing of fluid loading on the body. Due to the larger forwards-rear size of the induced water cavity, the vortex structures occupy a larger volume and the amount of splash is larger, extending both higher and wider. For Case 3, the cavity is even larger in the forwards-rear direction at 2.53 s. The entire body makes contact with the water meaning that the distribution and magnitudes of force are changed. The volume of displaced water and the size of the splash are further increased. These results suggest a direct relationship between angle of entry and the size of the splash and the magnitude and distribution of fluid forces on the body.

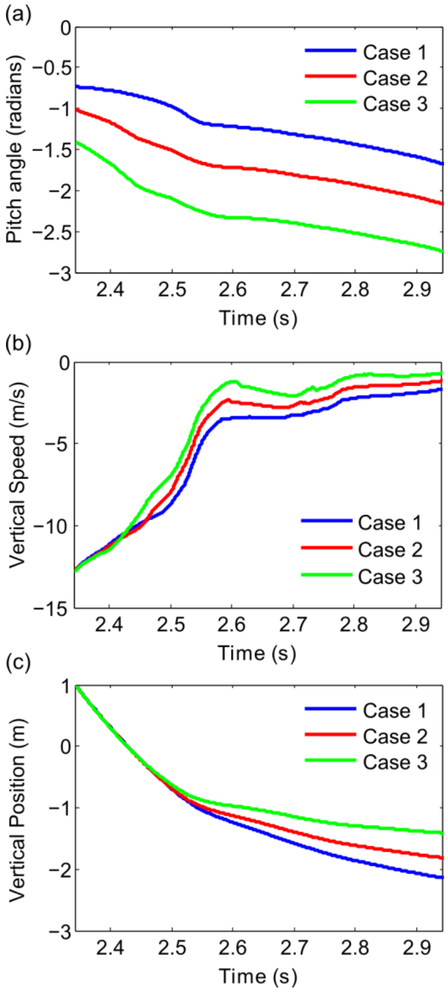

Figure 4: Pitch angle, vertical speed and vertical position of the centre of mass of the diver from the time of water entry (at *t* = 2.36 s), for the three entry pitch angles.

The differences in interaction between the athlete's body and the water for the three cases can be related to the differences in kinematics. As the entry pitch angle increases the projected area of the athlete into the plane of the water surface increases markedly. A larger projected area equates to larger drag forces from the water. These larger drag forces decelerate the athlete in a shorter amount of time.

The fluid force on the hands and torso are compared in Figure 6 for the three entry pitch angles. The fluid forces on the hands are very similar for all three cases, with only a small decrease with increasing angle. This is because the hands interact with the same undisturbed fluid at the same vertical speed. However, the first peak of force on the torso occurs earlier with increased pitch angle because the body rotates quicker and impacts the water earlier (see Figs 4 and 5). The force behaviour becomes similar again for all three cases after the torso is submerged (at 2.53 s). These earlier peaks of force on the torso in Cases 2 and 3 are additional loads on the body, which could add to injury risk.

Even though the extent of the variations in the fluid forces is not large, there is a strong dependence of peak joint torque on entry pitch angle. The net joint torques on the wrists are shown in Figure 7. They display two distinct peaks, one just after water impact and the other corresponding to when the arms move from above the head to the sides. In all three cases the magnitudes of joint torque are very large and near to the maximal limits of human abilities (Fukunaga et al., 2001). The net torques, particularly their peaks, increase with increasing pitch angle. In all cases, the net torque about the left wrist joint is approximately equal to that about the right wrist (which is not unreasonable since the dive is symmetric from left to right of the diver).

The joint torques are larger for the back than for the wrists and also dependent strongly on entry pitch angle (shown in Figure 8). They peak when the front of the torso makes contact with the fluid. This occurs earlier as the pitch angle increases. The torque in the lower back are larger than for the upper back, suggesting higher muscle and ligament forces and a larger risk of injury.

Whilst the peak fluid forces on the hands and torso did not increase significantly with increasing pitch angle, the wrist and back joint torques did increase strongly. As pitch angle increases, the body is less optimally posed to absorb the impact force from the water. The larger joint torques during Case 2 and Case 3 indicate that higher loading on the ligaments of the joints will occur and that larger muscle forces will be needed to stabilise the arm joints and the lower back during impact with the water. These larger forces are more likely to cause injuries.

The importance of correct joint orientation in relation to the direction of fluid loading is also indicated by the differing timing of peaks of force and joint torque. For instance, whilst fluid forces on the hand peak sharply within the first 100 ms, the joint torques at the wrists are large over the first 600 ms. These results suggest that analysis of fluid forces on limb segments alone is not sufficient for determining the timing and locations of possibly injurious loading during diving.

As high joint torques are an indicator of injury likelihood, our simulation results suggest that

1. the likelihood of musculoskeletal injury in the joints of the arm and the back is high, especially during the first 600 ms of water impact and when the arms are used to slow the body; and
2. the likelihood of musculoskeletal injury in the wrists and back increases strongly when the pitch angle increases away from a vertical entry.

It is worth noting that the joint torques may vary significantly when the form of the dive is altered, such as when somersaults and/or twists are added or when a rip entry is used (Brown et al., 1984). This will be the subject of future studies.

CONCLUSION

A coupled Biomechanical-SPH model of platform diving was developed. Using both digitised motion and a 3D laser scan of an Olympic athlete, a dynamic simulation, including water and diver-water interactions, of a reverse pike dive was performed. The effect of entry pitch angle was also explored. Dynamic interaction between the diver and the water and joint torques has not previously been predicted. The novel simulation framework allows the prediction of forces imparted onto the body and the resulting torques that are generated at key joints. This broadens the options for evaluation and optimisation of the performance of an athlete and the water behaviour resulting from the dive.

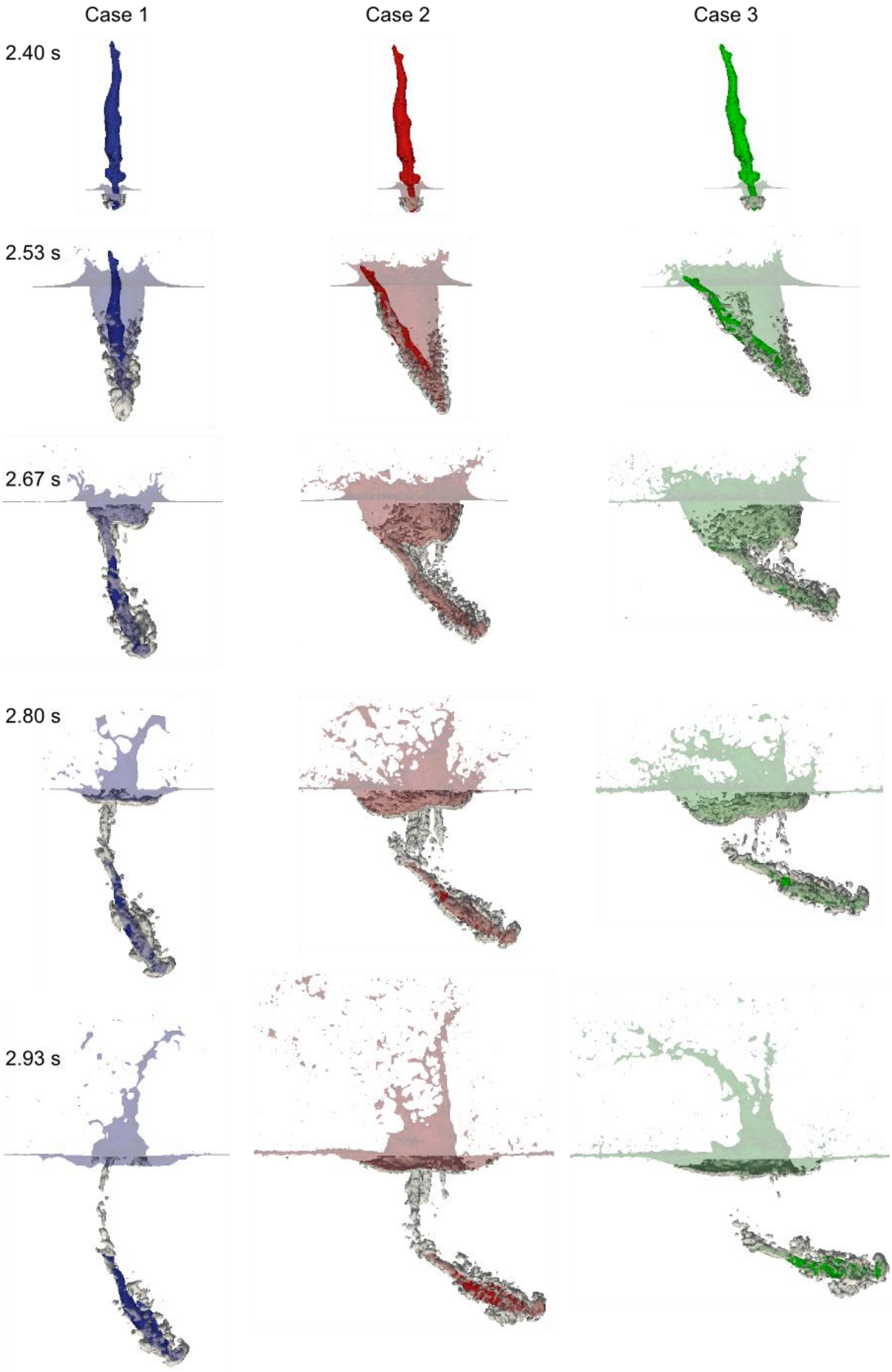

Figure 5: Visual comparison of the motion of the diver, the fluid free surface and 3D vortex structures for the three simulation cases (0°, 5° and 10° offset entry pitch angle),. The rows show the situation at five times from initial water impact onwards.

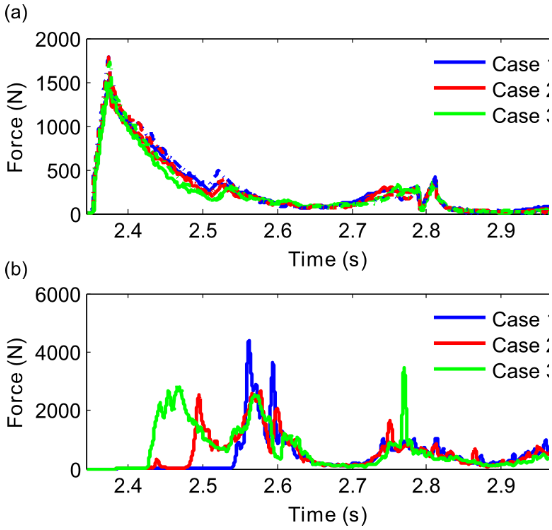

Figure 6: Magnitude of net force on (a) the hands and (b) the torso after water entry at *t* = 2.36 s for the three entry pitch angles.

Simulation results indicated that the body is decelerated over a small time period, resulting in large forces being imparted to the body by the water. Joint torques were large for all simulation cases, suggesting the presence of large muscle, ligament and joint forces in the wrists and lower back. These large loads are likely to be correlated to the known high risk of injuries to the wrists and lower back. Larger joint torques occurred in the wrists and the back as entry pitch angle was increased. As fluid forces on the hands and torso did not show the same dependence on pitch angle, the orientation and pose of the body must be the critical determinants of torque magnitude. Future work will investigate these relationships for more complicated dives and entries, and will involve the calculation of muscle and joint forces.

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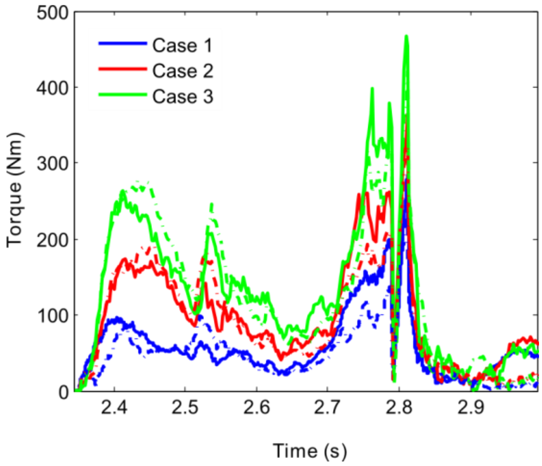

Figure 7: Magnitude of net torque about the right wrist joint (solid lines) and the left wrist joint (dashed lines) after water entry at *t* = 2.36 s for the three entry pitch angles.

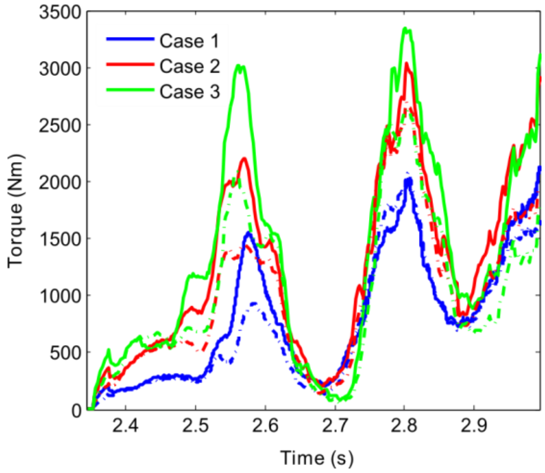

Figure 8: Magnitudes of net torque about the upper back (dashed lines) and lower back (solid lines) after water entry at *t* = 2.36 s for the three entry pitch angles.

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